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Linear Control Systems Engineering

线性控制系统工程

Morris Driels

清华大学出版社
http://www.tup.tsinghua.edu.cn

McGraw-Hill
http://www.mhhe.com

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清华大学出版社 McGraw-Hill

(京)新登字 158 号

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“国际知名大学原版教材系列”是由清华大学出版社和施普林格出版社共同策划。

This series of “Textbooks Adopted by World-famous Universities” is organized by Tsinghua University Press and Springer-Verlag.

图书在版编目(CIP)数据

线性控制系统工程:英文/(美)德赖斯(Driels, M.)著. —北京:清华大学出版社,2000.12
国际知名大学原版教材,信息技术与电气工程系列

ISBN 7-302-04141-5

Ⅰ.线… Ⅱ.①德… Ⅲ.①线性系统(自动化):控制系统-系统工程-高等学校-教材-英文 Ⅳ.TP271

中国版本图书馆 CIP 数据核字(2000)第 78373 号

出版者:清华大学出版社(北京清华大学学研大厦,邮编 100084)
http://www.tup.tsinghua.edu.cn
印刷者:清华大学印刷厂
发行者:新华书店总店北京发行所
开　本:787×960 1/16　印张:40.5
版　次:2000 年 12 月第 1 版　2000 年 12 月第 1 次印刷
书　号:ISBN 7-302-04141-5/TP·2444
印　数:0001~3000
定　价:54.00 元

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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。

Linear Control Systems Engineering

影印版序

由 Morris Driels 编著的“Linear Control Systems Engineering”一书出版于 1995 年。本书的定位是要为机械工程、电机工程、电子工程、计算机工程等非控制工程专业的本科生提供一本内容适度、实用性强和学时较少的控制理论教材。内容覆盖了经典控制理论和现代控制理论的基础部分，方法包括了频率响应法、根轨迹法和状态空间法。本书已被美国多所知名大学采用作为机械工程等专业的本科层次的控制理论教材或主要教学参考书。

书本的特点是，从非控制工程专业本科生对控制理论的需求和教学学时相对要少的实情出发，相比于流行的控制工程专业控制理论教材，在体系结构和内容安排上作了富有新意的改革。

(1)打破了章节式结构的常规，将全书的理论和方法的内容分解为相对独立的 25 个专题。每个专题作为一个教学单位时间的授课材料，各个专题具有大体相当的份量。并且，区分不同的情况，有的只由一个专题构成一个知识主题，有的则由二到三个专题构成一个知识主题。全书由若干个知识主题所组成，如反馈控制引论，一阶系统，二阶系统，高阶系统，基于稳态误差的系统分类，根轨迹法，Nyquist 分析，Bode 分析，频率响应法，系统补偿，状态空间描述，状态空间分析，状态空间设计等。

(2)打破了按一个结论引入例子的惯例，对每个专题都集中提供有相应的 3 个左右的具有实际工程背景的例子，以比较实际的方式来具体说明专题知识的运用，同时还配备有一批习题供学生来自行检验对专题知识的掌握。

(3)打破了只讲理论方法不讲案例研究的传统，在书中的最后部分专门给出有 7 个控制系统设计的案例研究的专题。例如，波能吸收装载，导弹姿态控制，机械手，液位控制，船舶驾驶控制，巡航导弹姿态控制，具有柔性的机床的功率驱动系统等。这些案例研究，问题来自专业工程，系统类型实际多样，设计方法选择不同，知识运用综合灵活。

本书作者的教学实践表明，这种体系结构和内容安排已经取得了很好的效果，通过较少的教学学时，既加深了学生对基本理论和基本方法的理解深度和运用能力，也提高了学生运用所学知识解决实际工程问题的能力，这对于非控制工程专业本科生的知识需要和认识规律无疑是很合适的。

本书可作为机械工程、电机工程、电子工程、计算机工程等非控制工程的各类工科专业的本科生作为教材或教学参考书之用，也可供相应领域的工程师和技术人员作为自学之用。

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清华大学自动化系
2000 年 10 月

About the Author

MORRIS DRIELS received his B.S. in Mechanical Engineering from the University of Surrey, and Ph.D. from City University, London. After working in the aerospace industry for some time, he became a Lecturer at Edinburgh University, Scotland. Moving to the United States in 1982, he held positions at the University of Rhode Island and Texas A&M. He is currently Professor in the Mechanical Engineering Department at the Naval Postgraduate School in Monterey, California. Dr. Driels is a Member of ASME, IEEE and a Fellow of The Institution of Mechanical Engineers.

Preface

Although I have been teaching linear control systems engineering to mechanical engineering undergraduate students for the last twenty years or so, I was never motivated to write a book on the subject until I had the opportunity to teach controls together with a first course in dynamics in the same academic quarter. This enabled me to directly compare the structure, style, and student use of the required texts in each subject. Such a comparison proved quite enlightening.

Both books had been around for more than a decade and had been through several editions. The controls book was, at the time, the best seller, as was the dynamics book. Their styles, however, were very different. The dynamics book was written in the following format:

- The subject matter was grouped into discrete amounts of material that could be comfortably covered in one lecture.
- Following this, two or three worked problems showed the student how this material is used to solve engineering problems.
- Finally, several homework problems were provided to enable the student to test his or her knowledge of the material.

The controls book was written in a more traditional style comprising chapters of around fifty pages followed by twenty or so problems.

In teaching both courses, it was apparent that the students made more use of the dynamics book; they were not overwhelmed by the amount of material covered in a class, and the abundance of solved and homework problems ensured a self-assessment of their understanding of the material and gave students a better perspective of the structure of the subject. From a professor's point of view, having the material already divided up into lecture-size pieces made the job of planning the course program much easier.

In this book, I have attempted to use the same philosophy as the dynamics books I have just described. I hope that the modular nature of the material will enable the book to be closely allied to the course of lectures, although there is still sufficient flexibility to allow the instructor the option of including additional topics or skipping over material he or she thinks the student already knows. Based on the student reviews of controls courses I have taught, the consensus on problem solving seems to be (a) there can never be too many solved problems and

(b) more detailed solutions to solved problems are welcome. I have attempted to address both these issues in this book. In particular, detailed solved problems are included at the end of each module so that the student may see the applicability of the material just covered. In order to provide students with an understanding of how control system analysis provides a basic tool in the design of complex engineering systems, I have also added several design case studies after Module 25. In many cases, these examples show alternative methods to achieve the required performance, and provide the student with a perspective of how the various analytical topics presented in the book may be used, combined, and applied to real engineering systems.

Originally, this book was intended primarily for undergraduate mechanical engineering students, although other engineering disciplines should find the material not too far from their own area. In most of these areas, a traditional systems stream would comprise:

- An introductory systems modeling course—sophomore level
- A linear controls systems course—junior level
- An advanced controls course—senior level

This book is aimed at the junior-level course and assumes the student is already familiar with systems modeling. Some material in this area is included in this book, but only to provide a smooth transition into controls rather than to teach techniques for modeling physical systems.

With regard to the issue of provision of software for the book, the objective has been to emphasize the fundamentals of control and not to become focused on computational techniques or tools. The student is encouraged to use whatever software is available to him or her, and where appropriate, examples have been given using FORTRAN, BASIC code, as well as proprietary packages such as MATLAB. For some of the problems in the text, involving laborious, though not difficult, manipulations, commercial packages such as MATLAB or $MATRIX_X$ are highly recommended.

Finally, I must thank a great number of people who have helped me write this book. The staff at McGraw-Hill have made the production process as near enjoyable as any author could reasonably expect. My students and colleagues at Edinburgh University, University of Rhode Island, Texas A&M, and the Naval Postgraduate School all deserve mention for their enthusiasm in reviewing material, discussing problems, and generally supporting my efforts over a considerable number of years. Special mention is due to Alan Linnett, Fotis Papoulias, and Tony Healey. The following reviewers provided many helpful comments and suggestions: Larry Banta, West Virginia University; Neyram Hemati, Drexel University; David Hullendar, University of Texas at Arlington; Leo LaFrance, New Mexico State University; Ronald A. Perez, University of Wisconsin, Milwaukee; and Gary Young, Oklahoma State University. All errors in the text are mine. Finally, the most thanks are due to my wife, Jenny, and children, Joanne, Chris, and Fiona. They supplied endless encouragement, help, motivation, and the ability to view all of life's pleasures and disappointments in the correct perspective.

Morris Driels

Contents

Introduction to Feedback Control

Feedback control systems are at work all around us. The study of control systems involves not so much the development of new engineering components or machines, but taking combinations of existing hardware to achieve a predetermined goal. A control *system* is the collection of components connected in such a way as to effect *control* over certain aspects of the domain in which the system operates. Control systems operate in almost every aspect of human activity, including walking, talking, and handling objects. In addition, control systems exist that require no human interaction, such as aircraft automatic pilots and automobile cruise control systems.

In dealing with control systems, particularly engineering control systems, we will deal with a variety of components, indicating that the subject is an interdisciplinary one. The control engineer needs a working knowledge of mechanics, electronics, electrical machines, fluid mechanics, thermodynamics, structures, material properties, and so on. Obviously not every control system contains elements from each of the above domains, but most useful control systems contain elements from more than one discipline.

Control system *analysis* involves the uniform treatment of different engineering components. What this means is that we try to represent the system elements in a common format and identify the connections between the elements in a similar way. When we do this, most control systems look the same in schematic form and lend themselves to common methods of analysis. This process usually involves a technique known as *block diagram representation,* discussed in Module 2, where each component is reduced to its basic function with one input variable and one output variable, the relationship between them known as a *transfer function.*

At this stage it is best to focus the discussion so far into a simple example. Suppose we attempt to analyze the mechanism at work when we adjust the water

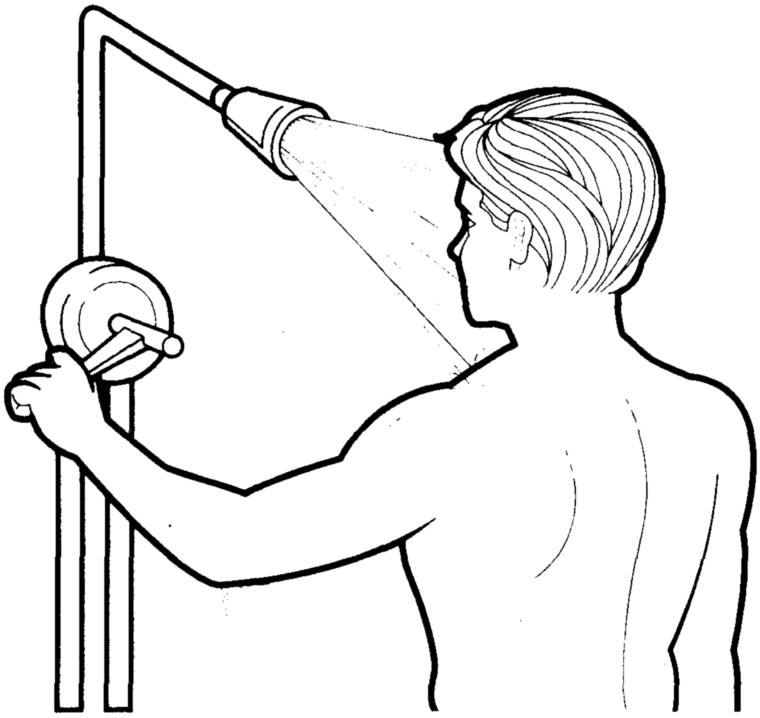

Fig. 1.1 Water temperature control system

temperature while taking a shower. The major components of the system are shown in Fig. 1.1. When we get into the shower, we have some idea of the water temperature we want. This temperature is not known in an absolute sense, such as 82 degrees, but qualitatively, such as cold, warm, or hot. Temperature sensors in our skin effectively measure the water temperature and convey the information to the brain, where it is compared to the water temperature we want. The brain computes the difference in terms of "too hot" or "too cold" and causes the hand muscles to manipulate the hot and cold mixer valve to reduce the temperature if it is too hot or increase the temperature if it is too cold. Once corrective action is taken, the process is repeated until the required water temperature is achieved.

The operation of the system and its major components are shown in Fig. 1.2. The boxes in the diagram represent processes that perform subtasks of the overall

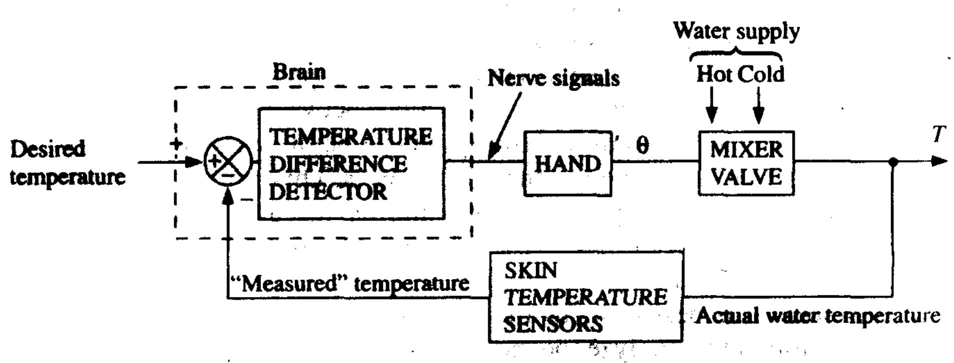

Fig. 1.2 System representation of temperature control

objective, such as measure the water temperature or actuate (move) the mixer valve. Such boxes transfer the input variable to the output variable by means of the transfer function mentioned previously. Some transfer functions are easily calculated, such as the mixer valve. This element has the valve handle angle θ as input variable and water temperature T as output variable. Making assumptions regarding the linearity of the valve might lead to the relationship

$$T = K_T\theta \tag{1.1}$$

where K_T may be defined as the valve temperature constant. Other transfer functions, such as the relationship between the nerve signals passing between the brain and the hand and the rotation of the mixer handle, will be much more difficult to represent in simple mathematical form.

The system described above will now be represented in the somewhat abstract form shown in Fig. 1.3. The purpose of doing this is because most control systems can be represented in the form of Fig. 1.3, and so analytical methods developed for use on this system will be applicable to most control problems without reference to the physical embodiment of the various elements. Shown in Fig. 1.3 is some of the terminology used throughout the book. Generally the plant represents the major component that is being controlled, and its transfer function is usually fixed. The controller is a component that the engineer designs using techniques outlined later in the book, so that the "best" performance may be obtained from the overall system. The feedback path is a critical part of the system and indicates how the output variable of interest from the plant (temperature in this case) is measured and fed back to be compared with the desired value. The magnitude of the error causes changes in the input to the plant, resulting in further changes in the output.

In the simplest controller design, the output is made proportional to the input. In our example, if the water temperature is far too cold, then the mixer handle is turned to maximize the hot-water content downstream of the valve. As the water temperature approaches the required value, smaller changes in the handle position occur. When the water is at the desired temperature, the two inputs to the differencing junction are equal and the output is zero, as is the output of the controller. The plant is therefore unperturbed and the whole system is in equilibrium.

The water temperature control system described above has a human as part of the control loop. For the immediate future, many control systems will continue

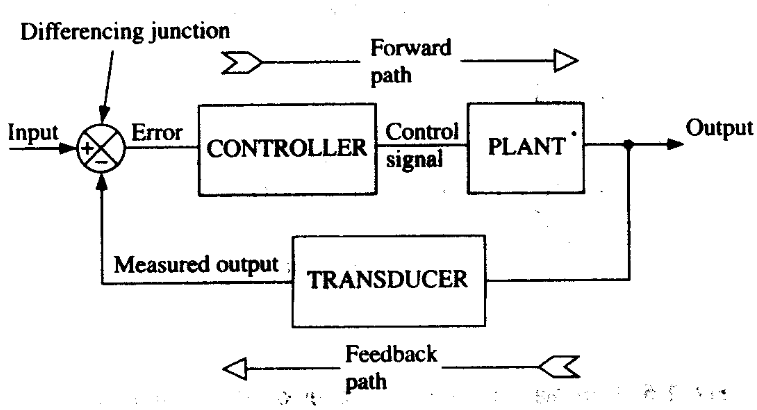

Fig. 1.3 Generalized feedback control system