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COMPUTER-CONTROLLED SYSTEMS

Theory and Design

(Third Edition)

计算机控制系统 理论与设计

（第3版）

KARL J. ÅSTRÖM
BJÖRN WITTENMARK

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THIRD EDITION

Karl J. Åström

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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"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。

Computer-Controlled Systems——Theory and Design

Third Edition

影印版序

由 K. J. Åström 和 B. Wittenmark 编著的"Computer-Controlled Systems——Theory and Design"一书初版于 1984 年。本书为第 3 版，出版于 1997 年。本书作者在国际控制界具有很高知名度。本书及前期版本被国外许多大学用作本科生高年级或研究生的教材。该书第 1 版曾被译成中文，在国内有相当影响。

随着计算机技术的迅速发展和应用的日益普及，越来越多的控制系统采用计算机进行控制。本书正是针对这种情况，对计算机控制系统的分析、设计和建模等问题进行了系统的介绍。

根据作者多年教学工作的经验积累并为适应技术进步的需求，新版对材料进行了彻底的重新组织，一半以上内容是重写的。由于对原有材料进行了适当的裁减，虽然书中加进了许多新的成果，与原版相比，整书的篇幅并未增加。

本书注意理论联系实际，书中不仅给出理论的结果，而且给出实用的算法和对一些实际问题的考虑。同时引入了 MATLAB 及 SIMULINK 作为计算机辅助设计控制系统的软件工具，从而使所介绍的理论和方法更易于被接受和应用。

全书共分 13 章，第 1 章概述了计算机控制系统的历史与发展，通过举例说明了计算机控制系统的主要特点。第 2 到第 5 章的内容从面向计算机的观点，仅讨论采样时刻系统的行为，以简化对系统的分析和设计。其中第 2 章介绍如何通过对连续系统进行采样得到离散系统，既包括状态模型也包括输入输出模型。第 3 章讨论离散系统的分析，包括稳定性、能控能观性及鲁棒性等。第 4 章讨论基于状态空间方法的极点配置法。第 5 章讨论基于多项式方法的极点配置法。

第 6 章讨论控制系统设计的一般方法，包括大系统的结构及由底向上和自顶向下技术。第 7 章从面向过程的观点讨论包括采样点之间的系统行为，如信号的采样与恢复及频率响应的混叠等。第 8 章介绍连续控制器的离散等效，包括基于传递函数和状态方法的近似等效、频率响应设计方法及数字 PID 控制器等内容。第 9 章介绍数字控制器实现中的一些实际问题，如计算延时、量化效应、前置滤波器及编程等。

第 10 章到第 12 章介绍一些更先进的优化设计方法。第 10 章介绍各种干扰模型，为其后的优化设计准备了必要的基础知识。第 11 章介绍基于状态空间的优化设计方法，包括线性二次型最优控制、状态最优估计及 LQG 控制。第 12 章介绍基于传递函数的优化设计方法，包括最优预报及最小方差控制等。

第 13 章内容相对独立，用一章的篇幅扼要介绍了系统辨识的内容，重点介绍了最小二乘的参数估计原理及算法。

本书每章后面均附有总结、习题和参考文献，以帮助读者抓住每章的知识要点和巩固所学的内容。

本书内容丰富、取材适当，兼顾了系统性、先进性和实用性等方面的要求。

学习本书内容需要具备一般控制原理的基本知识。该书可作为工程专业的研究生或有选择地作为本科高年级学生的教材或参考书。

孙增圻
清华大学计算机科学与技术系
2001 年 9 月

Preface

A consequence of the revolutionary advances in microelectronics is that practically all control systems constructed today are based on microprocessors and sophisticated microcontrollers. By using computer-controlled systems it is possible to obtain higher performance than with analog systems, as well as new functionality. New software tools have also drastically improved the engineering efficiency in analysis and design of control systems.

Goal of the book This book provides the necessary insight, knowledge, and understanding required to effectively analyze and design computer-controlled systems.

The new edition This third edition is a major revision based on the advances in technology and the experiences from teaching to academic and industrial audiences. The material has been drastically reorganized with more than half the text rewritten. The advances in theory and practice of computer-controlled systems and a desire to put more focus on design issues have provided the motivation for the changes in the third edition. Many new results have been incorporated. By ruthless trimming and rewriting we are now able to include new material without increasing the size of the book. Experiences of teaching from a draft version have shown the advantages of the changes. We have been very pleased to note that students can indeed deal with design at a much earlier stage. This has also made it possible to go much more deeply into design and implementation.

Another major change in the third edition is that the computational tools MATLAB® and SIMULINK® have been used extensively. This changes the pedagogy in teaching substantially. All major results are formulated in such a way that the computational tools can be applied directly. This makes it easy to deal with complicated problems. It is thus possible to deal with many realistic design issues in the courses. The use of computational tools has been balanced by a strong emphasis of principles and ideas. Most key results have also been illustrated by simple pencil and paper calculations so that the students understand the workings of the computational tools.

Outline of the Book

Background Material A broad outline of computer-controlled systems is presented in the first chapter. This gives a historical perspective on the development of computers, control systems, and relevant theory. Some key points of the theory and the behavior of computer-control systems are also given, together with many examples.

Analysis and Design of Discrete-Time Systems It is possible to make drastic simplifications in analysis and design by considering only the behavior of the system at the sampling instants. We call this the computer-oriented view. It is the view of the system obtained by observing its behavior through the numbers in the computer. The reason for the simplicity is that the system can be described by linear difference equations with constant coefficients. This approach is covered in Chapters 2, 3, 4 and 5. Chapter 2 describes how the discrete-time systems are obtained by sampling continuous-time systems. Both state-space models and input-output models are given. Basic properties of the models are also given together with mathematical tools such as the z-transform. Tools for analysis are presented in Chapter 3.

Chapter 4 deals with the traditional problem of state feedback and observers, but it goes much further than what is normally covered in similar textbooks. In particular, the chapter shows how to deal with load disturbances, feedforward, and command-signal following. Taken together, these features give the controller a structure that can cope with many of the cases typically found in applications. An educational advantage is that students are equipped with tools to deal with real design issues after a very short time.

Chapter 5 deals with the problems of Chapter 4 from the input-output point of view, thereby giving an alternative view on the design problem. All issues discussed in Chapter 4 are also treated in Chapter 5. This affords an excellent way to ensure a good understanding of similarities and differences between state-space and polynomial approaches. The polynomial approach also makes it possible to deal with the problems of modeling errors and robustness, which cannot be conveniently handled by state-space techniques.

Having dealt with specific design methods, we present general aspects of the design of control systems in Chapter 6. This covers structuring of large systems as well as bottom-up and top-down techniques.

Broadening the View Although many issues in computer-controlled systems can be dealt with using the computer-oriented view, there are some questions that require a detailed study of the behavior of the system between the sampling instants. Such problems arise naturally if a computer-controlled system is investigated through the analog signals that appear in the process. We call this the process-oriented view. It typically leads to linear systems with periodic coefficients. This gives rise to phenomena such as aliasing, which may lead to very undesirable effects unless special precautions are taken. It is very important to understand both this and the design of anti-aliasing filters when investigating computer-controlled systems. Tools for this are developed in Chapter 7.

When upgrading older control equipment, sometimes analog designs of controllers may be available already. In such cases it may be cost effective to have methods to translate analog designs to digital control directly. Methods for this are given in Chapter 8.

Implementation It is not enough to know about methods of analysis and design. A control engineer should also be aware of implementation issues. These are treated in Chapter 9, which covers matters such as prefiltering and computational delays, numerics, programming, and operational aspects. At this stage the reader is well prepared for all steps in design, from concepts to computer implementation.

More Advanced Design Methods To make more effective designs of control systems it is necessary to better characterize disturbances. This is done in Chapter 10. Having such descriptions it is then possible to design for optimal performance. This is done using state-space methods in Chapter 11 and by using polynomial techniques in Chapter 12. So far it has been assumed that models of the processes and their disturbances are available. Experimental methods to obtain such models are described in Chapter 13.

Prerequisites

The book is intended for a final-year undergraduate or a first-year graduate course for engineering majors. It is assumed that the reader has had an introductory course in automatic control. The book should be useful for an industrial audience.

Course Configurations

The book has been organized so that it can be used in different ways. An introductory course in computer-controlled systems could cover Chapters 1, 2, 3, 4, 5, and 9. A more advanced course might include all chapters in the book. A course for an industrial audience could contain Chapters 1, parts of Chapters 2, 3, 4, and 5, and Chapters 6, 7, 8, and 9. To get the full benefit of a course, it is important to supplement lectures with problem-solving sessions, simulation exercises, and laboratory experiments.

Computational Tools

Computer tools for analysis, design, and simulation are indispensable tools when working with computer-controlled systems. The methods for analysis and design presented in this book can be performed very conveniently using MATLAB®. Many of the exercises also cover this. Simulation of the system can similarly be done with Simnon® or SIMULINK®. There are 30 figures that illustrate various aspects of analysis and design that have been performed using MATLAB®, and 73 figures from simulations using SIMULINK®. Macros and m-files are available from anonymous FTP from `ftp.control.lth.se`, directory `/pub/books/ccs`. Other tools such as Simnon® and Xmath® can be used also.

Supplements

Complete solutions are available from the publisher for instructors who have adopted our book. Simulation macros, transparencies, and examples of examinations are available on the World Wide Web at `http://www.control.lth.se`; see Education/Computer-Controlled Systems.

Wanted: Feedback

As teachers and researchers in automatic control, we know the importance of feedback. Therefore, we encourage all readers to write to us about errors, potential miscommunications, suggestions for improvement, and also about what may be of special valuable in the material we have presented.

Acknowledgments

During the years that we have done research in computer-controlled systems and that we have written the book, we have had the pleasure and privilege of interacting with many colleagues in academia and industry throughout the world. Consciously and subconsciously, we have picked up material from the knowledge base called computer control. It is impossible to mention everyone who has contributed ideas, suggestions, concepts, and examples, but we owe each one our deepest thanks. The long-term support of our research by the Swedish Board of Industrial and Technical Development (NUTEK) and by the Swedish Research Council for Engineering Sciences (TFR) are gratefully acknowledged.

Finally, we want to thank some people who, more than others, have made it possible for us to write this book. We wish to thank Leif Andersson, who has been our TEXpert. He and Eva Dagnegård have been invaluable in solving many of our TEX problems. Eva Dagnegård and Agneta Tuszynski have done an excellent job of typing many versions of the manuscript. Most of the illustrations have been done by Britt-Marie Mårtensson. Without all their patience and understanding of our whims, never would there have been a final book. We also want to thank the staff at Prentice Hall for their support and professionalism in textbook production.

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Contents

1

Computer Control

1.1 Introduction

Practically all control systems that are implemented today are based on computer control. It is therefore important to understand computer-controlled systems well. Such systems can be viewed as approximations of analog-control systems, but this is a poor approach because the full potential of computer control is not used. At best the results are only as good as those obtained with analog control. It is much better to master computer-controlled systems, so that the full potential of computer control can be used. There are also phenomena that occur in computer-controlled systems that have no correspondence in analog systems. It is important for an engineer to understand this. The main goal of this book is to provide a solid background for understanding, analyzing, and designing computer-controlled systems.

A computer-controlled system can be described schematically as in Fig. 1.1. The output from the process $y(t)$ is a continuous-time signal. The output is converted into digital form by the analog-to-digital (A-D) converter. The A-D converter can be included in the computer or regarded as a separate unit, according to one's preference. The conversion is done at the sampling times, t_k. The computer interprets the converted signal, $\{y(t_k)\}$, as a sequence of numbers, processes the measurements using an algorithm, and gives a new sequence of numbers, $\{u(t_k)\}$. This sequence is converted to an analog signal by a digital-to-analog (D-A) converter. The events are synchronized by the real-time clock in the computer. The digital computer operates sequentially in time and each operation takes some time. The D-A converter must, however, produce a continuous-time signal. This is normally done by keeping the control signal constant between the conversions. In this case the system runs open loop in the time interval between the sampling instants because the control signal is constant irrespective of the value of the output.

The computer-controlled system contains both continuous-time signals and *sampled*, or *discrete-time*, signals. Such systems have traditionally been called

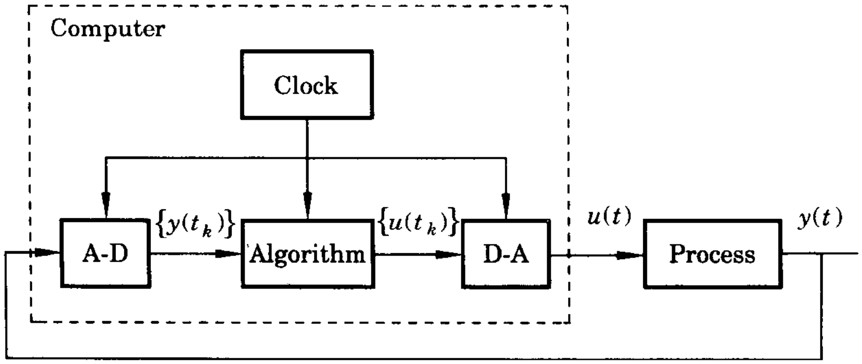

Figure 1.1 Schematic diagram of a computer-controlled system.

sampled-data systems, and this term will be used here as a synonym for *computer-controlled systems*.

The mixture of different types of signals sometimes causes difficulties. In most cases it is, however, sufficient to describe the behavior of the system at the sampling instants. The signals are then of interest only at discrete times. Such systems will be called *discrete-time systems*. Discrete-time systems deal with sequences of numbers, so a natural way to represent these systems is to use difference equations.

The purpose of the book is to present the control theory that is relevant to the analysis and design of computer-controlled systems. This chapter provides some background. A brief overview of the development of computer-control technology is given in Sec. 1.2. The need for a suitable theory is discussed in Sec. 1.3. Examples are used to demonstrate that computer-controlled systems cannot be fully understood by the theory of linear time-invariant continuous-time systems. An example shows not only that computer-controlled systems can be designed using continuous-time theory and approximations, but also that substantial improvements can be obtained by other techniques that use the full potential of computer control. Section 1.4 gives some examples of inherently sampled systems. The development of the theory of sampled-data systems is outlined in Sec. 1.5.

1.2 Computer Technology

The idea of using digital computers as components in control systems emerged around 1950. Applications in missile and aircraft control were investigated first. Studies showed that there was no potential for using the general-purpose digital computers that were available at that time. The computers were too big, they consumed too much power, and they were not sufficiently reliable. For this reason special-purpose computers—digital differential analyzers (DDAs)—were developed for the early aerospace applications.

The idea of using digital computers for process control emerged in the mid-1950s. Serious work started in March 1956 when the aerospace company Thomson Ramo Woodridge (TRW) contacted Texaco to set up a feasibility study. After preliminary discussions it was decided to investigate a polymerization unit at the Port Arthur, Texas, refinery. A group of engineers from TRW and Texaco made a thorough feasibility study, which required about 30 people-years. A computer-controlled system for the polymerization unit was designed based on the RW-300 computer. The control system went on-line March 12, 1959. The system controlled 26 flows, 72 temperatures, 3 pressures, and 3 compositions. The essential functions were to minimize the reactor pressure, to determine an optimal distribution among the feeds of 5 reactors, to control the hot-water inflow based on measurement of catalyst activity, and to determine the optimal recirculation.

The pioneering work done by TRW was noticed by many computer manufacturers, who saw a large potential market for their products. Many different feasibility studies were initiated and vigorous development was started. To discuss the dramatic developments, it is useful to introduce six periods:

Pioneering period $\approx$ 1955

Direct-digital-control period $\approx$ 1962

Minicomputer period $\approx$ 1967

Microcomputer period $\approx$ 1972

General use of digital control $\approx$ 1980

Distributed control $\approx$ 1990

It is difficult to give precise dates, because the development was highly diversified. There was a wide difference between different application areas and different industries; there was also considerable overlap. The dates given refer to the emergence of new approaches.

Pioneering Period

The work done by TRW and Texaco evoked substantial interest in process industries, among computer manufacturers, and in research organizations. The industries saw a potential tool for increased automation, the computer industries saw new markets, and universities saw a new research field. Many feasibility studies were initiated by the computer manufacturers because they were eager to learn the new technology and were very interested in knowing what a proper process-control computer should look like. Feasibility studies continued throughout the sixties.

The computer systems that were used were slow, expensive, and unreliable. The earlier systems used vacuum tubes. Typical data for a computer around 1958 were an addition time of 1 ms, a multiplication time of 20 ms, and a mean time between failures (MTBF) for a central processing unit of 50–100 h. To make full use of the expensive computers, it was necessary to have them perform many