国际知名大学原版教材 —— 信息技术学科与电气工程学科系列 10

# Digital Control of Dynamic Systems

Third Edition

# 动态系统的数字控制

第 3 版

Gene F. Franklin
J. David Powell
Michael Workman

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Prentice Hall 培科

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

培生教育出版集团
http://www.pearsoned.com

THIRD EDITION

# Digital Control of Dynamic Systems

京新登字 158 号


北京市版权局著作权合同登记号：图字 01-2001-3463

书　名：Digital Control of Dynamic Systems (Third Edition)
　　　　动态系统的数字控制(第 3 版)
作　者：Gene F. Franklin　J.David Powell
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：北京牛山世兴印刷厂
发行者：新华书店总店北京发行所
开　本：787×960 1/16　印张：48.5
版　次：2001 年 9 月第 1 版　2001 年 9 月第 1 次印刷
书　号：ISBN 7-302-04747-2/TP・2812
印　数：0001～3000
定　价：59.00 元

# 国际知名大学原版教材

——信息技术学科与电气工程学科系列

# 出　版　说　明

郑大钟

清华大学信息技术科学与技术学院

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。

# Digital Control of Dynamic Systems

(第 3 版)

## 影印版序

由 G. F. Franklin, J. D. Powell 和 M. Workman 编著的“Digital Control of Dynamic Systems”一书初版于 1980 年，本书为第三版，出版于 1998 年。本书及前版本被国外许多大学用作本科生高年级或研究生的教材。该书是国际上关于计算机控制的一本权威性教材。

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，着重对数字控制系统（即计算机控制系统）的分析、设计和建模等问题进行了系统的介绍。其中尤以较多篇幅讨论了数字控制系统的设计方法。同时对于一些实际问题，如采样周期的选择、量化效应的分析等也进行了深入的讨论，并且有单独一章及一个附录专门介绍数字控制的应用。

本书注重理论联系实际，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 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 14 章，第 1 章是概论，第 2 章对连续控制系统理论进行了简单的复习，第 3 章介绍了采样过程和离散化。第 2 章和第 3 章是该第 3 版新增加的内容，它主要是为本书所需先修内容作一简要介绍，为后续章节的学习打下了必要的基础。第 4 到第 6 章介绍离散和采样系统的基本分析方法，其中第 4 章介绍 Z 变换，第 5 章介绍采样数据系统，第 6 章讨论连续系统的近似离散等效。第 7 章到第 9 章介绍数字控制系统的各种设计方法，这一部分是全书的重点。其中第 7 章介绍基于数学变换的经典设计方法，第 8 章介绍基于状态空间的极点配置设计方法，第 9 章介绍多变量系统的二次型最优控制。第 10 章和第 11 章介绍计算机控制系统所特有的一些实际问题，其中第 10 章分析量化效应，第 11 章讨论采样周期的选择。第 12 章讨论数字控制系统的建模问题，介绍了系统辨识和参数估计。第 13 章简要介绍了非线性控制的有关问题。第 14 章介绍了磁盘驱动器的伺服控制设计，以作为数字控制系统的一个典型应用。附录中还给出了应用举例、Z 变换表、矩阵变换和运算、随机过程及 Matlab 函数等基本材料，以备查用。

本书每章后面均有总结和习题，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。

该书可作为与控制工程相关各专业的研究生或高年级本科生的教材或参考书。

孙增圻　教授

清华大学计算机科学与技术系

2001 年 7 月

# • Preface •

This book is about the use of digital computers in the real-time control of dynamic systems such as servomechanisms, chemical processes, and vehicles that move over water, land, air, or space. The material requires some understanding of the Laplace transform and assumes that the reader has studied linear feedback controls. The special topics of discrete and sampled-data system analysis are introduced, and considerable emphasis is given to the $z$-transform and the close connections between the $z$-transform and the Laplace transform.

The book's emphasis is on designing digital controls to achieve good dynamic response and small errors while using signals that are sampled in time and quantized in amplitude. Both transform (classical control) and state-space (modern control) methods are described and applied to illustrative examples. The transform methods emphasized are the root-locus method of Evans and frequency response. The root-locus method can be used virtually unchanged for the discrete case; however, Bode's frequency response methods require modification for use with discrete systems. The state-space methods developed are the technique of pole assignment augmented by an estimator (observer) and optimal quadratic-loss control. The optimal control problems use the steady-state constant-gain solution; the results of the separation theorem in the presence of noise are stated but not proved.

Each of these design methods—classical and modern alike—has advantages and disadvantages, strengths and limitations. It is our philosophy that a designer must understand all of them to develop a satisfactory design with the least effort.

Closely related to the mainstream of ideas for designing linear systems that result in satisfactory dynamic response are the issues of sample-rate selection, model identification, and consideration of nonlinear phenomena. Sample-rate selection is discussed in the context of evaluating the increase in a least-squares performance measure as the sample rate is reduced. The topic of model making is treated as measurement of frequency response, as well as least-squares parameter estimation. Finally, every designer should be aware that all models are nonlinear and be familiar with the concepts of the describing functions of nonlinear systems, methods of studying stability of nonlinear systems, and the basic concepts of nonlinear design.

Material that may be new to the student is the treatment of signals which are discrete in time and amplitude and which must coexist with those that are continuous in both dimensions. The philosophy of presentation is that new material should be closely related to material already familiar, and yet, by the end, indicate a direction toward wider horizons. This approach leads us, for example, to relate the $z$-transform to the Laplace transform and to describe the implications of poles and zeros in the $z$-plane to the known meanings attached to poles and zeros in the $s$-plane. Also, in developing the design methods, we relate the digital control design methods to those of continuous systems. For more sophisticated methods, we present the elementary parts of quadratic-loss Gaussian design with minimal proofs to give some idea of how this powerful method is used and to motivate further study of its theory.

The use of computer-aided design (CAD) is universal for practicing engineers in this field, as in most other fields. We have recognized this fact and provided guidance to the reader so that learning the controls analysis material can be integrated with learning how to compute the answers with MATLAB, the most widely used CAD software package in universities. In many cases, especially in the earlier chapters, actual MATLAB scripts are included in the text to explain how to carry out a calculation. In other cases, the MATLAB routine is simply named for reference. All the routines given are tabulated in Appendix E for easy reference; therefore, this book can be used as a reference for learning how to use MATLAB in control calculations as well as for control systems analysis. In short, we have tried to describe the entire process, from learning the concepts to computing the desired results. But we hasten to add that it is mandatory that the student retain the ability to compute simple answers by hand so that the computer's reasonableness can be judged. The First Law of Computers for engineers remains "Garbage In, Garbage Out."

Most of the graphical figures in this third edition were generated using MATLAB® supplied by The Mathworks, Inc. The files that created the figures are available from Addison Wesley Longman at *ftp.aw.com* or from The Mathworks, Inc. at *ftp.mathworks.com/pub/books/franklin*. The reader is encouraged to use these MATLAB figure files as an additional guide in learning how to perform the various calculations.

To review the chapters briefly: Chapter 1 contains introductory comments. Chapters 2 and 3 are new to the third edition. Chapter 2 is a review of the prerequisite continuous control; Chapter 3 introduces the key effects of sampling in order to elucidate many of the topics that follow. Methods of linear analysis are presented in Chapters 4 through 6. Chapter 4 presents the $z$-transform. Chapter 5 introduces combined discrete and continuous systems, the sampling theorem, and the phenomenon of aliasing. Chapter 6 shows methods by which to generate discrete equations that will approximate continuous dynamics. The basic deterministic design methods are presented in Chapters 7 and 8—the root-locus and frequency response methods in Chapter 7 and pole placement and estimators in Chapter 8. The state-space material assumes no previous acquaintance with the phase plane or state space, and the necessary analysis is developed from the ground up. Some familiarity with simultaneous linear equations and matrix notation is expected, and a few unusual or more advanced topics such as eigenvalues, eigenvectors, and the Cayley-Hamilton theorem are presented in Appendix C. Chapter 9 introduces optimal quadratic-loss control: First the control by state feedback is presented and then the estimation of the state in the presence of system and measurement noise is developed, based on a recursive least-squares estimation derivation.

In Chapter 10 the nonlinear phenomenon of amplitude quantization and its effects on system error and system dynamic response are studied. Chapter 11 presents methods of analysis and design guidelines for the selection of the sampling period in a digital control system. It utilizes the design methods discussed in Chapters 7, 8, and 9, in examples illustrating the effects of sample rate. Chapter 12 introduces both nonparametric and parametric identification. Nonparametric methods are based on spectral estimation. Parametric methods are introduced by starting with deterministic least squares, introducing random errors, and completing the solution with an algorithm for maximum likelihood. Sub-space methods are also introduced for estimating the state matrices directly. Nonlinear control is the subject of Chapter 13, including examples of plant nonlinearities and methods for the analysis and design of controllers for nonlinear models. Simulation, stability analysis, and performance enhancement by nonlinear controllers and by adaptive designs are also included in Chapter 13. The chapter ends with a nonlinear design optimization alternative to the techniques presented in Chapter 9. The final chapter, 14, is a detailed design example of a digital servo for a disk drive head. Table P.1 shows the differences between the second and third editions of the book.

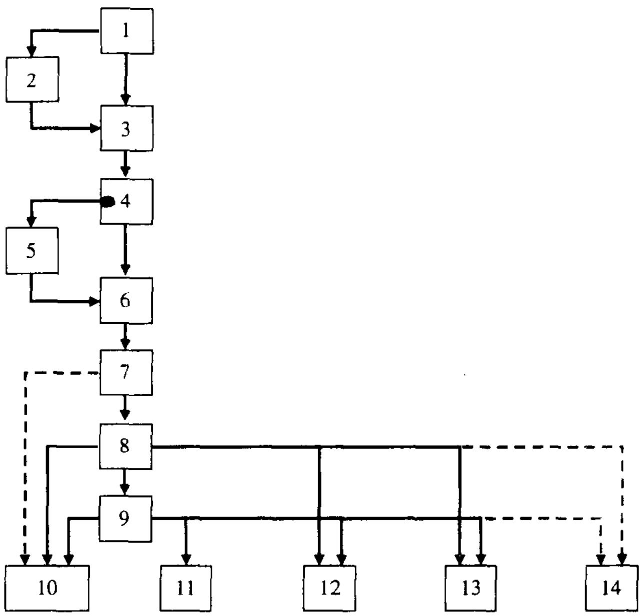
For purposes of organizing a course, Fig. P.1 shows the dependence of material in each chapter on previous chapters. By following the solid lines, the reader will have all the background required to understand the material in a particular chapter, even if the path omits some chapters. Furthermore, sections with a star (*) are optional and may be skipped with no loss of continuity. Chapters may also be skipped, as suggested by the dashed lines, if the reader is willing to take some details on faith; however, the basic ideas of the later chapters will be understood along these paths.

The first seven chapters (skipping or quickly reviewing Chapter 2) constitute a comfortable one-quarter course that would follow a course in continuous linear control using a text such as Franklin, Powell, and Emami-Naeini (1994). For a one-semester course, the first eight chapters represent a comfortable load. The

**Table P.1 Comparison of the Table of Contents**

| Chapter Title | 3rd Edition Chapter Number | 2nd Edition Chapter Number |
|---|---|---|
| Introduction | 1 | 1 |
| Review of Continuous Control | 2 | – |
| Introductory Digital Control | 3 | – |
| Discrete Analysis and the $z$-Transform | 4 | 2 |
| Sampled Data Systems | 5 | 3 |
| Discrete Equivalents | 6 | 4 |
| Design Using Transform Methods | 7 | 5 |
| Design Using State-Space Methods | 8 | 6 |
| Multivariable and Optimal Control | 9 | 9 |
| Quantization Effects | 10 | 7 |
| Sample-Rate Selection | 11 | 10 |
| System Identification | 12 | 8 |
| Nonlinear Control | 13 | 11 |
| Application of Digital Control | 14 | 12 |

**Figure P.1**




content of a second course has many possibilities. One possibility is to combine Chapters 8 and 9 with Chapter 10, 11, or 12. As can be seen from the figure, many options exist for including the material in the last five chapters. For a full-year course, all fourteen chapters can be covered. One of the changes made in this third edition is that the optimal control material no longer depends on the least-squares development in the system identification chapter, thus allowing for more flexibility in the sequence of teaching.

It has been found at Stanford that it is very useful to supplement the lectures with laboratory work to enhance learning. A very satisfactory complement of laboratory equipment is a digital computer having an A/D and a D/A converter, an analog computer (or equivalent) with ten operational amplifiers, a digital storage scope, and a CAD package capable of performing the basic computations and plotting graphs. A description of the laboratory equipment and experiments at Stanford is described in Franklin and Powell, *Control System Magazine* (1989).

There are many important topics in control that we have not been able to include in this book. There is, for example, no discussion of mu analysis or design, linear matrix inequalities, or convex optimization. It is our expectation, however, that careful study of this book will provide the student engineer with a sound basis for design of sampled-data controls and a foundation for the study of these and many other advanced topics in this most exciting field.

As do all authors of technical works, we wish to acknowledge the vast array of contributors on whose work our own presentation is based. The list of references gives some indication of those to whom we are in debt. On a more personal level, we wish to express our appreciation to Profs. S. Boyd, A. Bryson, R. Cannon, S. Citron, J. How, and S. Rock for their valuable suggestions for the book and especially to our long-time colleague, Prof. Dan DeBra, for his careful reading and many spirited suggestions. We also wish to express our appreciation for many valuable suggestions to the current and former students of E207 and E208, for whom this book was written.

In addition, we want to thank the following people for their helpful reviews of the manuscript: Fred Bailey, University of Minnesota; John Fleming, Texas A&M University; J.B. Pearson, Rice University; William Perkins, University of Illinois; James Carroll, Clarkson University; Walter Higgins, Jr., Arizona State University; Stanley Johnson, Lehigh University; Thomas Kurfess, Georgia Institute of Technology; Stephen Phillips, Case Western Reserve University; Chris Rahn, Clemson University; T. Srinivasan, Wilkes University; Hal Tharp, University of Arizona; Russell Trahan, Jr., University of New Orleans; and Gary Young, Oklahoma State University.

We also wish to express our appreciation to Laura Cheu, Emilie Bauer, and all the staff at Addison-Wesley for their quality production of the book.

*Stanford, California*

G.F.F
J.D.P
M.L.W.

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