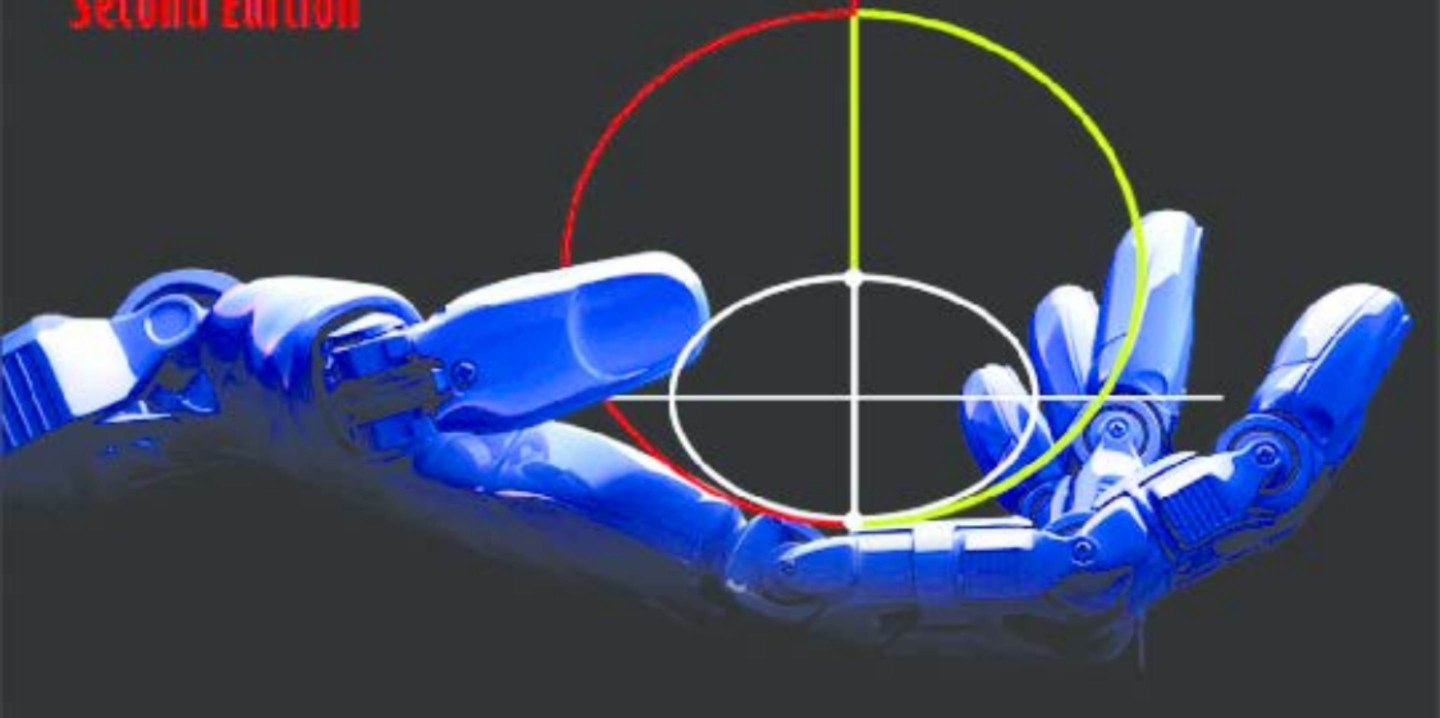
DIGITAL CONTROL ENGINEERING

Analysis and Design

Second Edition



M. SAMI FADALI   ANTONIO VISIOLI

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M. Sami Fadali

Antonio Visioli

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Preface

Approach

Control systems are an integral part of everyday life in today's society. They control our appliances, our entertainment centers, our cars, and our office environments; they control our industrial processes and our transportation systems; they control our exploration of land, sea, air, and space. Almost all of these applications use digital controllers implemented with computers, microprocessors, or digital electronics. Every electrical, chemical, or mechanical engineering senior or graduate student should therefore be familiar with the basic theory of digital controllers.

This text is designed for a senior or combined senior/graduate-level course in digital controls in departments of mechanical, electrical, or chemical engineering. Although other texts are available on digital controls, most do not provide a satisfactory format for a senior/graduate-level class. Some texts have very few examples to support the theory, and some were written before the wide availability of computer-aided-design (CAD) packages. Others use CAD packages in certain ways but do not fully exploit their capabilities. Most available texts are based on the assumption that students must complete several courses in systems and control theory before they can be exposed to digital control. We disagree with this assumption, and we firmly believe that students can learn digital control after a one-semester course covering the basics of analog control. As with other topics that started at the graduate level—linear algebra and Fourier analysis to name a few—the time has come for digital control to become an integral part of the undergraduate curriculum.

Features

To meet the needs of the typical senior/graduate-level course, this text includes the following features.

Numerous examples

The book includes a large number of examples. Typically, only one or two examples can be covered in the classroom because of time limitations. The student can use the remaining examples for self-study. The experience of the authors is that students need more examples to experiment with so as to gain a better understanding of the theory. The examples are varied to bring out subtleties of the theory that students may overlook.

Extensive use of CAD packages

The book makes extensive use of CAD packages. It goes beyond the occasional reference to specific commands to the integration of these commands into the modeling, design, and analysis of digital control systems. For example, root locus design procedures given in most digital control texts are not CAD procedures and instead emphasize paper-and-pencil design. The use of CAD packages, such as MATLAB®, frees students from the drudgery of mundane calculations and allows them to ponder more subtle aspects of control system analysis and design. The availability of a simulation tool like Simulink® allows the student to simulate closed-loop control systems, including aspects neglected in design such as nonlinearities and disturbances.

Coverage of background material

The book itself contains review material from linear systems and classical control. Some background material is included in the appendices that could either be reviewed in class or consulted by the student as necessary. The review material, which is often neglected in digital control texts, is essential for the understanding of digital control system analysis and design. For example, the behavior of discrete-time systems in the time domain and in the frequency domain is a standard topic in linear systems texts but often receives brief coverage. Root locus design is almost identical for analog systems in the s-domain and digital systems in the z-domain. The topic is covered much more extensively in classical control texts and inadequately in digital control texts. The digital control student is expected to recall this material or rely on other sources. Often, instructors are obliged to compile their own review materials, and the continuity of the course is adversely affected.

Inclusion of advanced topics

In addition to the basic topics required for a one-semester senior/graduate class, the text includes some advanced material to make it suitable for an introductory graduate-level class or for two quarters at the senior/graduate level. We would also hope that the students in a single-semester course would acquire enough background and interest to read the additional chapters on their own. Examples of optional topics are state−space methods, which may receive brief coverage in a one-semester course, and nonlinear discrete-time systems, which may not be covered.

Standard mathematics prerequisites

The mathematics background required for understanding most of the book does not exceed what can be reasonably expected from the average electrical, chemical, or mechanical engineering senior. This background includes three semesters of calculus, differential equations, and basic linear algebra. Some texts on digital control require more mathematical maturity and are therefore beyond the reach of the typical senior. On the other hand, the text does include optional topics for the more advanced student. The rest of the text does not require knowledge of this optional material so that it can be easily skipped if necessary.

Senior system theory prerequisites

The control and system theory background required for understanding the book does not exceed material typically covered in one semester of linear systems and one semester of control systems. Thus, students should be familiar with Laplace transforms, the frequency domain, and the root locus. They need not be familiar with the behavior of discrete-time systems in the frequency and time domain or have extensive experience with compensator design in the s-domain. For an audience with an extensive background in these topics, some topics can be skipped and the material can be covered at a faster rate.

Coverage of theory and applications

The book has two authors: the first is primarily interested in control theory and the second is primarily interested in practical applications and hardware implementation. Even though some control theorists have sufficient familiarity with practical issues such as hardware implementation and industrial applications to touch on the subject in their texts, the material included is often deficient because of the rapid advances in the area and the limited knowledge that theorists have of the subject.

New to this edition

We made several important changes and added material to the second edition:

1. We added a brief introduction to Simulink simulation of discrete-time systems to Chapter 3.
2. We moved the explanation of the bilinear transform to Chapter 4, where the bilinear transform is first introduced, from Chapter 6.
3. We added closed-loop Ziegler-Nichols design to Chapter 5.
4. We added pole-zero matching to Chapter 6. This is a simple design approach that was used in some examples but was not included in the first edition.
5. We have improved the explanation of the direct control design (Section 6.6) and of the finite settling time design (Section 6.7).
6. We added the Hankel realization to Chapter 8 to provide a systematic method for multi-input-multi-output system realization. Because this material is based on the singular value decomposition, a section on the singular value decomposition was added to Appendix III.

7. In the first edition, the Hamiltonian system was included, but the significance of its eigenstructure was not discussed. We added a section on the eigenstructure of the Hamiltonian system to Chapter 10.
8. The first edition did not include a discussion of the stability of the response of the system to an external input. We added input-output stability and the circle criterion to Chapter 11.
9. We added 23 new problems, including several new computer exercises.

It became clear to the first author that to have a suitable text for his course and similar courses, he needed to find a partner to satisfactorily complete the text. He gradually collected material for the text and started looking for a qualified and interested partner. Finally, he found a co-author who shared his interest in digital control and the belief that it can be presented at a level amenable to the average undergraduate engineering student.

For many years, Dr. Antonio Visioli has been teaching an introductory and a laboratory course on automatic control, as well as a course on control systems technology. Further, his research interests are in the fields of industrial regulators and robotics. Although he contributed to the material presented throughout the text, his major contribution was adding material related to the practical design and implementation of digital control systems. This material is rarely covered in control systems texts but is an essential prerequisite for applying digital control theory in practice.

The text is written to be as self-contained as possible. However, the reader is expected to have completed a semester of linear systems and classical control. Throughout the text, extensive use is made of the numerical computation and computer-aided-design package MATLAB. As with all computational tools, the enormous capabilities of MATLAB are no substitute for a sound understanding of the theory presented in the text. As an example of the inappropriate use of supporting technology, we recall the story of the driver who followed the instructions of his GPS system and drove into the path of an oncoming train![1] The reader must use MATLAB as a tool to support the theory without blindly accepting its computational results.

Organization of text

The text begins with an introduction to digital control and the reasons for its popularity. It also provides a few examples of applications of digital control from the engineering literature.

[1]The story was reported in the *Chicago Sun-Times*, on January 4, 2008. The driver, a computer consultant, escaped just in time before the train slammed into his car at 60 mph in Bedford Hills, New York.

Chapter 2 considers discrete-time models and their analysis using the **z-transform**. We review the z-transform, its properties, and its use to solve difference equations. The chapter also reviews the properties of the **frequency response** of discrete-time systems. After a brief discussion of the **sampling theorem**, we are able to provide rules of thumb for **selecting the sampling rate** for a given signal or for given system dynamics. This material is often covered in linear systems courses, and much of it can be skipped or covered quickly in a digital control course. However, the material is included because it serves as a foundation for much of the material in the text.

Chapter 3 derives simple mathematical models for linear discrete-time systems. We derive models for the analog-to-digital converter (ADC), the digital-to-analog converter (DAC), and an analog system with a DAC and an ADC. We include systems with time delays that are not an integer multiple of the sampling period. These transfer functions are particularly important because many applications include an analog plant with DAC and ADC. Nevertheless, there are situations where different configurations are used. We therefore include an analysis of a variety of configurations with samplers. We also characterize the **steady-state tracking error** of discrete-time systems and define error constants for the unity feedback case. These error constants play an analogous role to the error constants for analog systems. Using our analysis of more complex configurations, we are able to obtain the **error due to a disturbance input**.

In Chapter 4, we present stability tests for input-output systems. We examine the definitions of **input-output stability** and **internal stability** and derive conditions for each. By transforming the characteristic polynomial of a discrete-time system, we are able to test it using the standard **Routh-Hurwitz criterion** for analog systems. We use the **Jury criterion**, which allows us to directly test the stability of a discrete-time system. Finally, we present the **Nyquist criterion** for the z-domain and use it to determine closed-loop stability of discrete-time systems.

Chapter 5 introduces analog s-domain design of proportional (P), proportional-plus-integral (PI), proportional-plus-derivative (PD), and proportional-plus-integral-plus-derivative (PID) control using MATLAB. We use MATLAB as an integral part of the design process, although many steps of the design can be competed using a scientific calculator. It would seem that a chapter on analog design does not belong in a text on digital control. This is false. Analog control can be used as a first step toward obtaining a digital control. In addition, direct digital control design in the z-domain is similar in many ways to s-domain design.

Digital controller design is topic of Chapter 6. It begins with proportional control design then examines digital controllers based on analog design. The direct design of digital controllers is considered next. We consider root locus design in the z-plane for PI and PID controllers. We also consider a synthesis approach due to Ragazzini that allows us to specify the desired closed-loop transfer function. As a special case, we consider the design of deadbeat controllers that allow us to exactly track an input at the sampling points after a few sampling points. For completeness, we also examine frequency response design in the *w*-plane. This approach requires more experience because values of the stability margins must be significantly larger than in the more familiar analog design. As with analog design, MATLAB is an integral part of the design process for all digital control approaches.

Chapter 7 covers state–space models and state–space realizations. First, we discuss analog state–space equations and their solutions. We include nonlinear analog equations and their linearization to obtain linear state–space equations. We then show that the solution of the analog state equations over a sampling period yields a discrete-time state–space model. Properties of the solution of the analog state equation can thus be used to analyze the discrete-time state equation. The discrete-time state equation is a recursion for which we obtain a solution by induction. In Chapter 8, we consider important properties of state–space models: **stability**, **controllability**, and **observability**. As in Chapter 4, we consider internal stability and input-output stability, but the treatment is based on the properties of the state–space model rather than those of the transfer function. Controllability is a property that characterizes our ability to drive the system from an arbitrary initial state to an arbitrary final state in finite time. Observability characterizes our ability to calculate the initial state of the system using its input and output measurements. Both are structural properties of the system that are independent of its stability. Next, we consider **realizations** of discrete-time systems. These are ways of implementing discrete-time systems through their state–space equations using summers and delays.

Chapter 9 covers the design of controllers for state–space models. We show that the system dynamics can be arbitrarily chosen using state feedback if the system is controllable. If the state is not available for feedback, we can design a state estimator or **observer** to estimate it from the output measurements. These are dynamic systems that mimic the system but include corrective feedback to account for errors that are inevitable in any implementation. We give two types of observers. The first is a simpler but more computationally costly full-order observer that estimates the entire state vector. The second is a reduced-order observer with the order reduced by virtue of the fact that the measurements are available and need not be estimated. Either observer can be used to provide an estimate of the state for feedback control, or for other purposes. Control schemes based on state estimates are said to use **observer state feedback**.

Chapter 10 deals with the optimal control of digital control systems. We consider the problem of unconstrained optimization, followed by constrained optimization, then generalize to dynamic optimization as constrained by the system dynamics. We are particularly interested in the linear quadratic regulator where optimization results are easy to interpret and the prerequisite mathematics background is minimal. We consider both the finite time and steady-state regulator and discuss conditions for the existence of the steady-state solution. The first 10 chapters are mostly restricted to linear discrete-time systems. Chapter 11 examines the far more complex behavior of nonlinear discrete-time systems. It begins with equilibrium points and their stability. It shows how equivalent discrete-time models can be easily obtained for some forms of nonlinear analog systems using **global** or **extended linearization**. It provides stability theorems and instability theorems using Lyapunov stability theory. The theory gives sufficient conditions for nonlinear systems, and failure of either the stability or instability tests is inconclusive. For linear systems, Lyapunov stability yields necessary and sufficient conditions. Lyapunov stability theory also allows us to design controllers by selecting a control that yields a closed-loop system that meets the Lyapunov stability conditions. For the classes of nonlinear systems for which extended linearization is straightforward, linear design methodologies can yield nonlinear controllers.

Chapter 12 deals with practical issues that must be addressed for the successful implementation of digital controllers. In particular, the hardware and software requirements for the correct implementation of a digital control system are analyzed. We discuss the choice of the sampling frequency in the presence of antialiasing filters and the effects of quantization, rounding, and truncation errors. We also discuss **bumpless switching** from automatic to manual control, avoiding discontinuities in the control input. Our discussion naturally leads to approaches for the effective implementation of a PID controller. Finally, we consider nonuniform sampling, where the sampling frequency is changed during control operation, and multirate sampling, where samples of the process outputs are available at a slower rate than the controller sampling rate.

Supporting material

The following resources are available to instructors adopting this text for use in their courses. Please visit textbooks.elsevier.com to register for access to these materials:

Instructor Solutions Manual. Fully typeset solutions to the end-of-chapter problems in the text.

PowerPoint® Images. Electronic images of the figures and tables from the book, useful for creating lectures.