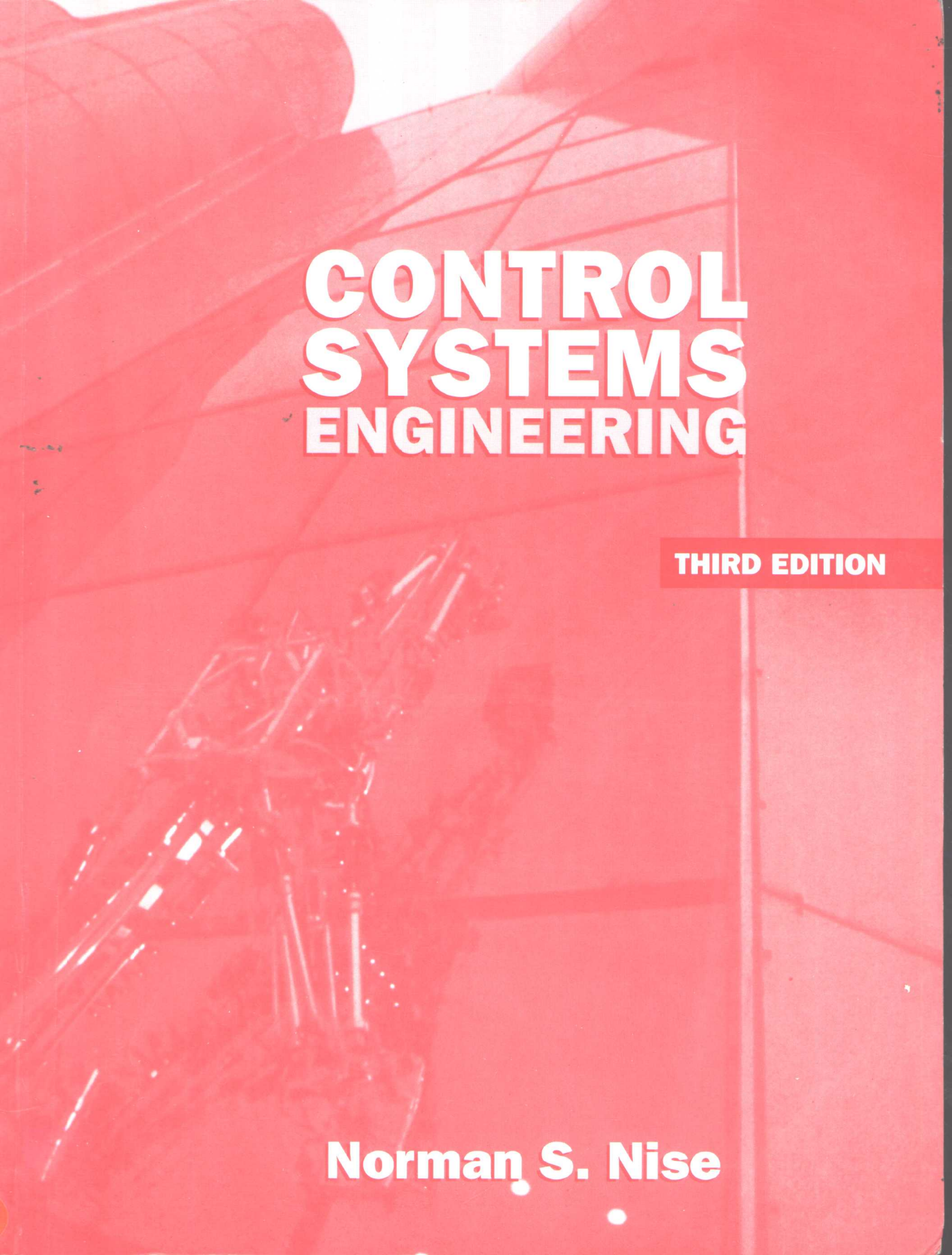
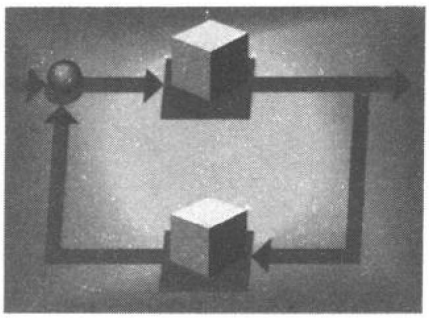


CONTROL SYSTEMS ENGINEERING

THIRD EDITION

Norman S. Nise



CONTROL SYSTEMS ENGINEERING

Third Edition

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Pomona

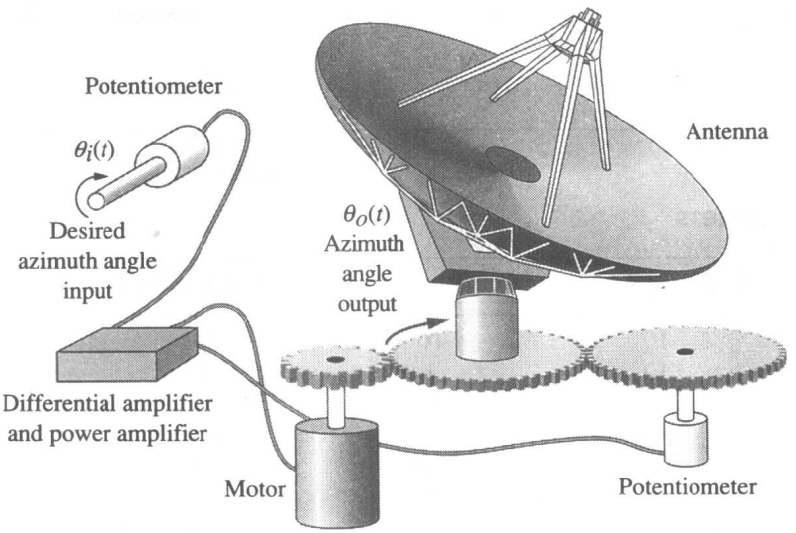
JOHN WILEY & SONS, INC.

New York ■ Chichester ■ Weinheim ■ Brisbane ■ Singapore ■ Toronto

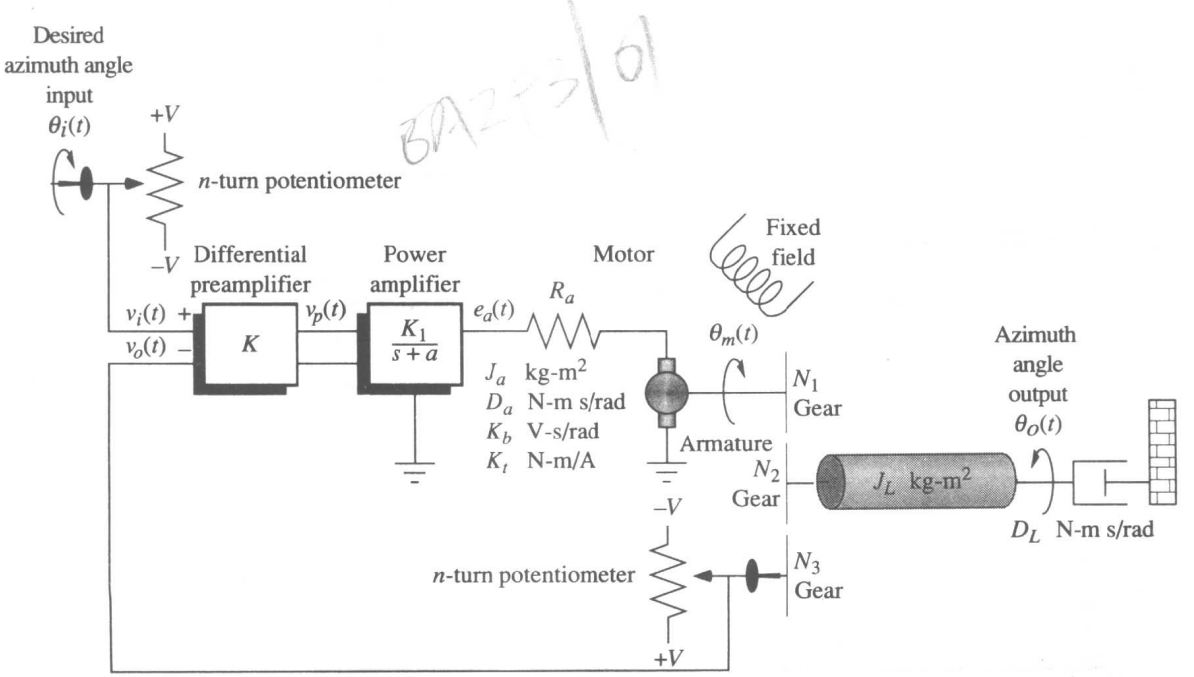
Library of Congress Cataloging-in-Publication Data:
Nise, Norman S.
Control Systems Engineering/Norman S. Nise.—3rd ed.
p. cm.
Includes bibliographical references.
ISBN 9971-51-323-4
1. Automatic control. 2. Systems engineering. I. Title.
TJ213 .N497 2000
629.8–dc21 99-049144
Printed and bound at Replika Press Pvt. Ltd. (100% EOU),Delhi 110 040, India.
10 9 8 7 6 5 4 3 2 1

Antenna Azimuth Position Control System

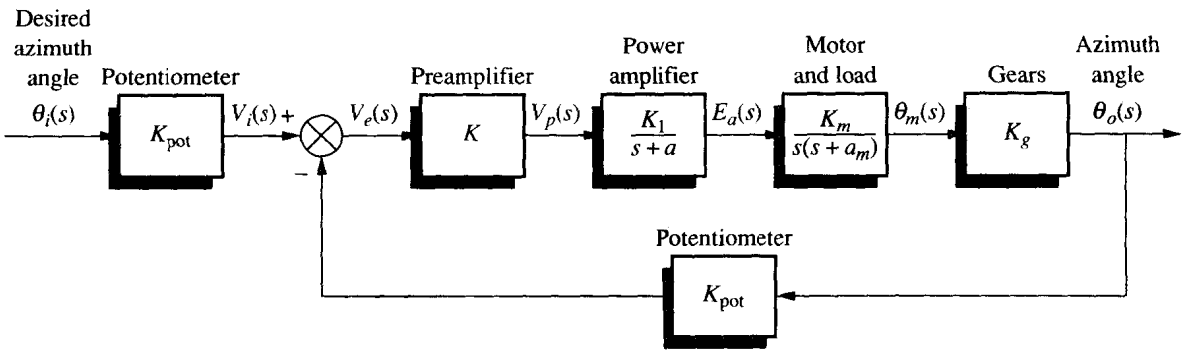
Layout



Schematic



Block Diagram



Schematic Parameters

Parameter	Configuration 1	Configuration 2	Configuration 3
V	10	10	10
n	10	1	1
K	—	—	—
K_1	100	150	100
a	100	150	100
R_a	8	5	5
J_a	0.02	0.05	0.05
D_a	0.01	0.01	0.01
K_b	0.5	1	1
K_t	0.5	1	1
N_1	25	50	50
N_2	250	250	250
N_3	250	250	250
J_L	1	5	5
D_L	1	3	3

Block Diagram Parameters

Parameter	Configuration 1	Configuration 2	Configuration 3
K_{pot}	0.318		
K	—		
K_1	100		
a	100		
K_m	2.083		
a_m	1.71		
K_g	0.1		

To my wife, Ellen;
sons, Benjamin and Alan;
and daughter, Sharon.

Preface

This book introduces students to the theory and practice of control systems engineering. The text emphasizes the practical application of the subject to the analysis and design of feedback systems.

The study of control systems engineering is essential for students pursuing degrees in electrical, mechanical, aerospace, or chemical engineering. Control systems are found in a broad range of applications within these disciplines, from aircraft and spacecraft to robots and process control systems.

Control Systems Engineering is suitable for upper-division college and university engineering students and for those who wish to master the subject matter through self-study. The student using this text should have completed typical lower-division courses in physics and mathematics, through differential equations. Other required background material, including Laplace transforms and linear algebra, is incorporated in the text, either within chapter discussions or separately in the appendixes or on an accompanying CD-ROM. This review material can be omitted without loss of continuity if students do not require it.

Key Features

The key features of this third edition are

- Standardized chapter organization
- Qualitative and quantitative explanations
- Examples, skill-assessment exercises, and case studies throughout the text
- Abundant illustrations
- Numerous end-of-chapter problems
- Emphasis on design
- Flexible coverage
- Emphasis on computer-aided analysis and design

Let us look at each feature in more detail.

Standard Chapter Organization

Each chapter begins with a list of chapter objectives followed by a list of case study objectives that relate the chapter objectives to specific student performance in solving a practical case study problem, such as an antenna azimuth position control system.

Topics are then divided into clearly numbered and labeled sections containing explanations, examples, and, where appropriate, skill-assessment exercises with answers. These numbered sections are followed by one or more case studies, as outlined below. Each chapter ends with a brief summary, several review questions requiring short answers, and a set of homework problems.

Qualitative and Quantitative Explanations

Explanations are clear and complete and, where appropriate, include a brief review of required background material. Topics build upon and support one another in a logical fashion. Groundwork for new concepts and terminology is carefully laid to avoid overwhelming the student and to facilitate self-study.

Although quantitative solutions are obviously important, a qualitative or intuitive understanding of problems and methods of solution is vital to producing the insight required to develop sound designs. Therefore, whenever possible, new concepts are discussed from a qualitative perspective before quantitative analysis and design are addressed. For example, in Chapter 8, the student can simply look at the root locus and describe qualitatively the changes in transient response that will occur as a system parameter, such as gain, is varied. This ability is developed with the help of a few simple equations from Chapter 4.

Examples, Skill-Assessment Exercises, and Case Studies

Explanations are clearly illustrated by means of numerous numbered and labeled examples throughout the text. Where appropriate, a section concludes with skill-assessment exercises. These are computation drills, most with answers, that test comprehension and provide immediate feedback. Complete solutions can be found on the accompanying CD-ROM.

Broader examples in the form of case studies can be found after the last numbered section of every chapter, with the exception of Chapter 1. These case studies are practical application problems that demonstrate the concepts introduced in the chapter. Each case study concludes with a challenge problem that students may work in order to test their understanding of the material.

One of the case studies, concerning an antenna azimuth position control system, is carried throughout the book. The purpose is to illustrate the application of new material in each chapter to the same physical system, thus highlighting the continuity of the design process. Another, more challenging case study, involving an Unmanned Free-Swimming Submersible Vehicle, is developed over the course of five chapters.

Abundant Illustrations

The ability to visualize concepts and processes is critical to the student's understanding. For this reason, approximately 750 photos, diagrams, graphs, and tables appear throughout the book to illustrate the topics under discussion.

Numerous End-of-Chapter Problems

Each chapter ends with a variety of homework problems that allow students to test their understanding of the material presented in the chapter. Problems vary in degree of difficulty and complexity, and most chapters include several practical, "real life" problems to help maintain students' motivation. Also, the homework problems contain a progressive analysis and design problem that uses the same practical system to demonstrate the concepts of each chapter.

Emphasis on Design

This textbook places a heavy emphasis on design. Chapters 8, 9, 11, 12, and 13 focus primarily on design. But even in chapters that emphasize analysis, simple design examples are included wherever possible.

Throughout the book, design examples involving physical systems are identified by a **Design** icon. End-of-chapter problems that involve the design of physical systems are included under the separate heading Design Problems and also, in chapters covering design, under the heading Progressive Analysis and Design Problem. In these examples and problems, a desired response is specified and the student must evaluate certain system parameters, such as gain, or specify a system configuration along with parameter values. In addition, the text includes numerous design examples and problems (not identified by an icon) that involve purely mathematical systems.

Because visualization is so vital to understanding design, this text carefully relates indirect design specifications to more familiar ones. For example, the less familiar and indirect phase margin is carefully related to the more direct and familiar percent overshoot before being used as a design specification.

For each general type of design problem introduced in the text, a methodology for solving the problem is presented—in many cases in the form of a step-by-step procedure, beginning with a statement of design objectives. Example problems serve to demonstrate the methodology by following the procedure, making simplifying assumptions, and presenting the results of the design in tables or plots that compare the performance of the original system to that of the improved system. This comparison also serves as a check on the simplifying assumptions.

Transient response design topics are covered comprehensively in the text. They include

- Design via gain adjustment using the root locus
- Design of compensation and controllers via the root locus
- Design via gain adjustment using sinusoidal frequency response methods
- Design of compensation via sinusoidal frequency response methods
- Design of controllers in state space using pole-placement techniques
- Design of observers in state space using pole-placement techniques
- Design of digital control systems via gain adjustment on the root locus
- Design of digital control system compensation via s-plane design and the Tustin transformation

Steady-state error design is covered comprehensively in this textbook and includes

- Gain adjustment
- Design of compensation via the root locus
- Design of compensation via sinusoidal frequency response methods
- Design of integral control in state space

Finally, the design of gain to yield stability is covered from the following perspectives:

- Routh-Hurwitz criterion
- Root locus
- Nyquist criterion
- Bode plots

Flexible Coverage

The material in this book can be adapted for a one-quarter or a one-semester course. The organization is flexible, allowing the instructor to select the material that best suits the requirements and time constraints of the class.

Throughout the book, state-space methods are presented along with the classical approach. Chapters and sections (as well as examples, exercises, review questions, and problems) that cover state space are marked by a **State Space** icon and can be omitted without any loss of continuity. Those wishing to add a basic introduction to state-space modeling can include Chapter 3 in the syllabus.

In a one-semester course, the discussions of state-space analysis in Chapters 4, 5, 6, and 7, as well as state-space design in Chapter 12, can be covered along with the classical approach. Another option is to teach state space separately by gathering the appropriate chapters and sections marked with the **State Space** icon into a single unit that follows the classical approach. In a one-quarter course, Chapter 13, Digital Control Systems, could be eliminated.

Emphasis on Computer-Aided Analysis and Design

Control systems problems, particularly analysis and design problems using the root locus, can be tedious, since their solution involves trial and error. To solve these problems, students should be given access to computers or programmable calculators configured with appropriate software. In this third edition, MATLAB®[1] continues to be integrated into the text as an optional feature.

Many problems in this text can be solved with either a computer or a handheld, programmable calculator. For example, students can use the programmable calculator to (1) determine whether a point on the s-plane is also on the root locus, (2) find magnitude and phase frequency response data for Nyquist and Bode

[1]MATLAB is a registered trademark of The MathWorks, Inc.

diagrams, and (3) convert between the following representations of a second-order system:

- Pole location in polar coordinates
- Pole location in Cartesian coordinates
- Characteristic polynomial
- Natural frequency and damping ratio
- Settling time and percent overshoot
- Peak time and percent overshoot
- Settling time and peak time

Hand-held calculators have the advantage of easy accessibility for homework and exams. Please consult Appendix H, located on the enclosed CD-ROM, for a discussion of computational aids that can be adapted to hand-held calculators.

Personal computers are better suited for more computation-intensive applications, such as plotting time responses, root loci, and frequency response curves, as well as finding state-transition matrices. These computers also give the student a real-world environment in which to analyze and design control systems. Those not using MATLAB can write their own programs or use other programs, such as Program CC. Please consult Appendix H, on the accompanying CD-ROM, for a discussion of computational aids that can be adapted for use on computers that do not have MATLAB installed.

Without access to computers or programmable calculators, students cannot obtain meaningful analysis and design results and the learning experience will be limited.

New to this Edition

In this third edition, we have revised and added material in response to suggestions from students and professors who adopted the second edition of the text. The following list describes the key changes in the third edition:

End-of-chapter problems There is at least a 30% change in the problems at the end of the chapters. Old problems have been revised and new problems have been added. A practical progressive analysis and design problem, which makes use of the same physical system, has been added to the problem sets in each chapter.

MATLAB The use of MATLAB for computer-aided analysis and design continues to be integrated into discussions and problems as an optional feature in the third edition. The MATLAB tutorial has been updated to MATLAB Version 5 and the Control System Toolbox Version 4.

MATLAB's Simulink®[2] Simulink has been added to show the effects of nonlinearities upon the time response of open-loop and closed-loop systems. We also use Simulink to demonstrate how to simulate digital systems. To assist you, an appendix tutorial covering Simulink basics has been added.

[2]Simulink is a registered trademark of The MathWorks, Inc.

MATLAB's GUI Tools Two MATLAB tools that use graphical user interfaces (GUI) make their debut in this 3rd edition. The first is the LTI (linear time-invariant object) Viewer, which is a convenient tool for evaluating characteristics of system time and frequency response plots. The second tool is the Root Locus Design GUI, which is a convenient and intuitive tool for root locus analysis and design. An appendix tutorial covering MATLAB's GUI tools has been added to assist you.

MATLAB's Symbolic Math Toolbox The Symbolic Math Toolbox has been added to appropriate sections as an optional feature to aid in computation. To assist you, an appendix tutorial covering the Symbolic Math Toolbox basics has been added.

Skill-assessment exercises Focused exercises and answers have been added at the end of appropriate sections. These exercises give students immediate feedback by which to measure their basic understanding of the section.

Progressive analysis and design problems A progressive analysis and design problem has been added to the end-of-chapter problem sets. This problem gives you the opportunity to progressively apply the analysis and design lessons of each chapter to the same physical system.

CD-ROM A CD-ROM disk accompanies the textbook. Selected appendixes and sections from the second edition have been moved to the CD-ROM to make room for additional text material. The disk contains the following:

- All M-files used in the MATLAB, Simulink, GUI Tools, and Symbolic Math Toolbox tutorials
- PowerPoint®[3] and Acrobat®[4] files containing selected figures from the textbook
- Solutions to skill-assessment exercises
- Appendix B of the second edition: Matrices, Determinants, and Systems of Equations
- Appendix D, Section 4.11, and all other material in the second edition dealing with the use of computer-aided analysis and design that does not use MATLAB, have been revised and combined into a single appendix presenting alternatives to MATLAB.
- Appendix F of the second edition: Solution of State Equations for $t_0 \neq 0$
- Appendix G of the second edition: Root Locus Rules: Derivations

Icons Several icons have been added to the third edition to identify coverage and optional material. Specifically, icons for Simulink, MATLAB's GUI Tools (the LTI Viewer and the Root Locus Design GUI), and the Symbolic Math Toolbox have been added to the previous MATLAB, state-space, and design icons. The icons are summarized as follows:

The MATLAB icon identifies MATLAB discussion, examples, exercises, and problems. MATLAB coverage is provided as an enhancement and is not required to use the text.

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[3]PowerPoint is a registered trademark of Microsoft Corporation.
[4]Acrobat is a registered trademark of Adobe Systems Incorporated.

Simulink The Simulink icon identifies Simulink discussion, examples, exercises, and problems. Simulink coverage is provided as an enhancement and is not required to use the text.

GUI Tool The GUI Tool icon identifies MATLAB GUI Tools discussion, examples, exercises, and problems. The discussion of the tools, which includes the LTI Viewer and the Root Locus Design GUI, is provided as an enhancement and is not required to use the text.

Symbolic Math The Symbolic Math icon identifies Symbolic Math Toolbox discussion, examples, exercises, and problems. Symbolic Math Toolbox coverage is provided as an enhancement and is not required to use the text.

State Space The State Space icon highlights state-space discussions, examples, exercises, and problems. Like MATLAB, state-space material is optional and can be omitted without loss of continuity.

Design The Design icon clearly identifies design problems involving physical systems.

Chapter 4 Effects of nonlinearities upon time response for open-loop systems using Simulink has been added to Chapter 4. The relationship between rise time and damping ratio has been curve fit to a cubic equation, which should make calculating rise time easier and more direct. The LTI Viewer is introduced in Chapter 4 via a tutorial appendix. Section 4.11 of the 2nd edition, Time Response via Computer Simulation, as well as other non-MATLAB computer methods, has been moved to Appendix H on the accompanying CD-ROM.

Chapter 5 Effects of nonlinearities upon time response for closed-loop systems using Simulink has been added to the problem set in Chapter 5.

Chapter 7 Steady-state error analysis for systems represented in state space has been moved to Chapter 7 from Chapter 12.

Chapter 9 A subsection covering the notch filter has been added to Section 9.4.

Chapter 13 Digital stability analysis on the s-plane using the bilinear transformation has been added to Section 13.6, Stability. In addition, two sections have been added: (1) Cascade Compensation via the s-plane, which makes use of the Tustin transformation, and (2) Implementing the Digital Compensator.

Second Edition Appendix B: Matrices, Determinants, and Systems of Equations This has been moved to the CD-ROM and is now Appendix G

Second Edition Appendix C: MATLAB Tutorial This is now Appendix B.

Third Edition Appendix C: *MATLAB's Simulink Tutorial* This is a new appendix.

Second Edition Appendix D: Microsoft®[5] QuickBASIC Programs Appendix D has been revised, combined with all other non-MATLAB discussion, and moved to the accompanying CD-ROM, Appendix H.

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[5]Microsoft is a registered trademark of Microsoft Corporation.

Third Edition Appendix D: MATLAB's GUI Tools This is a new appendix, which includes the LTI Viewer and the Root Locus Design GUI.

Second Edition Appendix E: Derivation of a Schematic for a DC Motor This is now Appendix F.

Third Edition Appendix E: MATLAB's Symbolic Math Toolbox Tutorial This is a new appendix.

Second Edition Appendix F: Solution of State Equations for $t_0 \neq 0$ Appendix F has been moved to the accompanying CD-ROM and is now Appendix I.

Second Edition Appendix G: Root Locus Rules: Derivations Appendix G has been moved to the accompanying CD-ROM and is now Appendix J.

Chapter Organization

Many times it is helpful to understand an author's reasoning behind the organization of the course material. The following paragraphs hopefully shed light on this topic.

The primary goal of Chapter 1 is to motivate students. In this chapter students learn about the many applications of control systems in everyday life and about the advantages of study and a career in this field. Control systems engineering design objectives, such as transient response, steady-state error, and stability, are introduced, as is the path to obtaining these objectives. New and unfamiliar terms also are included in the Glossary.

Many students have trouble with an early step in the analysis and design sequence: transforming a physical system into a schematic. This step requires many simplifying assumptions based on experience the typical college student does not yet possess. Identifying some of these assumptions in Chapter 1 helps to fill the experience gap.

Chapters 2, 3, and 5 address the representation of physical systems. Chapters 2 and 3 cover modeling of open-loop systems, using frequency response techniques and state-space techniques, respectively. Chapter 5 discusses the representation and reduction of systems formed of interconnected open-loop subsystems. Only a representative sample of physical systems can be covered in a textbook of this length. Electrical, mechanical (both translational and rotational), and electromechanical systems are used as examples of physical systems that are modeled, analyzed, and designed. Linearization of a nonlinear system—one technique used by the engineer to simplify a system in order to represent it mathematically—is also introduced.

Chapter 4 provides an introduction to system analysis, that is, finding and describing the output response of a system. It may seem more logical to reverse the order of Chapters 4 and 5, to present the material in Chapter 4 along with other chapters covering analysis. However, many years of teaching control systems have taught me that the sooner students see an application of the study of system representation, the higher their motivation levels remain.

Chapters 6, 7, 8, and 9 return to control systems analysis and design with the study of stability (Chapter 6), steady-state errors (Chapter 7), and transient response of higher-order systems using root locus techniques (Chapter 8). Chapter 9 covers design of compensators and controllers using the root locus.

Chapters 10 and 11 focus on sinusoidal frequency analysis and design. Chapter 10, like Chapter 8, covers basic concepts for stability, transient response, and steady-state error analysis. However, Nyquist and Bode methods are used in place of root locus. Chapter 11, like Chapter 9, covers the design of compensators, but from the point of view of sinusoidal frequency techniques rather than root locus.

An introduction to state-space design and digital control systems analysis and design completes the text in Chapters 12 and 13, respectively. Although these chapters can be used as an introduction for students who will be continuing their study of control systems engineering, they are useful by themselves and as a supplement to the discussion of analysis and design in the previous chapters. The subject matter cannot be given a comprehensive treatment in two chapters, but the emphasis is clearly outlined and logically linked to the rest of the book.

The Teaching Package

The following materials comprise the teaching package for Control Systems Engineering, third edition. Be sure to periodically check http://www.wiley.com/college/elec/nise366013 for up-to-date information on this publication.

PowerPoint and Acrobat Lecture Graphics Key figures from the text are available as full-color electronic graphics in Microsoft's PowerPoint and as pdf files for Adobe Acrobat. These files can be found on the accompanying CD-ROM and at http://www.wiley.com/college/elec/nise366013.

Control System Design Software All MATLAB M-files and Simulink files used in the appendixes of this textbook can be found on the accompanying CD-ROM and at http://www.wiley.com/college/elec/nise366013.

***Solutions Manual for Control Systems Engineering*, third edition** by Norman S. Nise, this manual contains detailed solutions to most of the problems in the text. The Solutions Manual is available only to qualifying faculty.

Acknowledgments

The author would like to acknowledge the contributions of my colleagues at California State Polytechnic University, Pomona, who contributed to this and previous editions of *Control Systems Engineering*. Without their support this volume may not have come to fruition. Those who contributed to this third edition require special thanks here. The continued support through all phases of this project by the Electrical and Computer Engineering Department and Yi Cheng, Chair, as well as the College of Engineering and Edward Hohmann, Dean, was invaluable for the completion of this work.

This third edition was completely error-checked by my colleague M. Samy El-Sawah and for that I and the students reading it are grateful.

I would especially like to thank my students who used the previous editions over the last eight years. Their suggestions for this new edition were invaluable. In particular, I want to give special thanks to Michael House for the many suggestions he gave to me. The rise-time polynomials in Chapter 4 are a direct result of his suggestions and effort.

My appreciation is extended to Alan H. Nise for the numerous hours spent in creating the stand-alone applications for time response and root locus analysis and design that are on the accompanying CD-ROM. These programs will certainly be appreciated by readers who do not have access to MATLAB.

The author would like to thank all reviewers whose mastery of the subject and laudable attention to details yielded many suggestions for and improvements to this third edition. The reviewers include the following faculty: Darren Dawson, Clemson University; Mahlon D. Heller, California State University, Sacramento; Vojislav D. Kalanovic, South Dakota School of Mines and Technology; Leslie R. Koval, The University of Missouri-Rolla; Marca J. Lam, The Cooper Union for the Advancement of Science and Art; Fu Li, Portland State University; Jure Medanic, University of Illinois at Urbana-Champaign; Medhat M. Morcos, Kansas State University; Satish S. Nair, University of Missouri, Columbia; Charles P. Neuman, Carnegie Mellon; J. William Ray, Jr., Louisiana Tech University; and Michael J. Rider, Ohio Northern University.

I also would like to express my appreciation to Wayne E. Whiteman, United States Military Academy, for voluntarily sending me numerous suggestions for improving content and accuracy.

Prior to the transfer of this title to John Wiley & Sons, Inc. several people provided valuable guidance and help in the early stages of development of this third edition. I am grateful for their contributions. In particular I want to thank the following at Addison-Wesley: Paul Becker, Acquisitions Editor; Anna Eberhard Friedlander, Assistant Editor; and Royden Tonomura, Editorial Assistant. During its brief transfer to Prentice Hall, Tom Robbins, Editor, guided this title through its development.

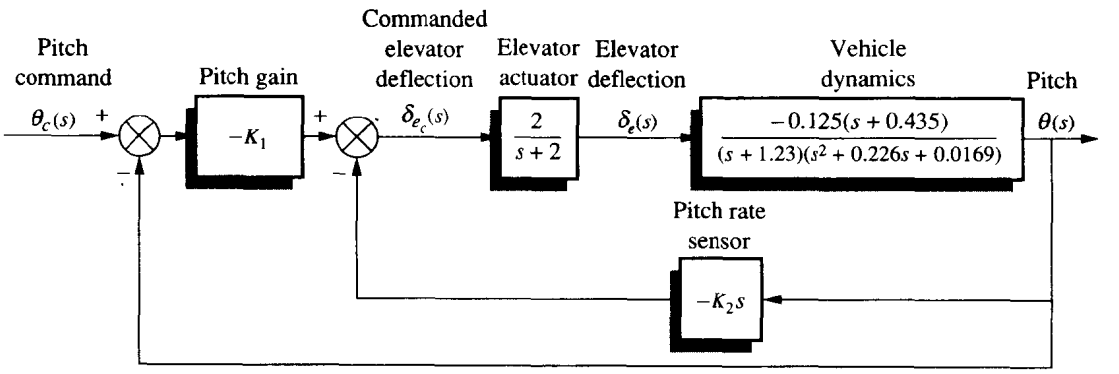
And of course the author would like to thank John Wiley & Sons, Inc. and its staff for providing professional support for this project through all phases of its development. Specifically, the following are due recognition for their contributions: Peter M. Janzow, Publisher, who gave full executive support to the whole project; Bill Zobrist, Acquisitions Editor, who provided professional editorial guidance; Jennifer Welter, Editorial Assistant, who was always there to provide timely answers to my numerous questions; and Robin Factor, Senior Production Editor, who saw the book through all phases of production. I would also like to acknowledge Karin Kincheloe, Senior Designer, for her contribution to the striking cover; Lisa Gee, Photo Editor, for researching the new photos you see in the book; and Katherine Hepburn, Marketing Manager, for letting you know of this book's existence. There are others to thank; namely those with whom I did not have the pleasure of interacting personally, but whose contributions are extremely valuable, nevertheless.

Finally, kudos go out to Publication Services and its staff for producing the final version of the book under great pressure and time limitations. Specifically, I want to thank Jan Fisher, Customer Service Representative, for smoothly paving the way to production and fielding my many questions. Also, thanks is due to Bilal Dardai, Editor and Ken Churchill, Production Coordinator for the final editing and production of the book in a spirit of cooperation. Especially appreciated was their willingness to make last-minute refinements that will be appreciated by the reader.

Norman S. Nise

Unmanned Free-Swimming Submersible Vehicle

Pitch Control System



Heading Control System