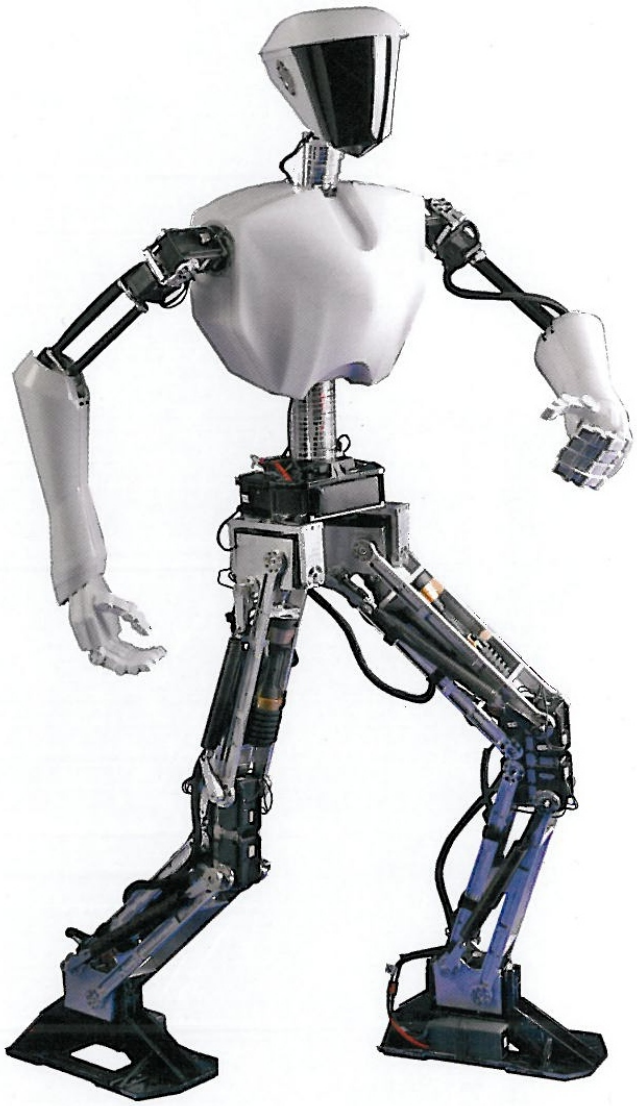
NORMAN S. NISE

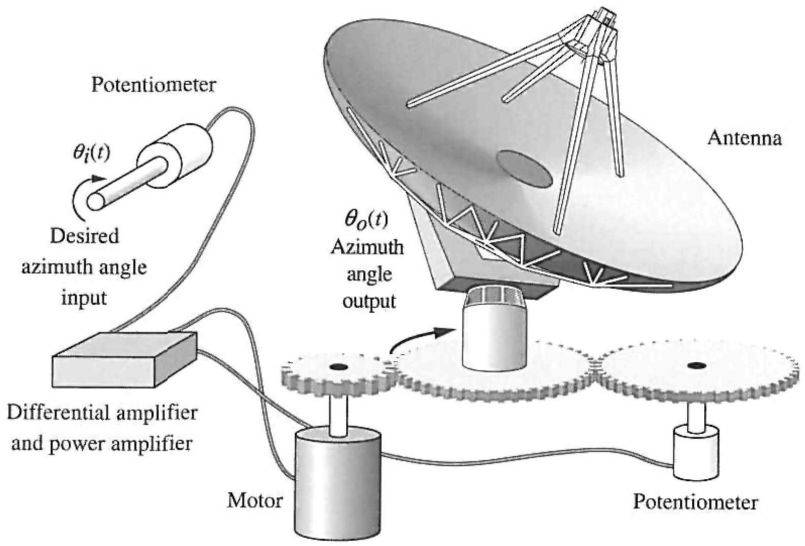


CONTROL SYSTEMS ENGINEERING

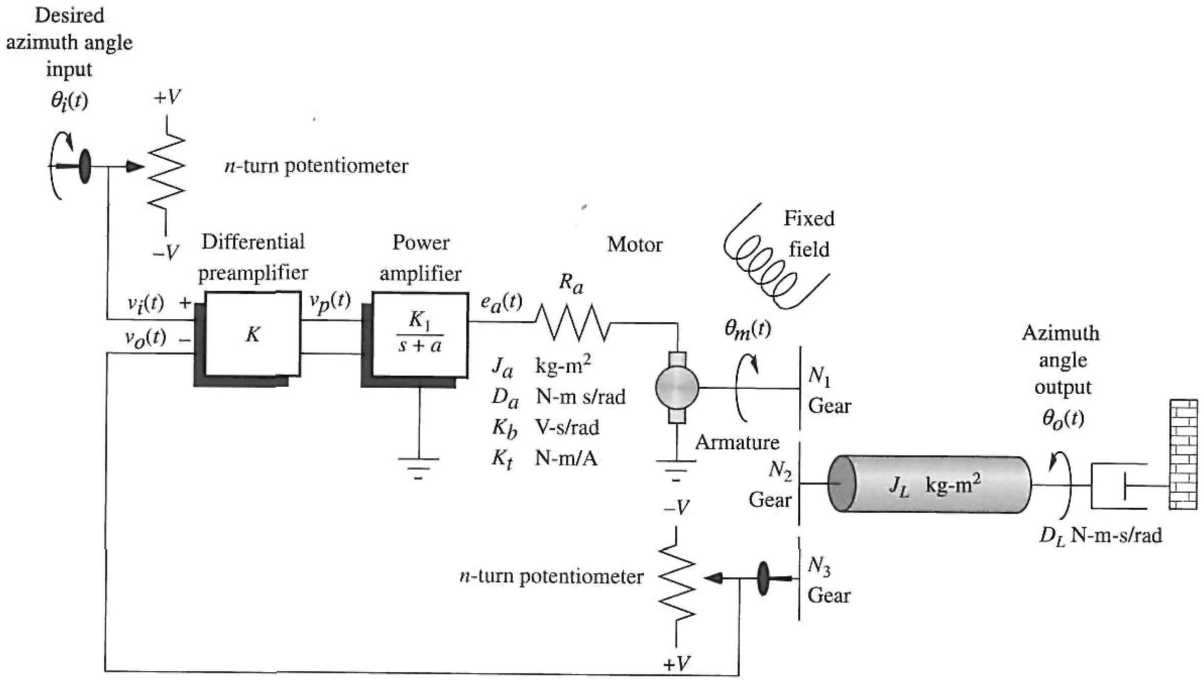
SIXTH EDITION

Antenna Azimuth Position Control System

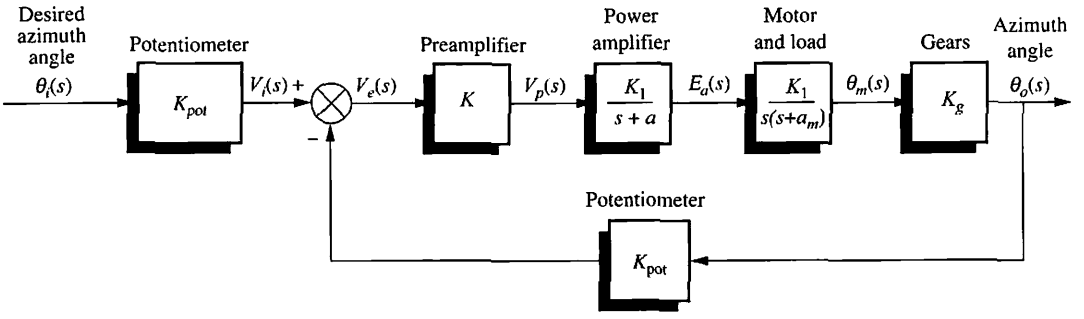
Layout



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		

Note: reader may fill in Configuration 2 and Configuration 3 columns after completing the antenna control Case Study challenge problems in Chapters 2 and 10, respectively.

CONTROL SYSTEMS ENGINEERING
Sixth Edition

Norman S. Nise
California State Polytechnic University, Pomona

John Wiley & Sons, Inc.

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

Vice President & Publisher	Don Fowley
Publisher	Daniel Sayre
Senior Editorial Assistant	Katie Singleton
Associate Director of Marketing	Amy Scholz
Marketing Manager	Christopher Ruel
Production Manager	Dorothy Sinclair
Production Editor	Sandra Dumas
Creative Director	Harry Nolan
Cover Designer	James O'Shea
Cover Photo	Jim Stroup, Virginia Tech
Photo Department Manager	Hilary Newman
Photo Editor	Sheena Goldstein
Executive Media Editor	Thomas Kulesa
Associate Media Editor	Jennifer Mullin
Production Management Services	Integra Software Services Inc.

This book was typeset in 10/12 TimesRoman at Thomson and printed and bound by R. R. Donnelley (Jefferson City). The cover was printed by R. R. Donnelley (Jefferson City).

The paper in this book was manufactured by a mill whose forest management programs include sustained yield-harvesting of its timberlands. Sustained yield harvesting principles ensure that the number of trees cut each year does not exceed the amount of new growth.

This book is printed on acid-free paper. ♾

On the cover: CHARLI, a 5-foot tall autonomous humanoid robot built by Dr. Dennis Hong and his students at RoMeLa (Robotics and Mechanisms Laboratory) in the College of Engineering of Virginia Tech.

Founded in 1807, John Wiley & Sons, Inc. has been a valued source of knowledge and understanding for more than 200 years, helping people around the world meet their needs and fulfill their aspirations. Our company is built on a foundation of principles that include responsibility to the communities we serve and where we live and work, in 2008, we launched a Corporate Citizenship initiative, a global effort to address the environmental, social, economic, and ethical challenges we face in our business. Among the issues we are addressing are carbon impact, paper specifications and procurement, ethical conduct within our business and among our vendors, and community and charitable support. For more information, please visit our website: www.wiley.com/go/citizenship.

The software programs available with this book have been included for their instructional value. They have been tested with care but are not guaranteed for any particular purpose. The publisher and author do not offer any warranties or restrictions, nor do they accept any liabilities with respect to the programs.

Copyright © 2011, 2006, 2003, 1996 by John Wiley & Sons, Inc. All rights reserved.

No part of this publication may be reproduced, stored in a retrieval system or transmitted in any form or by any means, electronic, mechanical, photocopying recording, scanning or otherwise, except as permitted under Sections 107 or 108 of the 1976 United States Copyright Act, without either the prior written permission of the Publisher or authorization through payment of the appropriate per-copy fee to the Copyright Clearance Center, 222 Rosewood Drive, Danvers, MA 01923, (978) 750-8400, fax (978) 646-8600. Requests to the Publisher for permission should be addressed to the Permissions Department, John Wiley & Sons, Inc., 111 River Street, Hoboken, NJ 07030-5774, (201) 748-6011, fax (201) 748-6008.

Evaluation copies are provided to qualified academics and professionals for review purposes only, for use in their courses during the next academic year. These copies are licensed and may not be sold or transferred to a third party. Upon completion of the review period, please return the evaluation copy to Wiley. Return instructions and a free of charge return shipping label are available at www.wiley.com/go/returnlabel. Outside of the United States, please contact your local representative.

ISBN 13 978-0470-54756-4
ISBN 13 978-0470-91769-5

Printed in the United States of America.

10 9 8 7 6 5 4 3 2 1

Contents

PREFACE, ix

1. INTRODUCTION, 1

1.1 Introduction, 2
1.2 A History of Control Systems, 4
1.3 System Configurations, 7
1.4 Analysis and Design Objectives, 10
Case Study, 12
1.5 The Design Process, 15
1.6 Computer-Aided Design, 20
1.7 The Control Systems Engineer, 21
Summary, 23
Review Questions, 23
Problems, 24
Cyber Exploration Laboratory, 30
Bibliography, 31

2. MODELING IN THE FREQUENCY DOMAIN, 33

2.1 Introduction, 34
2.2 Laplace Transform Review, 35
2.3 The Transfer Function, 44
2.4 Electrical Network Transfer Functions, 47
2.5 Translational Mechanical System Transfer Functions, 61
2.6 Rotational Mechanical System Transfer Functions, 69
2.7 Transfer Functions for Systems with Gears, 74
2.8 Electromechanical System Transfer Functions, 79
2.9 Electric Circuit Analogs, 84
2.10 Nonlinearities, 88
2.11 Linearization, 89
Case Studies, 94
Summary, 97
Review Questions, 97
Problems, 98
Cyber Exploration Laboratory, 112
Bibliography, 115

3. MODELING IN THE TIME DOMAIN, 117

3.1 Introduction, 118
3.2 Some Observations, 119
3.3 The General State-Space Representation, 123
3.4 Applying the State-Space Representation, 124
3.5 Converting a Transfer Function to State Space, 132
3.6 Converting from State Space to a Transfer Function, 139
3.7 Linearization, 141
Case Studies, 144
Summary, 148
Review Questions, 149
Problems, 149
Cyber Exploration Laboratory, 157
Bibliography, 159

4. TIME RESPONSE, 161

4.1 Introduction, 162
4.2 Poles, Zeros, and System Response, 162
4.3 First-Order Systems, 166
4.4 Second-Order Systems: Introduction, 168
4.5 The General Second-Order System, 173
4.6 Underdamped Second-Order Systems, 177
4.7 System Response with Additional Poles, 186
4.8 System Response With Zeros, 191
4.9 Effects of Nonlinearities Upon Time Response, 196

4.10 Laplace Transform Solution of State Equations, 199
4.11 Time Domain Solution of State Equations, 203
Case Studies, 207
Summary, 213
Review Questions, 214
Problems, 215
Cyber Exploration Laboratory, 228
Bibliography, 232

5. REDUCTION OF MULTIPLE SUBSYSTEMS, 235

5.1 Introduction, 236
5.2 Block Diagrams, 236
5.3 Analysis and Design of Feedback Systems, 245
5.4 Signal-Flow Graphs, 248
5.5 Mason's Rule, 251
5.6 Signal-Flow Graphs of State Equations, 254
5.7 Alternative Representations in State Space, 256
5.8 Similarity Transformations, 266
Case Studies, 272
Summary, 278
Review Questions, 279
Problems, 280
Cyber Exploration Laboratory, 297
Bibliography, 299

6. STABILITY, 301

6.1 Introduction, 302
6.2 Routh-Hurwitz Criterion, 305
6.3 Routh-Hurwitz Criterion: Special Cases, 308
6.4 Routh-Hurwitz Criterion: Additional Examples, 314
6.5 Stability in State Space, 320
Case Studies, 323
Summary, 325
Review Questions, 325
Problems, 326
Cyber Exploration Laboratory, 335
Bibliography, 336

7. STEADY-STATE ERRORS, 339

7.1 Introduction, 340
7.2 Steady-State Error for Unity Feedback Systems, 343
7.3 Static Error Constants and System Type, 349
7.4 Steady-State Error Specifications, 353
7.5 Steady-State Error for Disturbances, 356
7.6 Steady-State Error for Nonunity Feedback Systems, 358
7.7 Sensitivity, 362
7.8 Steady-State Error for Systems in State Space, 364
Case Studies, 368
Summary, 371
Review Questions, 372
Problems, 373
Cyber Exploration Laboratory, 384
Bibliography, 386

8. ROOT LOCUS TECHNIQUES, 387

8.1 Introduction, 388
8.2 Defining the Root Locus, 392
8.3 Properties of the Root Locus, 394
8.4 Sketching the Root Locus, 397
8.5 Refining the Sketch, 402
8.6 An Example, 411
8.7 Transient Response Design via Gain Adjustment, 415
8.8 Generalized Root Locus, 419
8.9 Root Locus for Positive-Feedback Systems, 421
8.10 Pole Sensitivity, 424
Case Studies, 426
Summary, 431
Review Questions, 432
Problems, 432
Cyber Exploration Laboratory, 450
Bibliography, 452

9. DESIGN VIA ROOT LOCUS, 455

9.1 Introduction, 456
9.2 Improving Steady-State Error via *Cascade Compensation*, 459
9.3 Improving Transient Response via Cascade Compensation, 469
9.4 Improving Steady-State Error and Transient Response, 482
9.5 Feedback Compensation, 495
9.6 Physical Realization of Compensation, 503
Case Studies, 508
Summary, 513
Review Questions, 514
Problems, 515
Cyber Exploration Laboratory, 530
Bibliography, 531

10. FREQUENCY RESPONSE TECHNIQUES, 533

10.1 Introduction, 534
10.2 Asymptotic Approximations: Bode Plots, 540
10.3 Introduction to the Nyquist Criterion, 559
10.4 Sketching the Nyquist Diagram, 564
10.5 Stability via the Nyquist Diagram, 569
10.6 Gain Margin and Phase Margin via the Nyquist Diagram, 574
10.7 Stability, Gain Margin, and Phase Margin via Bode Plots, 576
10.8 Relation Between Closed-Loop Transient and Closed-Loop Frequency Responses, 580
10.9 Relation Between Closed- and Open-Loop Frequency Responses, 583
10.10 Relation Between Closed-Loop Transient and Open-Loop Frequency Responses, 589
10.11 Steady-State Error Characteristics from Frequency Response, 593
10.12 Systems with Time Delay, 597
10.13 Obtaining Transfer Functions Experimentally, 602
Case Study, 606
Summary, 607
Review Questions, 609
Problems, 610
Cyber Exploration Laboratory, 621
Bibliography, 623

11. DESIGN VIA FREQUENCY RESPONSE, 625

11.1 Introduction, 626
11.2 Transient Response via Gain Adjustment, 627
11.3 Lag Compensation, 630
11.4 Lead Compensation, 635
11.5 Lag-Lead Compensation, 641
Case Studies, 650
Summary, 652
Review Questions, 653
Problems, 653
Cyber Exploration Laboratory, 660
Bibliography, 661

12. DESIGN VIA STATE SPACE, 663

12.1 Introduction, 664
12.2 Controller Design, 665
12.3 Controllability, 672
12.4 Alternative Approaches to Controller Design, 676
12.5 Observer Design, 682
12.6 Observability, 689
12.7 Alternative Approaches to Observer Design, 693
12.8 Steady-State Error Design Via Integral Control, 700
Case Study, 704
Summary, 709
Review Questions, 710
Problems, 711
Cyber Exploration Laboratory, 719
Bibliography, 721

13. DIGITAL CONTROL SYSTEMS, 723

13.1 Introduction , 724
13.2 Modeling the Digital Computer, 727

13.3 The *z*-Transform, 730
13.4 Transfer Functions, 735
13.5 Block Diagram Reduction, 739
13.6 Stability, 742
13.7 Steady-State Errors, 749
13.8 Transient Response on the *z*-Plane, 753
13.9 Gain Design on the *z*-Plane, 755
13.10 Cascade Compensation via the *s*-Plane, 758
13.11 Implementing the Digital Compensator, 762
Case Studies, 765
Summary, 769
Review Questions, 770
Problems, 771
Cyber Exploration Laboratory, 778
Bibliography, 780

Appendix A List of Symbols, 783

Appendix B MATLAB Tutorial, 787

B.1 Introduction, 787
B.2 MATLAB Examples, 788
B.3 Command Summary, 833
Bibliography, 835

Appendix C MATLAB's Simulink Tutorial, 836

C.1 Introduction, 836
C.2 Using Simulink, 836
C.3 Examples, 841
Summary, 855
Bibliography, 856

Appendix D LabVIEW Tutorial, 857

D.1 Introduction, 857
D.2 Control Systems Analysis, Design, and Simulation, 858
D.3 Using LabVIEW, 859
D.4 Analysis and Design Examples, 862
D.5 Simulation Examples, 876
Summary, 885
Bibliography, 886

Glossary, 887

Answers to Selected Problems, 897

Credits, 903

Index, 907

Appendix E MATLAB's GUI Tools Tutorial (Online)

Appendix F MATLAB's Symbolic Math Toolbox Tutorial (Online)

Appendix G Matrices, Determinants, and Systems of Equations (Online)

Appendix H Control System Computational Aids (Online)

Appendix I Derivation of a Schematic for a DC Motor (Online)

Appendix J Derivation of the Time Domain Solution of State Equations (Online)

Appendix K Solution of State Equations for $t_0 \neq 0$ (Online)

Appendix L Derivation of Similarity Transformations (Online)

Appendix M Root Locus Rules: Derivations (Online)

Control Systems Engineering Toolbox (Online)

Cyber Exploration Laboratory Experiments Covers Sheets (Online)

Lecture Graphics (Online)

Solutions to Skill-Assessment Exercises (Online)

Online location is www.wiley.com/college/nise

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, biomedical, 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 the book's Companion Web site. This review material can be *omitted without loss of continuity if the student does not require it.*

Key Features

The key features of this sixth edition are:

- Standardized chapter organization
- Qualitative and quantitative explanations
- **Examples, Skill-Assessment Exercises,** and **Case Studies** throughout the text
- WileyPLUS content management system for students and professors
- **Cyber Exploration Laboratory and Virtual Experiments**
- Abundant illustrations
- Numerous end-of-chapter problems
- Emphasis on design
- Flexible coverage
- Emphasis on computer-aided analysis and design including MATLAB®[1] and LabVIEW®[2]

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

[2] LabVIEW is a registered trademark of National Instruments Corporation.

- Icons identifying major topics

Let us look at each feature in more detail.

Standardized Chapter Organization

Each chapter begins with a list of chapter learning outcomes, followed by a list of case study learning outcomes that relate 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 will be outlined in a few paragraphs. Each chapter ends with a brief summary, several review questions requiring short answers, a set of homework problems, and experiments.

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, sections conclude with **Skill-Assessment Exercises**. These are computation drills, most with answers that test comprehension and provide immediate feedback. Complete solutions can be found at www.wiley.com/college/nise.

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 arc 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, 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 Unmannered Free-Swimming Submersible Vehicle, is developed over the course of five chapters.

WileyPLUS Content Management System for Students and Professors

WileyPLUS
WPCS
Control Solutions

WileyPLUS is an online suite of resources, including the full text, for students and instructors. For the sixth edition of *Control Systems Engineering*, this suite offers professors who adopt the book with WileyPLUS the ability to create homework assignments based on algorithmic problems or multi-part questions, which guide the student through a problem. Instructors also have the capability to integrate assets, such as the simulations, into their lecture presentations. Students will find a Read, Study, and Practice zone to help them work through problems based on the ones offered in the text.

Control Solutions (prepared by JustAsk) are included in the WileyPLUS platform. The student will find simulations and Control Solutions in the Read, Study, and Practice zone. The Control Solutions are highlighted in the text with a WileyPLUS icon.

A new addition to the WileyPLUS platform for this edition are National Instruments and Quanser Virtual Laboratories. You will find references to them in sidebar entries throughout the textbook.

Visit www.wiley.com or contact your local Wiley representative for information.

Cyber Exploration Laboratory and Virtual Experiments

Computer experiments using MATLAB, Simulink®[3] and the Control System Toolbox are found at the end of the Problems sections under the sub-heading **Cyber Exploration Laboratory**. New to this edition is LabVIEW, which is also used for experiments within the Cyber Exploration Laboratory section of the chapters. The experiments allow the reader to verify the concepts covered in the chapter via simulation. The reader also can change parameters and perform "what if" exploration to gain insight into the effect of parameter and configuration changes. The experiments are written with stated Objectives, Minimum Required Software Packages, as well as Prelab, Lab, and Postlab tasks and questions. Thus, the experiments may be used for a laboratory course that accompanies the class. Cover sheets for these experiments are available at www.wiley.com.college/nise.

In addition, and new to this sixth edition, are **Virtual Experiments**. These experiments are more tightly focused than the **Cyber Exploration Laboratory** experiments and use LabVIEW and Quanser virtual hardware to illustrate immediate discussion and examples. The experiments are referenced in sidebars throughout some chapters.

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

Abundant Illustrations

The ability to visualize concepts and processes is critical to the student's understanding. For this reason, approximately 800 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 progressive analysis and design problems that use the same practical systems 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 the icon shown in the margin. 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 Problems**. 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.

State Space
SS

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 the icon shown in the margin 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 slate-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 sixth edition, MATLAB continues to be integrated into the text as an optional feature. In addition, and new to this

edition, we have included LabVIEW as an option to computer-aided analysis and design.

Many problems in this text can be solved with either a computer or a hand-held 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 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

Handheld calculators have the advantage of easy accessibility for homework and exams. Please consult Appendix H, located at www.wiley.com/college/nise, for a discussion of computational aids that can be adapted to handheld 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 or LabVIEW can write their own programs or use other programs, such as Program CC. Please consult Appendix H at www.wiley.com/college/nise for a discussion of computational aids that can be adapted for use on computers that do not have MATLAB or LabVIEW installed.

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

Icons Identifying Major Topics

Several icons identify coverage and optional material. The icons are summarized as follows:

Control Solutions for the student are identified with a WileyPLUS icon. These problems, developed by JustAsk, are worked in detail and offer explanations of every facet of the solution.

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

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

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

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

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

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

The Design icon clearly identifies design problems involving physical systems.

Symbolic Math SM

LabVIEW LV

State Space SS

Design D

New to This Edition

The following list describes the key changes in this sixth edition

End-of-chapter problems More than 20% of the end-of-chapter problems are either new or revised. Also, an additional Progressive Analysis and Design Problem has been added at the end of the chapter problems. The new progressive problem analyzes and designs a hybrid electric vehicle.

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 sixth edition. The MATLAB tutorial has been updated to MATLAB Version 7.9 (R 2009b), the Control System Toolbox Version 8.4, and the Symbolic Math Toolbox Version 5.3

In addition, MATLAB code continues to be incorporated in the chapters in the form of sidebar boxes entitled TryIt.

Virtual Experiments Virtual experiments, developed by National Instruments and Quanser, are included via sidebar references to experiments on WileyPLUS. The experiments are performed with 3-D simulations of Quanser hardware using developed LabVIEW VIs. Virtual Experiments are tightly focused and linked to a discussion or example.

Cyber Exploration Laboratory Experiments using LabVIEW have been added. Cyber Exploration Laboratory experiments are general in focus and are envisioned to be used in an associated lab class.

MATLAB's Simulink The use of Simulink to show the effects of nonlinearities upon the time response of open-loop and closed-loop systems appears again in this sixth edition. We also continue to use Simulink to demonstrate how to simulate digital systems. Finally, the Simulink tutorial has been updated to Simulink 7.4

Chapter 11 Lag-lead compensator design using Nichols charts has been added to Section 11.5.

LabVIEW New to this edition is LabVIEW. A tutorial for this tool is included in Appendix D. LabVIEW is used in Cyber Exploration Laboratory experiments and other problems throughout the textbook.

Book Companion Site (BCS) at www.wiley.com/college/nise

The BCS for the sixth edition includes various student and instructor resources. This free resource can be accessed by going to www.wiley.com/college/nise and clicking on Student Companion Site. Professors also access their password-protected resources on the Instructor Companion Site available through this url. Instructors should contact their Wiley sales representative for access.

For the Student:

- All M-files used in the MATLAB, Simulink, GUI Tools, and Symbolic Math Toolbox tutorials, as well as the TryIt exercises
- Copies of the Cyber Exploration Laboratory experiments for use as experiment cover sheets
- Solutions to the Skill-Assessment Exercises in the text
- LabVIEW Virtual Experiments and LabVIEW VIs used in Appendix D

For the Instructor;

- PowerPoint®[4] files containing the figures from the textbook
- Solutions to end-of-chapter problem sets
- Simulations, developed by JustAsk, for inclusion in lecture presentations

Book Organization by Chapter

Many times it is helpful lo 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.

[4] PowerPoint is a registered trademark of Microsoft Corporation.

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.

Acknowledgments

The author would like to acknowledge the contributions of faculty and students, both at California State Polytechnic University, Pomona, and across the country, whose suggestions through all editions have made a positive impact on the new edition.

I am deeply indebted to my colleagues, Elhami T. Ibrahim, Salomon Oldak, and Norali Pernalete at California State Polytechnic University, Pomona for authoring the creative new problems you will find at the end of every chapter. Dr. Pernalete created the LabVIEW experiments and problems you will find in this new edition. The new progressive problem, hybrid vehicle, that is at the end of every chapter is the creation of Dr Ibrahim. In addition to his busy schedule as Electrical and Computer Engineering Department Chairman and author of many of the new problems, Professor Oldak also error checked new additions to the book and prevented *glitches from ever reaching you, the reader.*

I would like to express my appreciation to contributors to this sixth edition who participated in reviews, accuracy checking, surveys, or focus groups. They are: Jorge Aravena, Louisiana State University; Kurt Behpour, Cal Poly San Luis Obispo; Bill Diong, Texas Christian University; Sam Guccione, Eastern Illinois University; Pushkin Kachroo, Virginia Tech; Dmitriy Kalantarov, Cal State San Diego; Kamran Iqbal, University of Arkansas, Little Rock; Pushkin Kachroo, Virginia Tech; Kevin Lynch, Northwestern University; Tesfay Meressi, University of Massachusetts, Dartmouth; Luai Najim, University of Alabama at Birmingham; Dalton Nelson, University of Alabama at Birmingham; Marcio S. de Queiroz, Louisiana State University; John Ridgely, Cal Poly San Luis Obispo; John Schmitt, Oregon State University; Lili Tabrizi, California State University, Los Angeles; Raman Unnikrishnan, Cal State Fullerton; Stephen Williams, Milwaukee School of Engineering; Jiann-Shiou Yang, University of Minnesota, Duluth; and Ryan Zurakowski, University of Delaware.

The author would like to thank John Wiley & Sons, Inc. and its staff for once again providing professional support for this project through all phases of its development. Specifically, the following are due recognition for their contributions: Don Fowler, Vice President and Publisher, who gave full corporate support to the project; Daniel Sayre, Publisher, with whom I worked closely and who provided guidance and leadership throughout the development of the sixth edition; and Katie Singleton, Senior Editorial Assistant, who was always there to answer my questions and respond to my concerns in a professional manner. There are many others who

worked behind the scenes, but who should be thanked never the less. Rather than repeating their names and titles here, I refer the reader to the copyright page of this book where they are listed and credited. I am very thankful for their contributions.

Next, I want to acknowledge Integra Software Services, Inc. and its staff for turning the sixth edition manuscript into the finished product you are holding in your hands. Specifically, kudos go out to Heather Johnson, Managing Editor, who, once again, was always there to address my concerns in a timely and professional manner.

My sincere appreciation is extended to Erik Luther of National Instruments Corporation and Paul Gilbert and Michel Levis of Quanser for conceiving, coordinating, and developing the Virtual Experiments that I am sure will enhance your understanding of control systems.

Finally, last but certainly not least, I want to express my appreciation to my wife, Ellen, for her support in ways too numerous to mention during the writing of the past six editions. Specifically though, thanks to her proofing final pages for this sixth edition, you the reader hopefully will find comprehension rather than apprehension in the pages that follow.

Norman S. Nise