Feedback Control of Dynamic Systems

Eighth Edition

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330 Hudson Street, NY, NY 10013
To Valerie, Daisy, Annika, Davenport, Malahat, Sheila, Nima, and to the memory of Gene
Contents

Preface xiii

1 An Overview and Brief History of Feedback Control 1
   A Perspective on Feedback Control 1
   Chapter Overview 2
   1.1 A Simple Feedback System 3
   1.2 A First Analysis of Feedback 6
   1.3 Feedback System Fundamentals 10
   1.4 A Brief History 11
   1.5 An Overview of the Book 18
   Summary 19
   Review Questions 20
   Problems 20

2 Dynamic Models 24
   A Perspective on Dynamic Models 24
   Chapter Overview 25
   2.1 Dynamics of Mechanical Systems 25
      2.1.1 Translational Motion 25
      2.1.2 Rotational Motion 32
      2.1.3 Combined Rotation and Translation 43
      2.1.4 Complex Mechanical Systems (W)** 46
      2.1.5 Distributed Parameter Systems 46
      2.1.6 Summary: Developing Equations of Motion
                  for Rigid Bodies 48
   2.2 Models of Electric Circuits 49
   2.3 Models of Electromechanical Systems 54
      2.3.1 Loudspeakers 54
      2.3.2 Motors 56
      2.3.3 Gears 60
   △ 2.4 Heat and Fluid-Flow Models 61
      2.4.1 Heat Flow 62
      2.4.2 Incompressible Fluid Flow 66
   2.5 Historical Perspective 73
   Summary 76
   Review Questions 76
   Problems 77

**Sections with (W) indicates that additional material is located on the web at
www.FPE8E.com or www.pearsonhighered.com/engineering-resources.
3 Dynamic Response  89
A Perspective on System Response  89
Chapter Overview  90
3.1 Review of Laplace Transforms  90
3.1.1 Response by Convolution  91
3.1.2 Transfer Functions and Frequency Response  96
3.1.3 The \( \mathcal{L} \)-Laplace Transform  106
3.1.4 Properties of Laplace Transforms  108
3.1.5 Inverse Laplace Transform by Partial-Fraction Expansion  110
3.1.6 The Final Value Theorem  112
3.1.7 Using Laplace Transforms to Solve Differential Equations  114
3.1.8 Poles and Zeros  116
3.1.9 Linear System Analysis Using Matlab  117
3.2 System Modeling Diagrams  123
3.2.1 The Block Diagram  123
3.2.2 Block-Diagram Reduction Using Matlab  127
3.2.3 Mason’s Rule and the Signal Flow Graph (W)  128
3.3 Effect of Pole Locations  128
3.4 Time-Domain Specifications  137
3.4.1 Rise Time  137
3.4.2 Overshoot and Peak Time  138
3.4.3 Settling Time  139
3.5 Effects of Zeros and Additional Poles  142
3.6 Stability  152
3.6.1 Bounded Input–Bounded Output Stability  152
3.6.2 Stability of LTI Systems  154
3.6.3 Routh’s Stability Criterion  155
3.7 Obtaining Models from Experimental Data: System Identification (W)  162
3.8 Amplitude and Time Scaling (W)  162
3.9 Historical Perspective  162
Summary  163
Review Questions  165
Problems  165

4 A First Analysis of Feedback  186
A Perspective on the Analysis of Feedback  186
Chapter Overview  187
4.1 The Basic Equations of Control  188
4.1.1 Stability  189
4.1.2 Tracking  190
4.1.3 Regulation  191
4.1.4 Sensitivity  192
4.2 Control of Steady-State Error to Polynomial Inputs:
   System Type 194
   4.2.1 System Type for Tracking 195
   4.2.2 System Type for Regulation and Disturbance Rejection 200
4.3 The Three-Term Controller: PID Control 202
   4.3.1 Proportional Control (P) 202
   4.3.2 Integral Control (I) 204
   4.3.3 Derivative Control (D) 207
   4.3.4 Proportional Plus Integral Control (PI) 207
   4.3.5 PID Control 211
   4.3.6 Ziegler–Nichols Tuning of the PID Controller 216
4.4 Feedforward Control by Plant Model Inversion 222
△ 4.5 Introduction to Digital Control (W) 224
△ 4.6 Sensitivity of Time Response to Parameter Change (W) 225
4.7 Historical Perspective 225
Summary 227
Review Questions 228
Problems 229

5 The Root-Locus Design Method 248
A Perspective on the Root-Locus Design Method 248
Chapter Overview 249
5.1 Root Locus of a Basic Feedback System 249
5.2 Guidelines for Determining a Root Locus 254
   5.2.1 Rules for Determining a Positive (180°) Root Locus 256
   5.2.2 Summary of the Rules for Determining a Root Locus 262
   5.2.3 Selecting the Parameter Value 263
5.3 Selected Illustrative Root Loci 266
5.4 Design Using Dynamic Compensation 279
   5.4.1 Design Using Lead Compensation 280
   5.4.2 Design Using Lag Compensation 285
   5.4.3 Design Using Notch Compensation 288
△ 5.4.4 Analog and Digital Implementations (W) 290
5.5 Design Examples Using the Root Locus 290
5.6 Extensions of the Root-Locus Method 301
   5.6.1 Rules for Plotting a Negative (0°) Root Locus 301
△ 5.6.2 Successive Loop Closure 304
△ 5.6.3 Time Delay (W) 309
5.7 Historical Perspective 309
Contents

Summary 311
Review Questions 313
Problems 313

6 The Frequency-Response Design Method 331
A Perspective on the Frequency-Response Design Method 331
Chapter Overview 332
6.1 Frequency Response 332
   6.1.1 Bode Plot Techniques 340
   6.1.2 Steady-State Errors 352
6.2 Neutral Stability 354
6.3 The Nyquist Stability Criterion 357
   6.3.1 The Argument Principle 357
   6.3.2 Application of The Argument Principle to Control Design 358
6.4 Stability Margins 371
6.5 Bode’s Gain–Phase Relationship 380
6.6 Closed-Loop Frequency Response 385
6.7 Compensation 386
   6.7.1 PD Compensation 387
   6.7.2 Lead Compensation (W) 388
   6.7.3 PI Compensation 398
   6.7.4 Lag Compensation 398
   6.7.5 PID Compensation 404
   6.7.6 Design Considerations 411
   △ 6.7.7 Specifications in Terms of the Sensitivity Function 413
   △ 6.7.8 Limitations on Design in Terms of the Sensitivity Function 418
   △ 6.8 Time Delay 421
   6.8.1 Time Delay via the Nyquist Diagram (W) 423
   △ 6.9 Alternative Presentation of Data 423
   6.9.1 Nichols Chart 423
   6.9.2 The Inverse Nyquist Diagram (W) 428
6.10 Historical Perspective 428
Summary 429
Review Questions 431
Problems 432

7 State-Space Design 457
A Perspective on State-Space Design 457
Chapter Overview 458
7.1 Advantages of State-Space 458
7.2 System Description in State-Space 460
7.3 Block Diagrams and State-Space 466
Contents

7.4 Analysis of the State Equations 469
    7.4.1 Block Diagrams and Canonical Forms 469
    7.4.2 Dynamic Response from the State Equations 481
7.5 Control-Law Design for Full-State Feedback 486
    7.5.1 Finding the Control Law 487
    7.5.2 Introducing the Reference Input with Full-State Feedback 496
7.6 Selection of Pole Locations for Good Design 500
    7.6.1 Dominant Second-Order Poles 500
    7.6.2 Symmetric Root Locus (SRL) 502
    7.6.3 Comments on the Methods 511
7.7 Estimator Design 512
    7.7.1 Full-Order Estimators 512
    7.7.2 Reduced-Order Estimators 518
    7.7.3 Estimator Pole Selection 522
7.8 Compensator Design: Combined Control Law and Estimator (W) 525
7.9 Introduction of the Reference Input with the Estimator (W) 537
    7.9.1 General Structure for the Reference Input 539
    7.9.2 Selecting the Gain 548
7.10 Integral Control and Robust Tracking 549
    7.10.1 Integral Control 549
    7.10.2 Robust Tracking Control: The Error-Space Approach 551
    7.10.3 Model-Following Design 563
    7.10.4 The Extended Estimator 567
7.11 Loop Transfer Recovery 570
7.12 Direct Design with Rational Transfer Functions 576
7.13 Design for Systems with Pure Time Delay 580
7.14 Solution of State Equations (W) 583
7.15 Historical Perspective 585
Summary 586
Review Questions 589
Problems 590

8 Digital Control 614
A Perspective on Digital Control 614
Chapter Overview 614
8.1 Digitization 615
8.2 Dynamic Analysis of Discrete Systems 618
    8.2.1 z-Transform 618
    8.2.2 z-Transform Inversion 619
Contents

8.2.3 Relationship Between $s$ and $z$ 621
8.2.4 Final Value Theorem 623
8.3 Design Using Discrete Equivalents 625
  8.3.1 Tustin’s Method 625
  8.3.2 Zero-Order Hold (ZOH) Method 629
  8.3.3 Matched Pole-Zero (MPZ) Method 631
  8.3.4 Modified Matched Pole-Zero (MMPZ) Method 635
  8.3.5 Comparison of Digital Approximation Methods 636
  8.3.6 Applicability Limits of the Discrete Equivalent Design Method 637
8.4 Hardware Characteristics 637
  8.4.1 Analog-to-Digital (A/D) Converters 638
  8.4.2 Digital-to-Analog Converters 638
  8.4.3 Anti-Alias Prefilters 639
  8.4.4 The Computer 640
8.5 Sample-Rate Selection 641
  8.5.1 Tracking Effectiveness 642
  8.5.2 Disturbance Rejection 643
  8.5.3 Effect of Anti-Alias Prefilter 643
  8.5.4 Asynchronous Sampling 644
△ 8.6 Discrete Design 644
  8.6.1 Analysis Tools 645
  8.6.2 Feedback Properties 646
  8.6.3 Discrete Design Example 648
  8.6.4 Discrete Analysis of Designs 650
8.7 Discrete State-Space Design Methods (W) 652
8.8 Historical Perspective 652
Summary 653
Review Questions 655
Problems 655

9 Nonlinear Systems 661
A Perspective on Nonlinear Systems 661
Chapter Overview 662
9.1 Introduction and Motivation: Why Study Nonlinear Systems? 663
9.2 Analysis by Linearization 665
  9.2.1 Linearization by Small-Signal Analysis 665
  9.2.2 Linearization by Nonlinear Feedback 670
  9.2.3 Linearization by Inverse Nonlinearity 671
9.3 Equivalent Gain Analysis Using the Root Locus 672
  9.3.1 Integrator Antiwindup 679
9.4 Equivalent Gain Analysis Using Frequency Response: Describing Functions 684
9.4.1 Stability Analysis Using Describing Functions 690

△ 9.5 Analysis and Design Based on Stability 694
9.5.1 The Phase Plane 695
9.5.2 Lyapunov Stability Analysis 701
9.5.3 The Circle Criterion 709

9.6 Historical Perspective 715

Summary 716
Review Questions 717
Problems 717

10 Control System Design: Principles and Case Studies 729

A Perspective on Design Principles 729
Chapter Overview 729
10.1 An Outline of Control Systems Design 731
10.2 Design of a Satellite's Attitude Control 737
10.3 Lateral and Longitudinal Control of a Boeing 747 755
10.3.1 Yaw Damper 760
10.3.2 Altitude-Hold Autopilot 767
10.4 Control of the Fuel–Air Ratio in an Automotive Engine 773
10.5 Control of a Quadrotor Drone 781
10.6 Control of RTP Systems in Semiconductor Wafer Manufacturing 797
10.7 Chemotaxis, or How *E. Coli* Swims Away from Trouble 811
10.8 Historical Perspective 821
Summary 823
Review Questions 825
Problems 825

Appendix A Laplace Transforms 843

A.1 The $\mathcal{L}$-Laplace Transform 843
A.1.1 Properties of Laplace Transforms 844
A.1.2 Inverse Laplace Transform by Partial-Fraction Expansion 852
A.1.3 The Initial Value Theorem 855
A.1.4 Final Value Theorem 856
Appendix B  Solutions to the Review Questions  858
Appendix C  Matlab Commands  875

Bibliography  881
Index  890

List of Appendices on the web at www.FPE8e.com and www.pearsonhighered.com/engineering-resources

Appendix WA: A Review of Complex Variables
Appendix WB: Summary of Matrix Theory
Appendix WC: Controllability and Observability
Appendix WD: Ackermann’s Formula for Pole Placement
Appendix W2.1.4: Complex Mechanical Systems
Appendix W3.2.3: Mason’s Rule and Signal-Flow Graph
Appendix W3.6.3.1: Routh Special Cases
Appendix W3.7: System Identification
Appendix W3.8: Amplitude and Time Scaling
Appendix W4.1.4.1: The Filtered Case
Appendix W4.2.2.1: Truxal’s Formula for the Error Constants
Appendix W4.5: Introduction to Digital Control
Appendix W4.6: Sensitivity of Time Response to Parameter Change
Appendix W5.4.4: Analog and Digital Implementations
Appendix W5.6.3: Root Locus with Time Delay
Appendix W6.7.2: Digital Implementation of Example 6.15
Appendix W6.8.1: Time Delay via the Nyquist Diagram
Appendix W6.9.2: The Inverse Nyquist Diagram
Appendix W7.8: Digital Implementation of Example 7.31
Appendix W7.9: Digital Implementation of Example 7.33
Appendix W7.14: Solution of State Equations
Appendix W8.7: Discrete State-Space Design Methods
Preface

In this Eighth Edition we again present a text in support of a first course in control and have retained the best features of our earlier editions. For this edition, we have responded to a survey of users by adding some new material (for example, drone dynamics and control) and deleted other little-used material from the book. We have also updated the text throughout so that it uses the improved features of MATLAB®. Drones have been discussed extensively in the controls literature as well as the common press. They are being used in mining, construction, aerial photography, search and rescue, movie industry, package delivery, mapping, surveying, farming, animal research, hurricane hunting, and defense. Since feedback control is a necessary component of all the drones, we develop the equations of motion in Chapter 2, and follow that with control design examples in the chapters 5, 6, 7, and 10. They have great potential for many tasks and could speed up and lessen the cost of these activities. The figure below symbolizes the widespread interest in this exciting new field.

"Fresh pepper?"

Source: Edward Koren/ The New Yorker © Conde Nast
Preface

The basic structure of the book is unchanged and we continue to combine analysis with design using the three approaches of the root locus, frequency response, and state-variable equations. The text continues to include many carefully worked out examples to illustrate the material. As before, we provide a set of review questions at the end of each chapter with answers in the back of the book to assist the students in verifying that they have learned the material.

In the three central chapters on design methods we continue to expect the students to learn how to perform the very basic calculations by hand and make a rough sketch of a root locus or Bode plot as a sanity check on the computer results and as an aid to design. However, we introduce the use of Matlab early on in recognition of the universal use of software tools in control analysis and design. As before, we have prepared a collection of all the Matlab files (both “m” files and SIMULINK® “slx” files) used to produce the figures in the book. These are available along with the advanced material described above at our website at www.FPE8e.com or at www.pearsonhighered.com/engineering-resources.

New to this Edition

We feel that this Eighth Edition presents the material with good pedagogical support, provides strong motivation for the study of control, and represents a solid foundation for meeting the educational challenges. We introduce the study of feedback control, both as a specialty of itself and as support for many other fields.

A more detailed list of the changes is:

- Deleted the disk drive and tape drive examples from Chapters 2, 7, and 10
- Added drone examples and/or problems in Chapters 2, 5, 6, 7, and 10
- Added a thermal system control example to Chapters 2 and 4
- Added a section on anti-windup for integral control in Chapter 9
- Added Cramer’s Rule to chapter 2 and Appendix WB
- Updated Matlab commands throughout the book and in Appendix C
- Updated the section on PID tuning in chapter 4
- Updated the engine control and chemotaxis case studies in Chapter 10
- Over 60 of the problems in this edition are either new or revised from the 7th edition

Addressing the Educational Challenges

Some of the educational challenges facing students of feedback control are long-standing; others have emerged in recent years. Some of the challenges remain for students across their entire engineering education;
others are unique to this relatively sophisticated course. Whether they are old or new, general or particular, the educational challenges we perceived were critical to the evolution of this text. Here, we will state several educational challenges and describe our approaches to each of them.

- **CHALLENGE**  
  Students must master design as well as analysis techniques.

  Design is central to all of engineering and especially so to control systems. Students find that design issues, with their corresponding opportunities to tackle practical applications, are particularly motivating. But students also find design problems difficult because design problem statements are usually poorly posed and lack unique solutions. Because of both its inherent importance and its motivational effect on students, design is emphasized throughout this text so confidence in solving design problems is developed from the start.

  The emphasis on design begins in Chapter 4 following the development of modeling and dynamic response. The basic idea of feedback is introduced first, showing its influence on disturbance rejection, tracking accuracy, and robustness to parameter changes. The design orientation continues with uniform treatments of the root locus, frequency response, and state variable feedback techniques. All the treatments are aimed at providing the knowledge necessary to find a good feedback control design with no more complex mathematical development than is essential to clear understanding.

  Throughout the text, examples are used to compare and contrast the design techniques afforded by the different design methods and, in the capstone case studies of Chapter 10, complex real-world design problems are attacked using all the methods in a unified way.

- **CHALLENGE**  
  New ideas continue to be introduced into control.

  Control is an active field of research and hence there is a steady influx of new concepts, ideas, and techniques. In time, some of these elements develop to the point where they join the list of things every control engineer must know. This text is devoted to supporting students equally in their need to grasp both traditional and more modern topics.

  In each of our editions, we have tried to give equal importance to root locus, frequency response, and state-variable methods for design. In this edition, we continue to emphasize solid mastery of the underlying techniques, coupled with computer-based methods for detailed calculation. We also provide an early introduction to data sampling and discrete controllers in recognition of the major role played by digital controllers in our field. While this material can be skipped to save time without harm to the flow of the text, we feel that it is very important for students to understand that computer control is widely used and that the most basic techniques of computer control are easily mastered.
Preface

- **CHALLENGE** Students need to manage a great deal of information.

The vast array of systems to which feedback control is applied and the growing variety of techniques available for the solution of control problems means that today's student of feedback control must learn many new ideas. How do students keep their perspective as they plow through lengthy and complex textual passages? How do they identify highlights and draw appropriate conclusions? How do they review for exams? Helping students with these tasks was a criterion for the Fourth, Fifth, Sixth, and Seventh Editions and continues to be addressed in this Eighth Edition. We outline these features below.

**FEATURE**

1. *Chapter openers* offer perspective and overview. They place the specific chapter topic in the context of the discipline as a whole, and they briefly overview the chapter sections.
2. *Margin notes* help students scan for chapter highlights. They point to important definitions, equations, and concepts.
3. *Shaded highlights* identify key concepts within the running text. They also function to summarize important design procedures.
4. *Bulleted chapter summaries* help with student review and prioritization. These summaries briefly reiterate the key concepts and conclusions of the chapter.
5. *Synopsis of design aids*. Relationships used in design and throughout the book are collected inside the back cover for easy reference.
6. *The color blue* is used (1) to highlight useful pedagogical features, (2) to highlight components under particular scrutiny within block diagrams, (3) to distinguish curves on graphs, and (4) to lend a more realistic look to figures of physical systems.
7. *Review questions* at the end of each chapter with solutions in the back to guide the student in self-study
8. *Historical perspectives* at the end of each chapter provide some background and color on how or why the material in that particular chapter evolved.

- **CHALLENGE** Students of feedback control come from a wide range of disciplines.

Feedback control is an interdisciplinary field in that control is applied to systems in every conceivable area of engineering. Consequently, some schools have separate introductory courses for control within the standard disciplines and some, such as Stanford, have a single set of courses taken by students from many disciplines. However, to restrict the examples to one field is to miss much of the range and power of feedback but to cover the whole range of applications is overwhelming. In this book, we develop the interdisciplinary nature of the field and
provide review material for several of the most common technologies so that students from many disciplines will be comfortable with the presentation. For Electrical Engineering students who typically have a good background in transform analysis, we include in Chapter 2 an introduction to writing equations of motion for mechanical mechanisms. For mechanical engineers, we include in Chapter 3 a review of the Laplace transform and dynamic response as needed in control. In addition, we introduce other technologies briefly and, from time to time, we present the equations of motion of a physical system without derivation but with enough physical description to be understood from a response point of view. Examples of some of the physical systems represented in the text include a quadrotor drone, a satellite tracking system, the fuel–air ratio in an automobile engine, and an airplane automatic pilot system.

Outline of the Book

The contents of the printed book are organized into ten chapters and three appendices. Optional sections of advanced or enrichment material marked with a triangle (Δ) are included at the end of some chapters. Examples and problems based on this material are also marked with a triangle (Δ). There are also four full appendices on the website plus numerous appendices that supplement the material in most of the chapters. The appendices in the printed book include Laplace transform tables, answers to the end-of-chapter review questions, and a list of Matlab commands. The appendices on the website include a review of complex variables, a review of matrix theory, some important results related to state-space design, and optional material supporting or extending several of the chapters.

In Chapter 1, the essential ideas of feedback and some of the key design issues are introduced. This chapter also contains a brief history of control, from the ancient beginnings of process control to flight control and electronic feedback amplifiers. It is hoped that this brief history will give a context for the field, introduce some of the key people who contributed to its development, and provide motivation to the student for the studies to come.

Chapter 2 is a short presentation of dynamic modeling and includes mechanical, electrical, electromechanical, fluid, and thermodynamic devices. This material can be omitted, used as the basis of review homework to smooth out the usual nonuniform preparation of students, or covered in-depth depending on the needs of the students.

Chapter 3 covers dynamic response as used in control. Again, much of this material may have been covered previously, especially by electrical engineering students. For many students, the correlation between pole locations and transient response and the effects of extra zeros and poles on dynamic response represent new material. Stability of dynamic
systems is also introduced in this chapter. This material needs to be covered carefully.

Chapter 4 presents the basic equations and transfer functions of feedback along with the definitions of the sensitivity function. With these tools, open-loop and closed-loop control are compared with respect to disturbance rejection, tracking accuracy, and sensitivity to model errors. Classification of systems according to their ability to track polynomial reference signals or to reject polynomial disturbances is described with the concept of system type. Finally, the classical proportional, integral, and derivative (PID) control structure is introduced and the influence of the controller parameters on a system’s characteristic equation is explored along with PID tuning methods.

Following the overview of feedback in Chapter 4, the core of the book presents the design methods based on root locus, frequency response, and state-variable feedback in Chapters 5, 6, and 7, respectively.

Chapter 8 develops the tools needed to design feedback control for implementation in a digital computer. However, for a complete treatment of feedback control using digital computers, the reader is referred to the companion text, *Digital Control of Dynamic Systems*, by Franklin, Powell, and Workman; Ellis-Kagle Press, 1998.

In Chapter 9, the nonlinear material includes techniques for the linearization of equations of motion, analysis of zero memory nonlinearity as a variable gain, frequency response as a describing function, the phase plane, Lyapunov stability theory, and the circle stability criterion.

In Chapter 10, the three primary approaches are integrated in several case studies, and a framework for design is described that includes a touch of the real-world context of practical control design.

**Course Configurations**

The material in this text can be covered flexibly. Most first-course students in controls will have some dynamics and Laplace transforms. Therefore, Chapter 2 and most of Chapter 3 would be a review for those students. In a ten-week quarter, it is possible to review Chapter 3, and cover all of Chapters 1, 4, 5, and 6. Most optional sections should be omitted. In the second quarter, Chapters 7 and 9 can be covered comfortably including the optional sections. Alternatively, some optional sections could be omitted and selected portions of Chapter 8 included. A semester course should comfortably accommodate Chapters 1–7, including the review materials of Chapters 2 and 3, if needed. If time remains after this core coverage, some introduction of digital control from Chapter 8, selected nonlinear issues from Chapter 9, and some of the case studies from Chapter 10 may be added.

The entire book can also be used for a three-quarter sequence of courses consisting of modeling and dynamic response (Chapters 2
and 3), classical control (Chapters 4–6), and modern control (Chapters 7–10).

Two basic 10-week courses are offered at Stanford and are taken by seniors and first-year graduate students who have not had a course in control, mostly in the departments of Aeronautics and Astronautics, Mechanical Engineering, and Electrical Engineering. The first course reviews Chapters 2 and 3 and covers Chapters 4–6. The more advanced course is intended for graduate students and reviews Chapters 4–6 and covers Chapters 7–10. This sequence complements a graduate course in linear systems and is the prerequisite to courses in digital control, nonlinear control, optimal control, flight control, and smart product design. Some of the subsequent courses include extensive laboratory experiments. Prerequisites for the course sequence include dynamics or circuit analysis and Laplace transforms.

Prerequisites to This Feedback Control Course

This book is for a first course at the senior level for all engineering majors. For the core topics in Chapters 4–7, prerequisite understanding of modeling and dynamic response is necessary. Many students will come into the course with sufficient background in those concepts from previous courses in physics, circuits, and dynamic response. For those needing review, Chapters 2 and 3 should fill in the gaps.

An elementary understanding of matrix algebra is necessary to understand the state-space material. While all students will have much of this in prerequisite math courses, a review of the basic relations is given in online Appendix WB and a brief treatment of particular material needed in control is given at the start of Chapter 7. The emphasis is on the relations between linear dynamic systems and linear algebra.

Supplements

The websites www.FPE8e.com and www.pearsonhighered.com/engineering-resources include the dot-m and dot-slx files used to generate all the Matlab figures in the book, and these may be copied and distributed to the students as desired. The websites also contain some more advanced material and appendices which are outlined in the Table of Contents. A Solutions Manual with complete solutions to all homework problems is available to instructors only.

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