

RICHARD C. DORF

ROBERT H. BISHOP

MODERN CONTROL SYSTEMS

TWELFTH EDITION

Design Examples and Design Problems (DP)

CHAPTER 1	PAGE	DP4.3	Velocity Control System	297
Example Hybrid Fuel Vehicles	22	DP4.4	Laser Eye Surgery	297
Example Wind Power	23	DP4.5	Pulse Generating Op Amp	298
Example Embedded Computers	24	DP4.6	Hydrobot	298
Example Smart Grid Control Systems	28	DP4.7	Unmanned Underwater Vehicles	298
Example Rotating Disk Speed Control	30	DP4.8	Mobile Remote-Controlled Video Camera	299
Example Insulin Delivery Control System	31			
Example Disk Drive Read System	32			
CDP1.1 Traction Drive Motor Control	46	CHAPTER 5		
DP1.1 Automobile Noise Control	46	Example Hubble Telescope Pointing		343
DP1.2 Automobile Cruise Control	46	Example Attitude Control of an Airplane		346
DP1.3 Dairy Farm Automation	46	Example Disk Drive Read System		360
DP1.4 Welder Control	46	CDP5.1 Traction Drive Motor Control		379
DP1.5 Automobile Traction Control	46	DP5.1 Jet Fighter Roll Angle Control		379
DP1.6 Hubble Telescope Vibration	47	DP5.2 Welding Arm Position Control		379
DP1.7 Nanorobotics in Medicine	47	DP5.3 Automobile Active Suspension		379
DP1.8 Human Transportation Vehicle	47	DP5.4 Satellite Orientation Control		380
		DP5.5 Deburring Robot for Machined Parts		380
CHAPTER 2		DP5.6 DC Motor Position Control		380
Example Photovoltaic Generators	91	DP5.7 Three-Dimensional Cam		381
Example Fluid Flow Modeling	94	DP5.8 Spray Paint Robot		381
Example Electric Traction Motor Control	104			
Example Mechanical Accelerometer	106	CHAPTER 6		
Example Laboratory Robot	109	Example Tracked Vehicle Turning		404
Example Low-Pass Filter	111	Example Robot-Controlled Motorcycle		406
Example Disk Drive Read System	128	Example Disk Drive Read System		421
CDP2.1 Traction Drive Motor Control	155	CDP6.1 Traction Drive Motor Control		438
DP2.1 Selection of Transfer Functions	155	DP6.1 Automobile Ignition Control		438
DP2.2 Television Beam Circuit	155	DP6.2 Mars Guided Vehicle Control		439
DP2.3 Transfer Function Determination	155	DP6.3 Parameter Selection		439
DP2.4 Op Amp Differentiating Circuit	155	DP6.4 Space Shuttle Rocket		439
DP2.5 Grandfather Clock Pendulum	156	DP6.5 Traffic Control System		439
		DP6.6 State Variable Feedback		439
CHAPTER 3		DP6.7 Inner and Outer Loop Control		440
Example Modeling the Orientation of a Space Station	193	DP6.8 PD Controller Design		440
Example Printer Belt Drive	200			
Example Disk Drive Read System	209	CHAPTER 7		
CDP3.1 Traction Drive Motor Control	230	Example Wind Turbine Speed Control		497
DP3.1 Shock Absorber for Motorcycle	230	Example Laser Manipulator Control		500
DP3.2 Diagonal Matrix Differential Equation	230	Example Robot Control System		502
DP3.3 Aircraft Arresting Gear	230	Example Automobile Velocity Control		505
DP3.4 Bungi Jumping System	230	Example Disk Drive Read System		516
DP3.5 State Variable Feedback	231	CDP7.1 Traction Drive Motor Control		543
		DP7.1 Pitch Rate Aircraft Control		543
CHAPTER 4		DP7.2 Helicopter Velocity Control		543
Example English Channel Boring Machines	254	DP7.3 Mars Rover		544
Example Mars Rover Vehicle	257	DP7.4 Remotely Controlled Welder		544
Example Blood Pressure Control	259	DP7.5 High-Performance Jet Aircraft		544
Example Disk Drive Read System	273	DP7.6 Control of Walking Motion		545
CDP4.1 Traction Drive Motor Control	296	DP7.7 Mobile Robot with Vision		545
DP4.1 Speed Control System	296	DP7.8 OP Amp Control System		545
DP4.2 Airplane Roll Angle Control	297	DP7.9 Robot Arm Elbow Joint Actuator		546

DP7.10	Four-Wheel-Steered Automobile	546	DP10.7	Aircraft Roll Angle Control	828
DP7.11	Pilot Crane Control	547	DP10.8	Windmill Radiometer	828
DP7.12	Planetary Rover Vehicle	547	DP10.9	Control with Time Delay	829
DP7.13	Roll Angle Aircraft Autopilot	548	DP10.10	Loop Shaping	830
DP7.14	PD Control of a Marginally Stable Process	548	DP10.11	Polymerase Chain Reaction Control	830
CHAPTER 8			CHAPTER 11		
Example	Maximum Power Pointing Tracking	583	Example	Automatic Test System	873
Example	Engraving Machine Control	585	Example	Diesel Electric Locomotive	876
Example	Control of a Six-Legged Robot	588	Example	Disk Drive Read System	888
Example	Disk Drive Read System	602	CDP11.1	Traction Drive Motor Control	903
CDP8.1	Traction Drive Motor Control	628	DP11.1	Levitation of a Steel Ball	903
DP8.1	Automobile Steering System	628	DP11.2	Automobile Carburetor	903
DP8.2	Autonomous Planetary Explorer-Ambler	628	DP11.3	State Variable Compensation	903
DP8.3	Vial Position Control Under a Dispenser	628	DP11.4	Helicopter Control	904
DP8.4	Automatic Anesthesia Control	628	DP11.5	Manufacturing of Paper	904
DP8.5	Black Box Control	630	DP11.6	Coupled-Drive Control	905
DP8.6	State Variable System Design	630	DP11.7	Tracking a Reference Input	905
DP8.7	PID Controller Design	631	CHAPTER 12		
CHAPTER 9			Example	Aircraft Autopilot	935
Example	PID Control of Wind Turbines	674	Example	Space Telescope Control	935
Example	Remotely Controlled Reconnaissance Vehicle	678	Example	Robust Bobbin Drive	938
Example	Hot Ingot Robot Control	681	Example	Ultra-Precision Diamond Turning Machine	940
Example	Disk Drive Read System	700	Example	Digital Audio Tape Controller	943
CDP9.1	Traction Drive Motor Control	735	Example	Disk Drive Read System	958
DP9.1	Mobile Robot for Toxic Waste Cleanup	735	CDP12.1	Traction Drive Motor Control	974
DP9.2	Control of a Flexible Arm	735	DP12.1	Turntable Position Control	974
DP9.3	Blood Pressure Regulator	735	DP12.2	Robust Parameter Design	974
DP9.4	Robot Tennis Player	735	DP12.3	Dexterous Hand Master	974
DP9.5	Electrohydraulic Actuator	735	DP12.4	Microscope Control	975
DP9.6	Steel Strip-Rolling Mill	735	DP12.5	Microscope Control	976
DP9.7	Lunar Vehicle Control	738	DP12.6	Artificial Control of Leg Articulation	976
DP9.8	High-Speed Steel-Rolling Mill	738	DP12.7	Elevator Position Control	977
DP9.9	Two-Tank Temperature Control	738	DP12.8	Electric Ventricular Assist Device	978
DP9.10	State Variable Feedback Control	739	DP12.9	Space Robot Control	978
DP9.11	Nuclear Reactor Control	739	DP12.10	Solar Panel Pointing Control	979
CHAPTER 10			DP12.11	Magnetically Levitated Train	979
Example	Rotor Winder Control System	783	DP12.12	Mars Guided Vehicle Control	979
Example	The X-Y Plotter	787	DP12.13	Benchmark Mass-Spring	979
Example	Milling Machine Control System	790	CHAPTER 13		
Example	Disk Drive Read System	802	Example	Worktable Motion Control	1009
CDP10.1	Traction Drive Motor Control	826	Example	Fly-by-wire Aircraft Control	1011
DP10.1	Two Cooperating Robots	826	Example	Disk Drive Read System	1023
DP10.2	Heading Control of a Bi-Wing Aircraft	826	CDP13.1	Traction Drive Motor Control	1034
DP10.3	Mast Flight System	826	DP13.1	Temperature Control System	1034
DP10.4	High-Speed Train Tilt Control	826	DP13.2	Disk Drive Read-Write Head-Positioning System	1034
DP10.5	Tape Transport Speed Control	828	DP13.3	Vehicle Traction Control	1034
DP10.6	Automobile Engine Control	828	DP13.4	Machine-Tool System	1035
			DP13.5	Polymer Extruder Control	1035
			DP13.6	Sampled-Data System	1035

Modern Control Systems

TWELFTH EDITION

Richard C. Dorf

University of California, Davis

Robert H. Bishop

Marquette University

Prentice Hall

Upper Saddle River Boston Columbus San Francisco New York
Indianapolis London Toronto Sydney Singapore Tokyo Montreal
Dubai Madrid Hong Kong Mexico City Munich Paris Amsterdam Cape Town

Vice President and Editorial Director, ECS: Marcia J. Horton
Senior Editor: Andrew Gilfillan
Associate Editor: Alice Dworkin
Editorial Assistant: William Opaluch
Vice President, Production: Vince O'Brien
Senior Managing Editor: Scott Disanno
Production Liaison: Jane Bonnell
Production Editor: Maheswari PonSaravanan, TexTech International
Senior Operations Supervisor: Alan Fischer
Operations Specialist: Lisa McDowell
Executive Marketing Manager: Tim Galligan
Marketing Assistant: Mack Patterson
Senior Art Director and Cover Designer: Kenny Beck
Cover Images: Front: Scarlet macaw flying/Frans Lanting/Corbis; Back: Courtesy of Dr. William Kaiser
and Dr. Philip Rundel of UCLA, and National Instruments
Art Editor: Greg Dulles
Media Editor: Daniel Sandin
Composition/Full-Service Project Management: TexTech International

LabVIEW is a trademark of National Instruments. MATLAB is a registered trademark of The MathWorks, Inc. Company and product names mentioned herein are the trademarks or registered trademarks of their respective owners.

Copyright © 2011, 2008, 2005, 2001 by Pearson Education, Inc., Upper Saddle River, New Jersey 07458. All rights reserved. Manufactured in the United States of America. This publication is protected by Copyright and permissions should be obtained from the publisher prior to any prohibited reproduction, storage in a retrieval system, or transmission in any form or by any means, electronic, mechanical, photocopying, recording, or likewise. To obtain permission(s) to use materials from this work, please submit a written request to Pearson Higher Education, Permissions Department, 1 Lake Street, Upper Saddle River, NJ 07458.

The author and publisher of this book have used their best efforts in preparing this book. These efforts include the development, research, and testing of the theories and programs to determine their effectiveness. The author and publisher make no warranty of any kind, expressed or implied, with regard to these programs or the documentation contained in this book. The author and publisher shall not be liable in any event for incidental or consequential damages in connection with, or arising out of, the furnishing, performance, or use of these programs.

Library of Congress Cataloging-in-Publication Data

Dorf, Richard C.

Modern control systems / Richard C. Dorf, Robert H. Bishop. — 12th ed.

p. cm.

ISBN-13: 978-0-13-602458-3

ISBN-10: 0-13-602458-0

1. Feedback control systems. I. Bishop, Robert H. II. Title.

TJ216.D67 2010

629.8'3—dc22

2010015651

Prentice Hall
is an imprint of



www.pearsonhighered.com

10 9 8 7 6 5 4 3 2 1

ISBN-13: 978-0-13-602458-3

ISBN-10: 0-13-602458-0

Contents

Preface xi

About the Authors xxii

CHAPTER 1 *Introduction to Control Systems 1*

- 1.1 Introduction 2
- 1.2 Brief History of Automatic Control 5
- 1.3 Examples of Control Systems 10
- 1.4 Engineering Design 17
- 1.5 Control System Design 18
- 1.6 Mechatronic Systems 21
- 1.7 Green Engineering 25
- 1.8 The Future Evolution of Control Systems 27
- 1.9 Design Examples 28
- 1.10 Sequential Design Example: Disk Drive Read System 32
- 1.11 Summary 34
 - Skills Check 35 • Exercises 37 • Problems 39 • Advanced Problems 44 • Design Problems 46 • Terms and Concepts 48

CHAPTER 2 *Mathematical Models of Systems 49*

- 2.1 Introduction 50
- 2.2 Differential Equations of Physical Systems 50
- 2.3 Linear Approximations of Physical Systems 55
- 2.4 The Laplace Transform 58
- 2.5 The Transfer Function of Linear Systems 65
- 2.6 Block Diagram Models 79
- 2.7 Signal-Flow Graph Models 84
- 2.8 Design Examples 90
- 2.9 The Simulation of Systems Using Control Design Software 113
- 2.10 Sequential Design Example: Disk Drive Read System 128
- 2.11 Summary 130
 - Skills Check 131 • Exercises 135 • Problems 141 • Advanced Problems 153 • Design Problems 155 • Computer Problems 157 • Terms and Concepts 159

CHAPTER 3 *State Variable Models 161*

- 3.1 Introduction 162
- 3.2 The State Variables of a Dynamic System 162

3.3	The State Differential Equation	166
3.4	Signal-Flow Graph and Block Diagram Models	171
3.5	Alternative Signal-Flow Graph and Block Diagram Models	182
3.6	The Transfer Function from the State Equation	187
3.7	The Time Response and the State Transition Matrix	189
3.8	Design Examples	193
3.9	Analysis of State Variable Models Using Control Design Software	206
3.10	Sequential Design Example: Disk Drive Read System	209
3.11	Summary	213
	Skills Check	214 • Exercises 217 • Problems 220 • Advanced Problems 227 • Design Problems 230 • Computer Problems 231 • Terms and Concepts 232

CHAPTER 4 *Feedback Control System Characteristics* **234**

4.1	Introduction	235
4.2	Error Signal Analysis	237
4.3	Sensitivity of Control Systems to Parameter Variations	239
4.4	Disturbance Signals in a Feedback Control System	242
4.5	Control of the Transient Response	247
4.6	Steady-State Error	250
4.7	The Cost of Feedback	253
4.8	Design Examples	254
4.9	Control System Characteristics Using Control Design Software	268
4.10	Sequential Design Example: Disk Drive Read System	273
4.11	Summary	277
	Skills Check	279 • Exercises 283 • Problems 287 • Advanced Problems 293 • Design Problems 296 • Computer Problems 300 • Terms and Concepts 303

CHAPTER 5 *The Performance of Feedback Control Systems* **304**

5.1	Introduction	305
5.2	Test Input Signals	305
5.3	Performance of Second-Order Systems	308
5.4	Effects of a Third Pole and a Zero on the Second-Order System Response	314
5.5	The s -Plane Root Location and the Transient Response	320
5.6	The Steady-State Error of Feedback Control Systems	322
5.7	Performance Indices	330
5.8	The Simplification of Linear Systems	339
5.9	Design Examples	342
5.10	System Performance Using Control Design Software	356
5.11	Sequential Design Example: Disk Drive Read System	360

- 5.12 Summary 364
Skills Check 364 • Exercises 368 • Problems 371 • Advanced
Problems 377 • Design Problems 379 • Computer Problems 382 •
Terms and Concepts 384

CHAPTER 6 *The Stability of Linear Feedback Systems* **386**

- 6.1 The Concept of Stability 387
6.2 The Routh–Hurwitz Stability Criterion 391
6.3 The Relative Stability of Feedback Control Systems 399
6.4 The Stability of State Variable Systems 401
6.5 Design Examples 404
6.6 System Stability Using Control Design Software 413
6.7 Sequential Design Example: Disk Drive Read System 421
6.8 Summary 424
Skills Check 425 • Exercises 428 • Problems 430 • Advanced
Problems 435 • Design Problems 438 • Computer Problems 440 •
Terms and Concepts 442

CHAPTER 7 *The Root Locus Method* **443**

- 7.1 Introduction 444
7.2 The Root Locus Concept 444
7.3 The Root Locus Procedure 449
7.4 Parameter Design by the Root Locus Method 467
7.5 Sensitivity and the Root Locus 473
7.6 PID Controllers 480
7.7 Negative Gain Root Locus 492
7.8 Design Examples 496
7.9 The Root Locus Using Control Design Software 510
7.10 Sequential Design Example: Disk Drive Read System 516
7.11 Summary 518
Skills Check 522 • Exercises 526 • Problems 530 • Advanced
Problems 539 • Design Problems 543 • Computer Problems 549 •
Terms and Concepts 551

CHAPTER 8 *Frequency Response Methods* **553**

- 8.1 Introduction 554
8.2 Frequency Response Plots 556
8.3 Frequency Response Measurements 577
8.4 Performance Specifications in the Frequency Domain 579
8.5 Log Magnitude and Phase Diagrams 582
8.6 Design Examples 583

- 8.7 Frequency Response Methods Using Control Design Software 596
- 8.8 Sequential Design Example: Disk Drive Read System 602
- 8.9 Summary 603
 - Skills Check 608 • Exercises 613 • Problems 616 • Advanced Problems 626 • Design Problems 628 • Computer Problems 631 • Terms and Concepts 633

CHAPTER 9 *Stability in the Frequency Domain* 634

- 9.1 Introduction 635
- 9.2 Mapping Contours in the s -Plane 636
- 9.3 The Nyquist Criterion 642
- 9.4 Relative Stability and the Nyquist Criterion 653
- 9.5 Time-Domain Performance Criteria in the Frequency Domain 661
- 9.6 System Bandwidth 668
- 9.7 The Stability of Control Systems with Time Delays 668
- 9.8 Design Examples 673
- 9.9 PID Controllers in the Frequency Domain 691
- 9.10 Stability in the Frequency Domain Using Control Design Software 692
- 9.11 Sequential Design Example: Disk Drive Read System 700
- 9.12 Summary 703
 - Skills Check 711 • Exercises 715 • Problems 721 • Advanced Problems 731 • Design Problems 735 • Computer Problems 740 • Terms and Concepts 742

CHAPTER 10 *The Design of Feedback Control Systems* 743

- 10.1 Introduction 744
- 10.2 Approaches to System Design 745
- 10.3 Cascade Compensation Networks 747
- 10.4 Phase-Lead Design Using the Bode Diagram 751
- 10.5 Phase-Lead Design Using the Root Locus 757
- 10.6 System Design Using Integration Networks 764
- 10.7 Phase-Lag Design Using the Root Locus 767
- 10.8 Phase-Lag Design Using the Bode Diagram 772
- 10.9 Design on the Bode Diagram Using Analytical Methods 776
- 10.10 Systems with a Prefilter 778
- 10.11 Design for Deadbeat Response 781
- 10.12 Design Examples 783
- 10.13 System Design Using Control Design Software 796
- 10.14 Sequential Design Example: Disk Drive Read System 802
- 10.15 Summary 804
 - Skills Check 806 • Exercises 810 • Problems 814 • Advanced Problems 823 • Design Problems 826 • Computer Problems 831 • Terms and Concepts 833

CHAPTER 11 *The Design of State Variable Feedback Systems* 834

- 11.1 Introduction 835
- 11.2 Controllability and Observability 835
- 11.3 Full-State Feedback Control Design 841
- 11.4 Observer Design 847
- 11.5 Integrated Full-State Feedback and Observer 851
- 11.6 Reference Inputs 857
- 11.7 Optimal Control Systems 859
- 11.8 Internal Model Design 869
- 11.9 Design Examples 873
- 11.10 State Variable Design Using Control Design Software 882
- 11.11 Sequential Design Example: Disk Drive Read System 888
- 11.12 Summary 890
 - Skills Check 890 • Exercises 894 • Problems 896 • Advanced Problems 900 • Design Problems 903 • Computer Problems 906 • Terms and Concepts 908

CHAPTER 12 *Robust Control Systems* 910

- 12.1 Introduction 911
- 12.2 Robust Control Systems and System Sensitivity 912
- 12.3 Analysis of Robustness 916
- 12.4 Systems with Uncertain Parameters 918
- 12.5 The Design of Robust Control Systems 920
- 12.6 The Design of Robust PID-Controlled Systems 926
- 12.7 The Robust Internal Model Control System 932
- 12.8 Design Examples 935
- 12.9 The Pseudo-Quantitative Feedback System 952
- 12.10 Robust Control Systems Using Control Design Software 953
- 12.11 Sequential Design Example: Disk Drive Read System 958
- 12.12 Summary 960
 - Skills Check 961 • Exercises 965 • Problems 967 • Advanced Problems 971 • Design Problems 974 • Computer Problems 980 • Terms and Concepts 982

CHAPTER 13 *Digital Control Systems* 984

- 13.1 Introduction 985
- 13.2 Digital Computer Control System Applications 985
- 13.3 Sampled-Data Systems 987
- 13.4 The z -Transform 990
- 13.5 Closed-Loop Feedback Sampled-Data Systems 995

13.6	Performance of a Sampled-Data, Second-Order System	999				
13.7	Closed-Loop Systems with Digital Computer Compensation	1001				
13.8	The Root Locus of Digital Control Systems	1004				
13.9	Implementation of Digital Controllers	1008				
13.10	Design Examples	1009				
13.11	Digital Control Systems Using Control Design Software	1018				
13.12	Sequential Design Example: Disk Drive Read System	1023				
13.13	Summary	1025				
	Skills Check	1025 • Exercises	1029 • Problems	1031 •		
	Advanced Problems	1033 • Design Problems	1034 • Computer	Problems	1036 • Terms and Concepts	1037

APPENDIX A *MATLAB Basics* **1038**

References **1056**

Index **1071**



WEB RESOURCES

APPENDIX B *MathScript RT Module Basics*

APPENDIX C *Symbols, Units, and Conversion Factors*

APPENDIX D *Laplace Transform Pairs*

APPENDIX E *An Introduction to Matrix Algebra*

APPENDIX F *Decibel Conversion*

APPENDIX G *Complex Numbers*

APPENDIX H *z-Transform Pairs Preface*

APPENDIX I *Discrete-Time Evaluation of the Time Response*