Modern Control Systems

Twelfth Edition

Richard C. Dorf
Robert H. Bishop

PEARSON

629.83
D695
2011
C-1

Modern Control Systems

TWELFTH EDITION

Richard C. Dorf
University of California, Davis

Robert H. Bishop
Marquette University

PEARSON

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

Contents

Preface 11
About the Authors 22

CHAPTER 1 *Introduction to Control Systems 23*

1.1 Introduction 24
1.2 Brief History of Automatic Control 27
1.3 Examples of Control Systems 32
1.4 Engineering Design 39
1.5 Control System Design 40
1.6 Mechatronic Systems 43
1.7 Green Engineering 47
1.8 The Future Evolution of Control Systems 49
1.9 Design Examples 50
1.10 Sequential Design Example: Disk Drive Read System 54
1.11 Summary 56
Skills Check 57 • Exercises 59 • Problems 61 • Advanced Problems 66 • Design Problems 68 • Terms and Concepts 70

CHAPTER 2 *Mathematical Models of Systems 71*

2.1 Introduction 72
2.2 Differential Equations of Physical Systems 72
2.3 Linear Approximations of Physical Systems 77
2.4 The Laplace Transform 80
2.5 The Transfer Function of Linear Systems 87
2.6 Block Diagram Models 101
2.7 Signal-Flow Graph Models 106
2.8 Design Examples 112
2.9 The Simulation of Systems Using Control Design Software 135
2.10 Sequential Design Example: Disk Drive Read System 150
2.11 Summary 152
Skills Check 153 • Exercises 157 • Problems 163 • Advanced Problems 175 • Design Problems 177 • Computer Problems 179 • Terms and Concepts 181

CHAPTER 3 *State Variable Models 183*

3.1 Introduction 184
3.2 The State Variables of a Dynamic System 184

3.3 The State Differential Equation 188
3.4 Signal-Flow Graph and Block Diagram Models 193
3.5 Alternative Signal-Flow Graph and Block Diagram Models 204
3.6 The Transfer Function from the State Equation 209
3.7 The Time Response and the State Transition Matrix 211
3.8 Design Examples 215
3.9 Analysis of State Variable Models Using Control Design Software 228
3.10 Sequential Design Example: Disk Drive Read System 231
3.11 Summary 235
Skills Check 236 • Exercises 239 • Problems 242 • Advanced Problems 249 • Design Problems 252 • Computer Problems 253 • Terms and Concepts 254

CHAPTER 4 *Feedback Control System Characteristics* 256

4.1 Introduction 257
4.2 Error Signal Analysis 259
4.3 Sensitivity of Control Systems to Parameter Variations 261
4.4 Disturbance Signals in a Feedback Control System 264
4.5 Control of the Transient Response 269
4.6 Steady-State Error 272
4.7 The Cost of Feedback 275
4.8 Design Examples 276
4.9 Control System Characteristics Using Control Design Software 290
4.10 Sequential Design Example: Disk Drive Read System 295
4.11 Summary 299
Skills Check 301 • Exercises 305 • Problems 309 • Advanced Problems 315 • Design Problems 318 • Computer Problems 322 • Terms and Concepts 325

CHAPTER 5 *The Performance of Feedback Control Systems* 326

5.1 Introduction 327
5.2 Test Input Signals 327
5.3 Performance of Second-Order Systems 330
5.4 Effects of a Third Pole and a Zero on the Second-Order System Response 336
5.5 The s-Plane Root Location and the Transient Response 342
5.6 The Steady-State Error of Feedback Control Systems 344
5.7 Performance Indices 352
5.8 The Simplification of Linear Systems 361
5.9 Design Examples 364
5.10 System Performance Using Control Design Software 378
5.11 Sequential Design Example: Disk Drive Read System 382

5.12 Summary 386
Skills Check 386 • Exercises 390 • Problems 393 • Advanced Problems 399 • Design Problems 401 • Computer Problems 404 • Terms and Concepts 406

CHAPTER 6 ***The Stability of Linear Feedback Systems 408***

6.1 The Concept of Stability 409
6.2 The Routh–Hurwitz Stability Criterion 413
6.3 The Relative Stability of Feedback Control Systems 421
6.4 The Stability of State Variable Systems 423
6.5 Design Examples 426
6.6 System Stability Using Control Design Software 435
6.7 Sequential Design Example: Disk Drive Read System 443
6.8 Summary 446
Skills Check 447 • Exercises 450 • Problems 452 • Advanced Problems 457 • Design Problems 460 • Computer Problems 462 • Terms and Concepts 464

CHAPTER 7 ***The Root Locus Method 465***

7.1 Introduction 466
7.2 The Root Locus Concept 466
7.3 The Root Locus Procedure 471
7.4 Parameter Design by the Root Locus Method 489
7.5 Sensitivity and the Root Locus 495
7.6 PID Controllers 502
7.7 Negative Gain Root Locus 514
7.8 Design Examples 518
7.9 The Root Locus Using Control Design Software 532
7.10 Sequential Design Example: Disk Drive Read System 538
7.11 Summary 540
Skills Check 544 • Exercises 548 • Problems 552 • Advanced Problems 561 • Design Problems 565 • Computer Problems 571 • Terms and Concepts 573

CHAPTER 8 ***Frequency Response Methods 575***

8.1 Introduction 576
8.2 Frequency Response Plots 578
8.3 Frequency Response Measurements 599
8.4 Performance Specifications in the Frequency Domain 601
8.5 Log Magnitude and Phase Diagrams 604
8.6 Design Examples 605

8.7 Frequency Response Methods Using Control Design Software 618
8.8 Sequential Design Example: Disk Drive Read System 624
8.9 Summary 625
Skills Check 630 • Exercises 635 • Problems 638 • Advanced Problems 648 • Design Problems 650 • Computer Problems 653 • Terms and Concepts 655

CHAPTER 9 *Stability in the Frequency Domain 656*

9.1 Introduction 657
9.2 Mapping Contours in the s-Plane 658
9.3 The Nyquist Criterion 664
9.4 Relative Stability and the Nyquist Criterion 675
9.5 Time-Domain Performance Criteria in the Frequency Domain 683
9.6 System Bandwidth 690
9.7 The Stability of Control Systems with Time Delays 690
9.8 Design Examples 695
9.9 PID Controllers in the Frequency Domain 713
9.10 Stability in the Frequency Domain Using Control Design Software 714
9.11 Sequential Design Example: Disk Drive Read System 722
9.12 Summary 725
Skills Check 733 • Exercises 737 • Problems 743 • Advanced Problems 753 • Design Problems 757 • Computer Problems 762 • Terms and Concepts 764

CHAPTER 10 *The Design of Feedback Control Systems 765*

10.1 Introduction 766
10.2 Approaches to System Design 767
10.3 Cascade Compensation Networks 769
10.4 Phase-Lead Design Using the Bode Diagram 773
10.5 Phase-Lead Design Using the Root Locus 779
10.6 System Design Using Integration Networks 786
10.7 Phase-Lag Design Using the Root Locus 789
10.8 Phase-Lag Design Using the Bode Diagram 794
10.9 Design on the Bode Diagram Using Analytical Methods 798
10.10 Systems with a Prefilter 800
10.11 Design for Deadbeat Response 803
10.12 Design Examples 805
10.13 System Design Using Control Design Software 818
10.14 Sequential Design Example: Disk Drive Read System 824
10.15 Summary 826
Skills Check 828 • Exercises 832 • Problems 836 • Advanced Problems 845 • Design Problems 848 • Computer Problems 853 • Terms and Concepts 855

CHAPTER 11 *The Design of State Variable Feedback Systems 856*

11.1 Introduction 857
11.2 Controllability and Observability 857
11.3 Full-State Feedback Control Design 863
11.4 Observer Design 869
11.5 Integrated Full-State Feedback and Observer 873
11.6 Reference Inputs 879
11.7 Optimal Control Systems 881
11.8 Internal Model Design 891
11.9 Design Examples 895
11.10 State Variable Design Using Control Design Software 904
11.11 Sequential Design Example: Disk Drive Read System 910
11.12 Summary 912
Skills Check 912 • Exercises 916 • Problems 918 • Advanced Problems 922 • Design Problems 925 • Computer Problems 928 • Terms and Concepts 930

CHAPTER 12 *Robust Control Systems 932*

12.1 Introduction 933
12.2 Robust Control Systems and System Sensitivity 934
12.3 Analysis of Robustness 938
12.4 Systems with Uncertain Parameters 940
12.5 The Design of Robust Control Systems 942
12.6 The Design of Robust PID-Controlled Systems 948
12.7 The Robust Internal Model Control System 954
12.8 Design Examples 957
12.9 The Pseudo-Quantitative Feedback System 974
12.10 Robust Control Systems Using Control Design Software 975
12.11 Sequential Design Example: Disk Drive Read System 980
12.12 Summary 982
Skills Check 983 • Exercises 987 • Problems 989 • Advanced Problems 993 • Design Problems 996 • Computer Problems 1002 • Terms and Concepts 1004

CHAPTER 13 *Digital Control Systems 1006*

13.1 Introduction 1007
13.2 Digital Computer Control System Applications 1007
13.3 Sampled-Data Systems 1009
13.4 The z-Transform 1012
13.5 Closed-Loop Feedback Sampled-Data Systems 1017

13.6 Performance of a Sampled-Data, Second-Order System 1021
13.7 Closed-Loop Systems with Digital Computer Compensation 1023
13.8 The Root Locus of Digital Control Systems 1026
13.9 Implementation of Digital Controllers 1030
13.10 Design Examples 1031
13.11 Digital Control Systems Using Control Design Software 1040
13.12 Sequential Design Example: Disk Drive Read System 1045
13.13 Summary 1047
Skills Check 1047 • Exercises 1051 • Problems 1053 • Advanced Problems 1055 • Design Problems 1056 • Computer Problems 1058 • Terms and Concepts 1059

APPENDIX A ***MATLAB Basics 1060***

References 1078

Index 1093

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***

Index

- **Absolute stability.** A system description that reveals whether a system is stable or not stable without consideration of other system attributes such as degree of stability. 409, 464
- **Acceleration error constant, K_a.** The constant evaluated as $\lim_{s \to 0}[s^2 G_c(s)G(s)]$. The steady-state error for a parabolic input, $r(t) = At^2/2$, is equal to A/K_a. 347, 406
- Acceleration input, steady-state error, 346–347
- Accelerometer, 101, 113, 128–131
- Ackermann's formula, 856, 867–868, 872, 877–878, 909–911, 920
- **Across-variable.** A variable determined by measuring the difference of the values at the two ends of an element. 73, 75
- **Actuator.** The device that causes the process to provide the output. The device that provides the motive power to the process. 92, 181
- **Additive perturbation.** A system perturbation model expressed in the additive form $G_a(s) = G(s) + A(s)$, where $G(s)$ is the nominal process function, $A(s)$ is the perturbation that is bounded in magnitude, and $G_a(s)$ is the family of perturbed process functions. 938, 1004
- Agricultural systems, 37
- Aircraft, and computer-aided design, 42
  - unmanned, 38
- Aircraft attitude control, 368–378
- Aircraft autopilot, 957
- Airplane control, 314, 554, 561–562, 848–849
- **All-pass network.** A nonminimum phase system that passes all frequencies with equal gain. 595–596, 655
- Alternative signal-flow graph, and block diagram models, 204–209
- Ambler, 610
- Amplidyne, 165
- Amplifier, feedback, 263–264
- **Amplitude quantization error.** The sampled signal available only with a limited precision. The error between the actual signal and the sampled signal. 1011–1012, 1059
- **Analogous variables.** Variables associated with electrical, mechanical, thermal, and fluid systems possessing similar solutions providing the analyst with the ability to extend the solution of one system to all analogous systems with the same describing differential equations. 77
- Analog-to-digital converter, 1007, 1011
- Analysis of robustness, 938–940
- Anesthesia, blood pressure control during, 281–289
- **Angle of departure.** The angle at which a locus leaves a complex pole in the s-plane. 480–481, 484, 499–501, 573
- **Angle of the asymptotes.** The angle that the asymptote makes with respect to the real axis, ϕ_A. 473, 476, 573
- Antiskid braking systems, 995
- Arc welding, 453
- Armature-controlled motor, 94, 95, 99, 111, 127, 150, 175, 177
- Array operations in MATLAB, 1067–1068
- Artificial hand, 34, 37, 66
- **Assumptions.** Statements that reflect situations and conditions that are taken for granted and without proof. In control systems, assumptions are often employed to simplify the physical dynamical models of systems under consideration to make the control design problem more tractable. 72, 116–117, 181
- **Asymptote.** The path the root locus follows as the parameter becomes very large and approaches infinity. The number of asymptotes is equal to the number of poles minus the number of zeros. 473, 573
  - of root locus, 473
- **Asymptote centroid.** The center of the linear asymptotes, σ_A. 474, 573
- Asymptotic approximation for a Bode diagram, 584
- Automated guided vehicle (AGV), 842
- Automatic control, history of, 27–31
- Automatic fluid dispenser, 251
- Automatic test system, 895–897
- **Automation.** The control of a process by automatic means. 29, 70
- Automobile steering control system, 32
- Automobile velocity control, 527–532
- Automobiles, hybrid fuel vehicles, 44, 70
- **Auxiliary polynomial.** The equation that immediately precedes the zero entry in the Routh array. 418, 464
- Avemar ferry hydrofoil, 837–838
- Axis shift, 422

- **Backward difference rule.** A computational method of approximating the time derivative of a function given by $\dot{x}(kT) = \dfrac{x(kT) - x((k-1)T)}{T}$, where $t = kT$, T is the sample time, and $k = 1, 2, \ldots$. 1030, 1059
- **Bandwidth.** The frequency at which the frequency response has declined 3 dB from its low-frequency value. 602, 655, 685, 764

- Bellman, R., 30
- Biological control system, 37
- Black, H. S., 28, 31, 168, 934
- **Block diagram.** Unidirectional, operational blocks that represent the transfer functions of the elements of the system. 101, 102, 181
- Block diagram models, 101–106, 142–149
  - alternative signal-flow graphs, 204–209
  - signal-flow graphs, 193–204
- Block diagram transformations, 103–104
- Blood pressure control and anesthesia, 281–289
- Bobbin drive, 960–962
- Bode, H. W., 582, 934
- **Bode plot.** The logarithm of magnitude of the transfer function is plotted versus the logarithm of ω, the frequency. The phase, ϕ, of the transfer function is separately plotted versus the logarithm of the frequency. 582–583, 625, 655, 656
  - asymptotic approximation, 584
  - Boring machine system, 276–279
- Bounded response, 409
- **Branch.** A unidirectional path segment in a signal-flow graph that relates the dependency of an input and an output variable. 106
- **Break frequency.** The frequency at which the asymptotic approximation of the frequency response for a pole (or zero) changes slope. 584, 587, 655
- **Breakaway point.** The point on the real axis where the locus departs from the real axis of the s-plane. 476–478, 573
- Bridge, Tacoma Narrows, 410–412

- Camera control, 357–361, 393
- **Canonical form.** A fundamental or basic form of the state variable model representation, including phase variable canonical form, input feedforward canonical form, diagonal canonical form, and Jordan canonical form. 195, 254
- Capek, Karel, 34
- **Cascade compensation network.** A compensator network placed in cascade or series with the system process. 767, 769–773, 855
- **Cauchy's theorem.** If a contour encircles Z zeros and P poles of $F(s)$ traversing clockwise, the corresponding contour in the $F(s)$-plane encircles the origin of the $F(s)$-plane $N = Z - P$ times clockwise. 657, 660–664, 764
- **Characteristic equation.** The relation formed by equating to zero the denominator of a transfer function. 82, 181, 440
- Circles, constant, 685
- **Closed-loop feedback control system.** A system that uses a measurement of the output and compares it with the desired output to control the process. 25, 70
- Closed-loop feedback sampled-data system, 1017–1021
- **Closed-loop frequency response.** The frequency response of the closed-loop transfer function $T(j\omega)$. 683, 764
- **Closed-loop system.** A system with a measurement of the output signal and a comparison with the desired output to generate an error signal that is applied to the actuator. 258, 325
- **Closed-loop transfer function.** A ratio of the output signal to the input signal for an interconnection of systems when all the feedback or feedforward loops have been closed or otherwise accounted for. Generally obtained by block diagram or signal-flow graph reduction. 104, 115, 181, 439–440
- **Command following.** An important aspect of control system design wherein a nonzero reference input is tracked. 879, 930
- **Compensation.** The alteration or adjustment of a control system in order to provide a suitable performance. 766, 855
  - of controls systems, 818
  - using a phase-lag network on the Bode diagram, 789
  - using a phase-lag network on the s-plane, 790
  - using a phase-lead network on the Bode diagram, 773
  - using a phase-lead network on the s-plane, 779
  - using analytical methods, 798
  - using integration networks, 786
  - using state-variable feedback, 856
- **Compensator.** An additional component or circuit that is inserted into the system to compensate for a performance deficiency. 557, 766, 855, 857
- Compensator design, full-state feedback and observer, 873
- **Complementary sensitivity function.** The function $T(s) = \dfrac{G_c(s)G(s)}{1 + G_c(s)G(s)}$ that satisfies the relationship $S(s) + T(s) = 1$, where $S(s)$ is the sensitivity function. The function $T(s)$ is the closed-loop transfer function. 260, 938, 1004
- **Complexity.** A measure of the structure, intricateness, or behavior of a system that characterizes the relationships and interactions between various components. 39, 325
  - in cost of feedback, 275–276
- **Complexity of design.** The intricate pattern of interwoven parts and knowledge required. 39, 70
- **Components.** The parts, subsystems, or subassemblies that comprise a total system. 325
  - in cost of feedback, 275
- Computer control systems, 1006, 1007
  - for electric power plant, 36
- Computer-aided design, 42
- Computer-aided engineering (CAE), 44
- Conditionally stable system, 556
- **Conformal mapping.** A contour mapping that retains the angles on the s-plane on the $F(s)$-plane. 659, 764
- Congress, 38
- Constant M circles, 686
- Constant N circles, 686
- Continuous design problem (CDP), 68, 177, 252, 318, 401, 460, 565, 650, 757, 848, 925, 996, 1056
- **Contour map.** A contour or trajectory in one plane is mapped into another plane by a relation $F(s)$. 658, 764
- Contours in the s-plane, 658–664
- Control engineering, 24, 29–30, 32

Control system. An interconnection of components forming a system configuration that will provide a desired response. 24, 70, 257
- characteristics using m-files, 291
- design, 40–43
- modern examples, 32–39

Controllability, 857–863

Controllability matrix. A linear system is (completely) controllable if and only if the controllability matrix $\mathbf{P}_c = [\mathbf{B} \quad \mathbf{AB} \quad \mathbf{A}^2\mathbf{B} \ldots \mathbf{A}^{n-1}\mathbf{B}]$ has full rank, where $\mathbf{A}$ is an $n \times n$ matrix. For single-input, single-output linear systems, the system is controllable if and only if the determinant of the $n \times n$ controllability matrix $\mathbf{P}_c$ is nonzero, 858, 930

Controllable system. A system is controllable on the interval $[t_0, t_f]$ if there exists a continuous input $u(t)$ such that any initial state $\mathbf{x}(t_0)$ can be driven to any arbitrary trial state $\mathbf{x}(t_f)$, in a finite time interval $t_f - t_0 > 0$, 858, 930

conv function, 138, 1075

Convolution signal, 329

Corner frequency. *See* Break frequency

Cost of feedback, 275–276

Coulomb damper. A type of mechanical damper where the model of the friction force is a nonlinear function of the mass velocity and possesses a discontinuity around zero velocity. Also known as dry friction, 75

Critical damping. The case where damping is on the boundary between underdamped and overdamped, 84, 136, 181

Critically damped system, 136

Damped oscillation. An oscillation in which the amplitude decreases with time, 86, 181

Dampers, 75

Damping ratio. A measure of damping. A dimensionless number for the second-order characteristic equation, 84, 181, 330, 332, 334–335
- estimation of, 334

DC amplifier, 100

DC motor. An electric actuator that uses an input voltage as a control variable, 92
- armature controlled, 94, 111, 181
- field controlled, 93

Deadbeat response. A system with a rapid response, minimal overshoot, and zero steady-state error for a step input, 803, 855

Decade. A factor of 10 in frequency (e.g., the range of frequencies from 1 rad/s to 10 rad/s is one decade), 584, 655
- of frequencies, 584

Decibel (dB). The units of the logarithmic gain, 583, 655

Decoupled state variable model, 205

Design. The process of conceiving or inventing the forms, parts, and details of a system to achieve a reasoned purpose, 39–40, 70

Design gap. A gap between the complex physical system and the design model intrinsic to the progression from the initial concept to the final product, 39, 70

Design of a control system. The arrangement or the plan of the system structure and the selection of suitable components and parameters, 766, 855
- robot control, 453
- in time domain, 857
- using a phase-lag network on the Bode diagram, 794
- using a phase-lag network on the *s*-plane, 789, 790
- using a phase-lead network on the Bode diagram, 773
- using a phase-lead network on the *s*-plane, 779
- using integration networks, 786
- using state-feedback, 856

Design specifications. A set of prescribed performance criteria, 327, 406

Detectable. A system in which the states that are unobservable are naturally stable, 861, 930

Dexterous Hand Master (DHM), 996

Diagonal canonical form. A decoupled canonical form displaying the *n* distinct system poles on the diagonal of the state variable representation **A** matrix, 205, 254

Diesel electric locomotive control, 898–904

Differential equations. An equation including differentials of a function, 72, 89, 181

Differential operator, 82

Differentiating circuit, 98

Digital audio tape controller, 965–974

Digital computer compensator. A system that uses a digital computer as the compensator element, 1023–1026, 1059

Digital control system. A control system using digital signals and a digital computer to control a process, 1006–1059

Digital control systems using control design software, 1040–1045

Digital controllers, implementation of, 1030–1031

Digital-to-analog converter, 1010

Direct-drive arm, 743

Discrete-time approximation, 239

Disk drive read system. *See* Sequential design example

Disturbance. An unwanted input signal that affects the output signal, 25, 70

Disturbance rejection property, 265–268

Disturbance signal. An unwanted input signal that affects the system's output signal, 264–269, 325

Dominant roots. The roots of the characteristic equation that represent or dominate the closed-loop transient response, 337, 406, 485, 473, 603, 655

Drebbel, Cornelis, 27

Dynamics of physical systems, 71

Electric power industry, 35, 36

Electric traction motor, 113, 126–128, 136, 148

Electric ventricular assist device (EVAD), 756–757

Electrohydraulic actuator, 95, 96, 166–167

Electrohydraulic servomechanisms, 744

Embedded control. Feedback control system that employs on-board special-purpose digital computers as integral components of the feedback loop. 46
Energy storage systems (green engineering), 48
Engineering design. The process of designing a technical system. 39–40, 70
English channel tunnel boring system, 276–279, 292–295
Engraving machine, 605, 607–610, 621–623
Environmental monitoring (green engineering), 48
Epidemic disease, model of, 206–207, 425–426
Equilibrium state, 207
Error, steady-state, 272–275
Error constants
  acceleration input, 346
  position, 345
  ramp, 346
  velocity, 346
Error signal. The difference between the desired output $R(s)$ and the actual output $Y(s)$. Therefore, $E(s) = R(s) - Y(s)$. 143, 181, 237, 259, 325
  analysis, 259–260
Error-squared performance indices, 882
Estimation error. The difference between the actual state and the estimated state $\mathbf{e}(t) = \mathbf{x}(t) - \hat{\mathbf{x}}(t)$. 869, 930
Evans, R., 466
Examples of control systems, 32–39
Exponential matrix function, 189
Extender, 172–173, 248, 843–844

Federal Reserve Board, 37
Feedback, 25
  amplifier, 263–264
  control system, 25, 32–34, 818–824
  cost of, 275–276
  full-state control design, 863
  negative, 25, 28
  positive, 61
  of state variables, 882, 884, 931
Feedback control system, and disturbance signals, 264–269
feedback function, 144, 145–146, 1075
Feedback signal. A measure of the output of the system used for feedback to control the system. 25, 70, 143
Feedback systems, history of, 27
Field current controlled motor, 93
Final value. The value that the output achieves after all the transient constituents of the response have faded. Also referred to as the steady-state value. 84, 181
  of response of $y(t)$, 84
Final value theorem. The theorem that states that $\lim_{t\to\infty} y(t) = \lim_{s\to 0} sY(s)$, where $Y(s)$ is the Laplace transform of $y(t)$. 84, 181
Flow graph. *See* Signal-flow graph
Fluid flow modeling, 116–126
Flyball governor. A mechanical device for controlling the speed of a steam engine. 27–28, 70
Fly-by-wire aircraft control surface, 1033–1039
Forward rectangular integration. A computational method of approximating the integration of a function given by $x(kT) \approx x((k-1)T) + T\dot{x}((k-1)T)$, where $t = kT$, T is the sample time, and $k = 1, 2, \ldots$. 1030, 1059
Fourier transform. The transformation of a function of time $f(t)$ into the frequency domain. 578, 655
Fourier transform pair. A pair of functions, one in the time domain, denoted by $f(t)$, and the other in the frequency domain, denoted by $F(\omega)$, related by the Fourier transform as $F(\omega) = \mathcal{F}\{f(t)\}$, where $\mathcal{F}$ denotes the Fourier transform. 577–578, 655
Frequency response. The steady-state response of a system to a sinusoidal input signal. 576, 655
  closed-loop, 683
  measurements, 599–601
  plots, 578–583
  using control design software, 618
Full-state feedback control law. A control law of the form $\mathbf{u} = -\mathbf{K}\mathbf{x}$ where $\mathbf{x}$ is the state of the system assumed known at all times. 857, 931
Fundamental matrix. *See* Transition matrix
Future evolution of control systems, 49–50

Gain margin. The increase in the system gain when phase = −180° that will result in a marginally stable system with intersection of the $-1 + j0$ point on the Nyquist diagram. 677, 715–716, 725, 764
Gamma-Ray Imaging Device (GRID), 1003
Gear train, 100
Global Positioning System (GPS), 30–31
Graphical evaluation of residues, 83
Graphics in MATLAB, 1060, 1068–1071
Gravity gradient torque, 216
Green engineering, 47
  applications of, 48–49
  principles of, 47
Gun controllers, 30
Gyroscope, 247

Halo orbit, 928
Hand, robotic, 34, 37, 66
Helicopter control, 552, 560
High-fidelity simulations, 123
History of automatic control, 27
Home appliances, 47
Homogeneity. The property of a linear system in which the system response, $y(t)$, to an input $u(t)$ leads to the response $\beta y(t)$ when the input is $\beta u(t)$. 77–78, 181
Hot ingot robot mechanism, 703–713
Hubble telescope, 364, 365–368
Hybrid fuel automobile. An automobile that uses a conventional internal combustion engine in combination with an energy storage device to provide a propulsion system. 44, 70
Hydraulic actuator, 96 97, 99, 166–167, 916

IAE, 353
Impulse signal, 328
Index of performance, 352–361, 406, 883

Inner product, matrix, 1066

Input feedforward canonical form. A canonical form described by n feedback loops involving the a_n coefficients of the nth order denominator polynomial of the transfer function and feed forward loops obtained by feeding forward the input signal, 200–201, 254

Input signals, 327–328

Instability. An attribute of a system that describes a tendency of the system to depart from the equilibrium condition when initially displaced, 253, 275, 325

  in cost of feedback, 275

Insulin delivery control system, 50, 53–54

Insulin injections, 391

Integral of absolute magnitude of the error, 353

Integral of square of error, 352

Integral of time multiplied by absolute error, 353

  optimum coefficient of $T(s)$, 356–357, 361

Integral of time multiplied by error squared, 353

Integral operator, 82

Integrating filter, 98

Integration network. A network that acts, in part, like an integrator, 772, 787, 855

Intelligent vehicle/highway systems (IVHS), 527

Internal model design. A method of tracking reference inputs with guaranteed steady-state tracking errors, 881, 891–894, 931

Internal model principle. The principle that states that if $G_c(s)G(s)$ contains the input $R(s)$, then the output $y(t)$ will track $R(s)$ asymptotically (in the steady-state) and the tracking is robust, 893, 954, 1004

Internal Revenue Service, 38

Inverse Laplace transform. A transformation of a function $F(s)$ from the complex frequency domain into the time domain yielding $f(t)$, 80, 82, 84–85, 182

Inverted pendulum, 208–209, 866–868, 875, 878, 922, 924

ISE, 352, 396

ITAE, 353

  optimum coefficient of $T(s)$, 356–357, 361

ITSE, 353

Jordan canonical form. A block diagonal canonical form for systems that do not possess distinct system poles, 205, 255

Kalman state-space decomposition. A partition of the state space that illuminates the states that are controllable and unobservable, uncontrollable and unobservable, controllable and observable, and uncontrollable and observable, 858, 861, 931

Kirchhoff voltage laws, 186

Laboratory robot, 113, 131–133

Lag network. *See* Phase-lag network

Laplace transform. A transformation of a function $f(t)$ from the time domain into the complex frequency domain yielding $F(s)$, 72, 80–87, 181, 184

Laplace transform pair. A pair of functions, one in the time domain, denoted by $f(t)$, and the other in the frequency domain, denoted by $F(s)$, related by the Laplace transform as $F(s) = \mathcal{L}\{f(t)\}$, where $\mathcal{L}$ denotes the Laplace transform, 81, 577, 578, 655

Laser manipulator control system, 518–519, 522–524

Lead network. *See* Phase-lead network

Lead-lag network. A network with the characteristics of both a lead network and a lag network, 798, 855

Linear approximation. An approximate model that results in a linear relationship between the output and the input of the device, 79, 181

Linear approximations of physical systems, 77–80

Linear quadratic regulator. An optimal controller designed to minimize the quadratic performance index

$$J = \int_0^\infty (\mathbf{x}^T\mathbf{Q}\mathbf{x} + \mathbf{u}^T\mathbf{R}\mathbf{u})dt,$$

where **Q** and **R** are design parameters, 891, 931

Linear system. A system that satisfies the properties of superposition and homogeneity, 77–78, 181

  simplification of, 361–364, 381

Linearized. Made linear or placed in a linear form. Taylor series approximations are commonly employed to obtain linear models of physical systems, 72, 182

Locus. A path or trajectory that is traced out as a parameter is changed, 465, 573

Logarithmic (decibel) measure. A measure of the gain margin defined as $20 \log_{10}(1/d)$, where $\frac{1}{d} = \frac{1}{|L(j\omega)|}$ when the phase shift is $-180°$, 677, 764

Logarithmic magnitude. The logarithm of the magnitude of the transfer function, usually expressed in units of 20 dB, thus $20 \log_{10}|G|$, 585–588, 604, 639–640, 655

Logarithmic plot. *See* Bode plot

Logarithmic sensitivity. A measure of the sensitivity of the system performance to specific parameter changes, given by

$$S_K^T(s) = \frac{\partial T(s)/T(s)}{\partial K/K},$$

where $T(s)$ is the system transfer function and K is the parameter of interest, 495, 573

Log-magnitude–phase diagram, 678

Loop. A closed path that originates and terminates on the same node of a signal-flow with no node being met twice along the path, 107

Loop gain. The ratio of the feedback signal to the controller actuating signal. For a unity feedback system we have $L(s) = G_c(s)G(s)$, 259

Loop on signal-flow graph, 99

Loss of gain. A reduction in the amplitude of the ratio of the output signal to the input signal through a system, usually measured in decibels, 277, 325

  in cost of feedback, 275

Low-fidelity simulations, 123
Low-pass filter, 113, 133–135
lsim function, 231, 232, 351–353, 354, 381, 929, 1041, 1075
Lunar excursion module (LEM), 836

M circles, 686
Magnetic levitation, 168, 844, 1001
Magnetic tape transport, 554
Manual control system, 32
Manual PID tuning. The process of determining the PID controller gains by trial-and-error with minimal analytic analysis. 505, 573
Mapping of contours in the *s*-plane, 658
Margin, gain, 677, 715–716, 725, 764
  phase, 678, 682, 715–716, 725, 764, 1025–1026
margin function, 714, 854, 1075
Marginally stable. A system is marginally stable if and only if the zero input response remains bounded as $t \rightarrow \infty$, 412, 464
Mars rover vehicle, 276, 279–281, 461, 566, 1001
Mason, 106
Mason loop rule. A rule that enables the user to obtain a transfer function by tracing paths and loops within a system. 157, 182
Mason's signal-flow gain formula, 100, 108, 112, 152, 166, 195, 211
Mathematical models. Descriptions of the behavior of a system using mathematics. 72, 182
Mathematical models of systems, 71–152
MATLAB, 1060
  basics, 1060–1077
  Bode plot, 618
  as case sensitive, 1062
  colon notation, 1068
  control system characteristics, 290
  double precision, 1064
  functions, 1075–1076
  graph display, 1069
  graphics, 1060, 1068–1071
  mathematical functions, 1062
  matrices, 1060, 1065–1068
  plots, 1068
  scripts, 1060, 1071–1076
  simulation of systems, 135–136
  state variables and, 228
  statements and variables, 1060–1064
  symbols, 1074
  system performance and, 378–382
  toolboxes, 1060
Matrices for MATLAB, 1066–1067
Matrix exponential function. An important matrix function, defined as $e^{\mathbf{A}t} = \mathbf{I} + \mathbf{A}t + (\mathbf{A}t)^2/2! + \cdots + (\mathbf{A}t)^k/k! + \cdots$ that plays a role in the solution of linear constant coefficient differential equations. 189, 255
Matrix laboratory, 1065
Maximum overshoot, 332
Maximum power point tracking (MPPT), 113
Maximum value of the frequency response. A pair of complex poles will result in a maximum value for the frequency response occurring at the resonant frequency. 589, 601, 655
Maxwell, J. C., 28, 31
Mean arterial pressure (MAP), 282, 283
Measurement noise. An unwanted input signal that affects the measured output signal. 25, 70
Measurement noise attenuation, 268–269
Mechanical accelerometer, 128–131
Mechatronics. The synergistic integration of mechanical, electrical, and computer systems. 43–47, 70
Metallurgical industry, 36
m-files, 1060, 1071
Microcomputer. A small personal computer (PC) based on a microprocessor. 1007, 1059
Microelectromechanical systems (MEMS), 44
Minicomputer. A stand-alone computer with size and performance between a microcomputer and a large mainframe. The term is not commonly used today, and computers in this class are now often known as midrange servers. 1007, 1059
Minimum phase transfer function. All the zeros of a transfer function lie in the left-hand side of the *s*-plane. 593, 655
Minorsky, N., 158
Milling machine control system, 812–818
Mobile robot, 347–350
Model of, DC motor, 92
  epidemic disease, 206–207, 425–426
  hydraulic actuator, 96, 97, 99, 166–167, 916
  inverted pendulum and cart, 208–209, 866–868, 875, 878, 922, 924
Multiloop feedback control system. A feedback control system with more than one feedback control loop. 26, 70
Multiloop reduction, 146–148
Multiple loop feedback system, 105
Multiplicative perturbation. A system perturbation model expressed in the multiplicative form $G_m(s) = G(s)(1 + M(s))$, where $G(s)$ is the nominal process function, $M(s)$ is the perturbation that is bounded in magnitude, and $G_m(s)$ is the family of perturbed process functions. 938, 939, 1004
Multivariable control system. A system with more than one input variable or more than one output variable. 26, 70

N circles, 686
Natural frequency. The frequency of natural oscillation that would occur for two complex poles if the damping were equal to zero. 84, 182, 613, 655
Necessary condition. A condition or statement that must be satisfied to achieve a desired effect or result. For example, for a linear system it is necessary that the input $u_1(t) + u_2(t)$ results in the response $y_1(t) + y_2(t)$, where the input $u_1(t)$ results in the response $y_1(t)$ and the input $u_2(t)$ results in the response $y_2(t)$. 77, 182
Negative feedback. An output signal fed back so that it subtracts from the input signal. 25, 70
Negative gain root locus. The root locus for negative values of the parameter of interest, where $-\infty < K \leq 0$. 514–518, 573
ngrid function, 714, 717, 1076

Nichols chart. A chart displaying the curves for the relationship between the open-loop and closed-loop frequency response. 686–690, 714, 717–719, 725, 764, 974
nichols function. 714, 717, 1076
Node. The input and output points or junctions in a signal-flow graph. 107
Nodes of signal flow graph. 107
Noise. 258–260, 264–269, 275, 283, 284, 285, 300, 317–319
Nomenclature. 75
Nonminimum phase transfer functions. Transfer functions with zeros in the right-hand s-plane. 592, 595–596, 655
Nontouching. Two loops in a signal-flow graph that do not have a common node. 107
Nontouching loops. 107
Nonunity feedback systems. 349–352
Nuclear reactor controls. 61, 245
Number of separate loci. Equal to the number of poles of the transfer function assuming that the number of poles is greater than the number of zeros of the transfer function. 473, 573
Numerical experiments. 123
Nyquist, H. 657
Nyquist contour. 664
Nyquist criterion. 664–675, 690, 725
nyquist function. 714, 1076
Nyquist stability criterion. A feedback system is stable if, and only if, the contour in the $L(s)$-plane does not encircle the $(-1, 0)$ point when the number of poles of $L(s)$ in the right-hand s-plane is zero. If $L(s)$ has P poles in the right-hand plane, then the number of counterclockwise encirclements of the $(-1, 0)$ point must be equal to P for a stable system. 656, 657, 664–675, 690, 725, 764

Obrero robot. 37
Observability. 857–863
Observability matrix. A linear system is (completely) observable if and only if the observability matrix $\mathbf{P}_o = [\mathbf{C}^T (\mathbf{CA})^T (\mathbf{CA}^2)^T \ldots (\mathbf{CA}^{n-1})^T]^T$ has full rank, where $\mathbf{A}$ is an $n \times n$ matrix. For single-input, single-output linear systems, the system is observable if and only if the determinant of the $n \times n$ observability matrix $\mathbf{P}_o$ is nonzero. 861, 931
Observable system. A system is observable on the interval $[t_0, t_f]$ if any state $\mathbf{x}(t_0)$ is uniquely determined by observing output $y(t)$ on the interval $[t_0, t_f]$. 858, 860, 931
Observer. A dynamic system used to estimate the state of another dynamic system given knowledge of the system inputs and measurements of the system outputs. 857, 931
Observer design. 869–872
Octave. The frequency interval $\omega_2 = 2\omega_1$ is an octave of frequencies (e.g., the range of frequencies from $\omega_1 = 100$ rad/s to $\omega_2 = 200$ rad/s is one octave). 585, 633
Octave of frequencies. 585, 602
Open-loop control system. A system that uses a device to control the process without using feedback. Thus the output has no effect upon the signal to the process. 24–25, 70
Open-loop system. A system without feedback that directly generates the output in response to an input signal. 257–258, 261, 262, 325
Operational amplifier. 827, 828, 982
Operators, differential and integral. 82
Optimal control system. A system whose parameters are adjusted so that the performance index reaches an extremum value. 352, 406, 881–891, 931
Optimization. The adjustment of the parameters to achieve the most favorable or advantageous design. 40, 70
Optimize parameters. 40
Optimum coefficient of $T(s)$ for ITAE. 356–357, 361
ORCA laboratory robot. 131–132
Outer product, matrix. 1066
Output equation. The algebraic equation that relates the state vector, $\mathbf{x}$, and the inputs, $\mathbf{u}$, to the outputs, $\mathbf{y}$, through the relationship $\mathbf{y} = \mathbf{Cx} + \mathbf{Du}$. 188, 255
Overdamped. The case where the damping ratio is $\zeta > 1$. 136, 182
Overshoot. 293

Padé approximation of a time delay. 693–695, 714
pade function. 714, 719, 1003, 1076
Papin, Dennis. 27
Parabolic input signal. 328
parallel function. 136, 143, 146, 1076
Parameter design. A method of selecting one or two parameters using the root locus method. 490, 573
Parameter variations and system sensitivity. 261–264
Parkinson, D. B. 29, 30
Path. A branch or a continuous sequence of branches that can be traversed from one signal (node) to another signal (node) in a signal-flow graph. 107
PD controller. *See* Proportional plus derivative (PD) controller
Peak time. The time for a system to respond to a step input and rise to a peak response. 332, 334, 406
Pendulum oscillator. 79–80
Percent overshoot. The amount by which the system output response proceeds beyond the desired response. 332, 406
  for a second-order system. 336
Performance index. A quantitative measure of the performance of a system. 352–361, 406
Performance of control system. 326
Performance of sampled second-order system. 1021–1023
Performance specifications in the frequency domain. 601–604, 781
Phase lock loop (detector). 454
Phase margin. The amount of phase shift of the $L(j\omega)$ at unity magnitude that will result in a marginally stable system with intersections of the $-1 + j0$ point on the Nyquist diagram. 678, 682, 715–716, 725, 764

Low-fidelity simulations, 123
Low-pass filter, 113, 133–135
lsim function, 231, 232, 351–353, 354, 381, 929, 1041, 1075
Lunar excursion module (LEM), 836

M circles, 686
Magnetic levitation, 168, 844, 1001
Magnetic tape transport, 554
Manual control system, 32
Manual PID tuning. The process of determining the PID controller gains by trial-and-error with minimal analytic analysis, 505, 573
Mapping of contours in the *s*-plane, 658
Margin, gain, 677, 715–716, 725, 764
  phase, 678, 682, 715–716, 725, 764, 1025–1026
margin function, 714, 854, 1075
Marginally stable. A system is marginally stable if and only if the zero input response remains bounded as $t \rightarrow \infty$, 412, 464
Mars rover vehicle, 276, 279–281, 461, 566, 1001
Mason, 106
Mason loop rule. A rule that enables the user to obtain a transfer function by tracing paths and loops within a system, 157, 182
Mason's signal-flow gain formula, 100, 108, 112, 152, 166, 195, 211
Mathematical models. Descriptions of the behavior of a system using mathematics, 72, 182
Mathematical models of systems, 71–152
MATLAB, 1060
  basics, 1060–1077
  Bode plot, 618
  as case sensitive, 1062
  colon notation, 1068
  control system characteristics, 290
  double precision, 1064
  functions, 1075–1076
  graph display, 1069
  graphics, 1060, 1068–1071
  mathematical functions, 1062
  matrices, 1060, 1065–1068
  plots, 1068
  scripts, 1060, 1071–1076
  simulation of systems, 135–136
  state variables and, 228
  statements and variables, 1060–1064
  symbols, 1074
  system performance and, 378–382
  toolboxes, 1060
Matrices for MATLAB, 1066–1067
Matrix exponential function. An important matrix function, defined as $e^{\mathbf{A}t} = \mathbf{I} + \mathbf{A}t + (\mathbf{A}t)^2/2! + \cdots + (\mathbf{A}t)^k/k! + \cdots$ that plays a role in the solution of linear constant coefficient differential equations, 189, 255
Matrix laboratory, 1065
Maximum overshoot, 332
Maximum power point tracking (MPPT), 113
Maximum value of the frequency response. A pair of complex poles will result in a maximum value for the frequency response occurring at the resonant frequency, 589, 601, 655
Maxwell, J. C., 28, 31
Mean arterial pressure (MAP), 282, 283
Measurement noise. An unwanted input signal that affects the measured output signal, 25, 70
Measurement noise attenuation, 268–269
Mechanical accelerometer, 128–131
Mechatronics. The synergistic integration of mechanical, electrical, and computer systems, 43–47, 70
Metallurgical industry, 36
m-files, 1060, 1071
Microcomputer. A small personal computer (PC) based on a microprocessor, 1007, 1059
Microelectromechanical systems (MEMS), 44
Minicomputer. A stand-alone computer with size and performance between a microcomputer and a large mainframe. The term is not commonly used today, and computers in this class are now often known as midrange servers, 1007, 1059
Minimum phase transfer function. All the zeros of a transfer function lie in the left-hand side of the *s*-plane, 593, 655
Minorsky, N., 158
Milling machine control system, 812–818
Mobile robot, 347–350
Model of, DC motor, 92
  epidemic disease, 206–207, 425–426
  hydraulic actuator, 96, 97, 99, 166–167, 916
  inverted pendulum and cart, 208–209, 866–868, 875, 878, 922, 924
Multiloop feedback control system. A feedback control system with more than one feedback control loop, 26, 70
Multiloop reduction, 146–148
Multiple loop feedback system, 105
Multiplicative perturbation. A system perturbation model expressed in the multiplicative form $G_m(s) = G(s)(1 + M(s))$, where $G(s)$ is the nominal process function, $M(s)$ is the perturbation that is bounded in magnitude, and $G_m(s)$ is the family of perturbed process functions, 938, 939, 1004
Multivariable control system. A system with more than one input variable or more than one output variable, 26, 70

N circles, 686
Natural frequency. The frequency of natural oscillation that would occur for two complex poles if the damping were equal to zero, 84, 182, 613, 655
Necessary condition. A condition or statement that must be satisfied to achieve a desired effect or result. For example, for a linear system it is necessary that the input $u_1(t) + u_2(t)$ results in the response $y_1(t) + y_2(t)$, where the input $u_1(t)$ results in the response $y_1(t)$ and the input $u_2(t)$ results in the response $y_2(t)$, 77, 182
Negative feedback. An output signal fed back so that it subtracts from the input signal, 25, 70
Negative gain root locus. The root locus for negative values of the parameter of interest, where $-\infty < K \leq 0$, 514–518, 573
ngrid function, 714, 717, 1076

Nichols chart. A chart displaying the curves for the relationship between the open-loop and closed-loop frequency response, 686–690, 714, 717–719, 725, 764, 974

nichols function, 714, 717, 1076

Node. The input and output points or junctions in a signal-flow graph, 107

Nodes of signal flow graph, 107

Noise, 258–260, 264–269, 275, 283, 284, 285, 300, 317–319

Nomenclature, 75

Nonminimum phase transfer functions. Transfer functions with zeros in the right-hand s-plane, 592, 595–596, 655

Nontouching. Two loops in a signal-flow graph that do not have a common node, 107

Nontouching loops, 107

Nonunity feedback systems, 349–352

Nuclear reactor controls, 61, 245

Number of separate loci. Equal to the number of poles of the transfer function assuming that the number of poles is greater than the number of zeros of the transfer function, 473, 573

Numerical experiments, 123

Nyquist, H., 657

Nyquist contour, 664

Nyquist criterion, 664–675, 690, 725

nyquist function, 714, 1076

Nyquist stability criterion. A feedback system is stable if, and only if, the contour in the $L(s)$-plane does not encircle the $(-1, 0)$ point when the number of poles of $L(s)$ in the right-hand s-plane is zero. If $L(s)$ has P poles in the right-hand plane, then the number of counterclockwise encirclements of the $(-1, 0)$ point must be equal to P for a stable system, 656, 657, 664–675, 690, 725, 764

Obrero robot, 37

Observability, 857–863

Observability matrix. A linear system is (completely) observable if and only if the observability matrix $\mathbf{P}_o = [\mathbf{C}^T (\mathbf{CA})^T (\mathbf{CA}^2)^T \ldots (\mathbf{CA}^{n-1})^T]^T$ has full rank, where $\mathbf{A}$ is an $n \times n$ matrix. For single-input, single-output linear systems, the system is observable if and only if the determinant of the $n \times n$ observability matrix $\mathbf{P}_o$ is nonzero, 861, 931

Observable system. A system is observable on the interval $[t_0, t_f]$ if any state $\mathbf{x}(t_0)$ is uniquely determined by observing output $y(t)$ on the interval $[t_0, t_f]$, 858, 860, 931

Observer. A dynamic system used to estimate the state of another dynamic system given knowledge of the system inputs and measurements of the system outputs, 857, 931

Observer design, 869–872

Octave. The frequency interval $\omega_2 = 2\omega_1$ is an octave of frequencies (e.g., the range of frequencies from $\omega_1 = 100$ rad/s to $\omega_2 = 200$ rad/s is one octave), 585, 633

Octave of frequencies, 585, 602

Open-loop control system. A system that uses a device to control the process without using feedback. Thus the output has no effect upon the signal to the process, 24–25, 70

Open-loop system. A system without feedback that directly generates the output in response to an input signal, 257–258, 261, 262, 325

Operational amplifier, 827, 828, 982

Operators, differential and integral, 82

Optimal control system. A system whose parameters are adjusted so that the performance index reaches an extremum value, 352, 406, 881–891, 931

Optimization. The adjustment of the parameters to achieve the most favorable or advantageous design, 40, 70

Optimize parameters, 40

Optimum coefficient of $T(s)$ for ITAE, 356–357, 361

ORCA laboratory robot, 131–132

Outer product, matrix, 1066

Output equation. The algebraic equation that relates the state vector, $\mathbf{x}$, and the inputs, $\mathbf{u}$, to the outputs, $\mathbf{y}$, through the relationship $\mathbf{y} = \mathbf{Cx} + \mathbf{Du}$, 188, 255

Overdamped. The case where the damping ratio is $\zeta > 1$, 136, 182

Overshoot, 293

Padé approximation of a time delay, 693–695, 714

pade function, 714, 719, 1003, 1076

Papin, Dennis, 27

Parabolic input signal, 328

parallel function, 136, 143, 146, 1076

Parameter design. A method of selecting one or two parameters using the root locus method, 490, 573

Parameter variations and system sensitivity, 261–264

Parkinson, D. B., 29, 30

Path. A branch or a continuous sequence of branches that can be traversed from one signal (node) to another signal (node) in a signal-flow graph, 107

PD controller. *See* Proportional plus derivative (PD) controller

Peak time. The time for a system to respond to a step input and rise to a peak response, 332, 334, 406

Pendulum oscillator, 79–80

Percent overshoot. The amount by which the system output response proceeds beyond the desired response, 332, 406
  for a second-order system, 336

Performance index. A quantitative measure of the performance of a system, 352–361, 406

Performance of control system, 326

Performance of sampled second-order system, 1021–1023

Performance specifications in the frequency domain, 601–604, 781

Phase lock loop (detector), 454

Phase margin. The amount of phase shift of the $L(j\omega)$ at unity magnitude that will result in a marginally stable system with intersections of the $-1 + j0$ point on the Nyquist diagram, 678, 682, 715–716, 725, 764

Phase variable canonical form. A canonical form described by n feedback loops involving the coefficients of the n-th order denominator polynomial of the transfer function and m feed-forward loops involving the b_m coefficients of the m-th order numerator polynomial of the transfer function. 197, 255

Phase variables. The state variables associated with the phase variable canonical form. 197, 255

Phase-lag compensation. A widely-used compensator that possesses one zero and one pole with the pole closer to the origin of the s-plane. This compensator reduces the steady-state tracking errors. 772, 855

Phase-lag network. A network that provides a negative phase angle and a significant attenuation over the frequency range of interest. 772–773, 855

Phase-lead compensation. A widely-used compensator that possesses one zero and one pole with the zero closer to the origin of the s-plane. This compensator increases the system bandwidth and improves the dynamic response. 768–771, 827, 855

Phase-lead network. A network that provides a positive phase angle over the frequency range of interest. Thus, phase lead can be used to cause a system to have an adequate phase margin. 769, 855

Photovoltaic generators. 113–115, 605–607

Physical state variables. 186–187

Physical variables. The state variables representing the physical variables of the system. 204–205, 255

PI controller. *See* Proportional plus integral (PI) controller

PID controller. A widely used controller used in industry of the form

$$G_c(s) = K_p + \frac{K_I}{s} + K_D s,$$

where K_p is proportional gain, K_1 is the integral gain, and K_D is the derivative gain. 285, 286, 287, 289, 502–514, 573

  design of robust. 948–954, 1004–1005

  in discrete-time,

$$G_c(z) = K_1 + \frac{K_2 T s}{z-1} + K_3 \frac{z-1}{Tz},$$

1031, 1059

  in frequency domain. 713–714

  of wind turbines for clean energy. 696–699

PID tuning. The process of determining the PID controller gains. 505, 573

Plant. *See* Process

Plastic extrusion. 1057

Plotting using MATLAB. 149, 1068, 1076

Pneumatica. 27

Polar plot. A plot of the real part of $G(j\omega)$ versus the imaginary part of $G(j\omega)$. 579, 655

Pole placement. A design methodology wherein the objective is to place the eigenvalues of the closed-loop system in desired regions of the complex plane. 858, 931

Poles. The roots of the denominator polynomial (i.e., the roots of the characteristic equation) of the transfer function. 82–83, 182

Pole-zero map. 139, 140–141

Political feedback model. 38

poly function. 136, 441, 928, 1076

polyval function. 136, 1076

Polzunov, I. 27

Pontryagin, L. S. 30

Position error constant K_p. The constant evaluated as $\lim_{s \to 0} G_c(s)G(s)$. The steady-state error for a step input (of magnitude A) is equal to $A/(1 + K_p)$. 345, 406

Positive feedback. An output signal fed back so that it adds to the input signal. 61–62, 70

Positive feedback loop. A feedback loop wherein the output signal fed back so that it adds to the input signal. 105

Potentiometer. 100

Power flow. 52

Power plants. 36

Power quality monitoring (green engineering). 48

Precision. The degree of exactness or discrimination with which a quantity is stated. 1011, 1059

Precision speed control system. 555

Prefilter. A transfer function $G_p(s)$ that filters the input signal $R(s)$ prior to calculating the error signal. 800–803, 855, 1005

Principle of superposition. The law that states that if two inputs are scaled and summed and routed through a linear, time-invariant system, then the output will be identical to the sum of outputs due to the individual scaled inputs when routed through the same system. 77, 182

Principle of the argument. *See* Cauchy's theorem

Printer belt drive. 222–228

Process. The device, plant, or system under control. 24, 70

Process controller. *See* PID controller

Productivity. The ratio of physical output to physical input of an industrial process. 29, 70

Proportional plus derivative (PD) controller. A two-term controller of the form $G_c(s) = K_p + K_D s$, where K_p is the proportional gain and K_1 is the derivative gain. 503, 574, 855

Proportional plus integral (PI) controller. A two-term controller of the form $G_c(s) = K_p + \frac{K_I}{s}$, where K_p is the proportional gain and K_1 is the integral gain. 503, 574, 787, 855

Pseudo-quantitative feedback system. 974–975

pzmap function. 136, 139, 163, 1076

Quantitative feedback theory (QFT). 974

Quarter amplitude decay. The amplitude of the closed loop response is reduced approximately to one-fourth of the maximum value in one oscillatory period. 505, 574

Rack and pinion, 97, 101
Radio-based navigation system, 30–31
Ramp input, optimum coefficients of $T(s)$, 361
  steady-state error, 346
  test signal equation, 328
Reaction curve. The response obtained by taking the controller off-line and introducing a step input. The underlying process is assumed to be a first-order system with a transport delay. 509
Reduced sensitivity, 261
Reference input. The input to a control system often representing the desired output, denoted by $R(s)$. 143, 182, 879–881
Regulator problem, 864
Regulatory bodies, 37
Relative stability. The property that is measured by the relative real part of each root or pair of roots of the characteristic equation. 409, 421, 464
  by the Nyquist criterion, 675–682
  by the Routh-Hurwitz criterion, 421
Remote manipulators, 247, 839
Remotely operated vehicle, 700–703, 720–722
Residues. The constants k_i associated with the partial fraction expansion of the output $Y(s)$ when the output is written in a residue-pole format. 83, 85, 86, 182
Resonant frequency. The frequency, ω_r, at which the maximum value of the frequency response of a complex pair of poles is attained. 588–589, 655
Rise time. The time for a system to respond to a step input and attain a response equal to a percentage of the magnitude of the input. The 0–100% rise time, T_r, measures the time to 100% of the magnitude of the input. Alternatively, T_{r1} measures the time from 10% to 90% of the response to the step input. 332, 406–407
Risk. Uncertainties embodied in the unintended consequences of a design. 39, 40, 70
Robot. Programmable computers integrated with a manipulator. A reprogrammable, multifunctional manipulator used for a variety of tasks. 33–34, 70
  controlled motorcycle, 428–434
  design of laboratory, 113, 131–133
  mobile, steering control, 380–381
  replication, 524–527
Robot control system, 524–527, 942–948, 1005
Robust control system. A system that exhibits the desired performance in the presence of significant plant uncertainty. 932–1005
  using control design software, 975–979
Robust PID control, 948–954
Robust stability criterion. A test for robustness with respect to multiplicative perturbations in which stability is guaranteed if $|M(j\omega)| < \left|1 + \frac{1}{G(j\omega)}\right|$, for all ω, where $M(s)$ is the multiplicative perturbation. 938–939, 1005
Roll-wrapping machine (RWM), 990, 991
Root contours. The family of loci that depict the effect of varying two parameters on the roots of the characteristic equation. 494, 574
Root locus. The locus or path of the roots traced out on the s-plane as a parameter is changed. 466–470, 574, 725, 1026–1030
  angle of departure, 480
  asymptote, 473
  breakaway point, 476
  concept, 466–470
  of digital control systems, 1026–1030
  plot, obtaining, 533–537
  sensitivity and, 495–502, 538
  steps in sketching, 482
  using control design software, 532–538
  in the z-plane, 1027–1028
Root locus method. The method for determining the locus of roots of the characteristic equation $1 + KP(s) = 0$ as K varies from 0 to infinity. 466, 471–489, 574
  parameter design, 489–494
Root locus segments on the real axis. The root locus lying in a section of the real axis to the left of an odd number of poles and zeros. 472, 474, 574
Root sensitivity. The sensitivity of the roots as a parameter changes from its normal value. The root sensitivity is given by $S_K^r = \frac{\partial r}{\partial K/K}$, the incremental changes in the root divided by the proportional change of the parameter. 495, 574
  to parameters. A measure of the sensitivity of the roots (i.e., the poles and zeros) of the system to changes in a parameter defined by $S_\alpha^{r_i} = \frac{\partial r_i}{\partial \alpha/\alpha}$ where α is the parameter and r_i is the root. 934, 1005
roots function, 136, 436, 440, 441, 1076
Rotating disk speed control, 52–53
Rotor wind system, 805–809, 818–824
Routh–Hurwitz criterion. A criterion for determining the stability of a system by examining the characteristic equation of the transfer function. The criterion states that the number of roots of the characteristic equation with positive real parts is equal to the number of changes of sign of the coefficients in the first column of the Routh array. 413–421, 426, 435–437, 464
Routh–Hurwitz stability, 408
R.U.R. (play), 34

Sampled data. Data obtained for the system variables only at discrete intervals. Data obtained once every sampling period. 1009, 1059
Sampled-data system. A system where part of the system acts on sampled data (sampled variables). 1009–1012, 1059
Sampling period. The period when all the numbers leave or enter the computer. The period for which the sampled variable is held constant. 1009, 1059
Scanning tunneling microscope (STM), 997

Scripts, 1060, 1071–1076
  comments, 1072
  defined, 1071
  header, 1072
  invoking, 1071
  TeX characters use of, 1072–1073
Second order system response, effect of third pole and zero, 336–342
Second-order system, performance of, 330–336
Self-balancing scale, 485–489
Self-healing process, 52
Semiconductors, 35
Sensitivity. *See also* System sensitivity
  of control systems to parameter variations, 261–264
  of root control systems, 496
  root locus and, 495–502, 538
Sensitivity function. The function $S(s) = [1 + G_c(s)G(s)]^{-1}$ that satisfies the relationship $S(s) + T(s) = 1$, where $T(s)$ is the complementary sensitivity function, 260, 265, 268, 287, 300, 938, 1005
Separation principle. The principle that states that the full-state feedback law and the observer can be designed independently and when connected will function as an integrated control system in the desired manner (i.e., stable), 863, 874, 931
Sequential design example, 54–56, 150–152, 231–235, 295–299, 382–386, 443–446, 538–540, 624–625, 722–725, 824–826, 910–912, 980–982, 1045–1047
Series connection, 142–145
series function, 136, 142, 145, 146, 1076
Settling time. The time required for the system output to settle within a certain percentage of the input amplitude, 333, 407
Ship stabilization, 309, 837–838
Signal-flow graph. A diagram that consists of nodes connected by several directed branches and that is a graphical representation of a set of linear relations, 106–112, 182
  block diagram models and, 193–204
  models, 106
Simplification of linear systems, 361–364
Simulation. A model of a system that is used to investigate the behavior of a system by utilizing actual input signals, 123, 135–149, 182
Smart grid
  control systems, 50–52
  definition, 47, 50
Smart meters, 50
Social feedback model, 38
Solar cells, 113
Solar energy (green engineering), 48
Space shuttle, 643–644, 744–746, 1051–1052
Space station, 215–221
Space telescope, 957–960
Spacecraft, 160, 163, 215–221
Specifications. Statements that explicitly state what the device or product is to be and is to do. A set of prescribed performance criteria, 39, 70
Speed control system, 265–267, 270–272, 290–292, 314, 318, 319
  for automobiles, 311
  for power generator, 553
  for steel rolling mill, 265
***s*-plane**. The complex plane where, given the complex number $s = s + j\omega$, the x-axis (or horizontal axis) is the s-axis, and the y-axis (or vertical axis) is the $j\omega$-axis, 82, 182
Spring-mass-damper system, 136–140
Stability. A performance measure of a system. A system is stable if all the poles of the transfer function have negative real parts, 409, 464
  in frequency domain, 656–764
  of linear feedback systems, 408–464
  of state variable systems, 423–426
  for unstable process, 441–443
  using Nyquist criterion, 664
  using Routh–Hurwitz criterion, 413–421, 426, 435–437
Stability of a sampled-data system. The stable condition exists when all the poles of the closed-loop transfer function $T(z)$ are within the unit circle on the z-plane, 1059
Stabilizable. A system in which the states that are not controllable are naturally stable, 858, 931
Stabilizing controller. A controller that stabilizes the closed-loop system, 875, 931
Stable system. A dynamic system with a bounded system response to a bounded input, 409, 464
State differential equation. The differential equation for the state vector: $\dot{\mathbf{x}} = \mathbf{A}\mathbf{x} + \mathbf{B}\mathbf{u}$, 188–193, 255
State of a system. A set of numbers such that the knowledge of these numbers and the input function will, with the equations describing the dynamics, provide the future state of the system, 184–187, 255
State transition matrix, $\Phi(t)$. The matrix exponential function that describes the unforced response of the system, 190
State variable feedback. The use of control signal formed as a direct function of all the state variables, 248, 277, 882, 884, 931
State variable system design using control design software, 904–910
State variables. The set of variables that describe the system, 184–254, 255
  of dynamic system, 184–187
State vector. The vector matrix containing all n state variables, $x_1, x_2, \ldots, x_n$, 188, 255
Statements and variables, MATLAB, 1060–1064
State-space representation. A time-domain model comprised of the state differential equation, $\dot{\mathbf{x}} = \mathbf{A}\mathbf{x} + \mathbf{B}\mathbf{u}$, and the output equation, $\mathbf{y} = \mathbf{C}\mathbf{x} + \mathbf{D}\mathbf{u}$, 189, 228–231, 255
Steady state. The value that the output achieves after all the transient constituents of the response have faded. Also referred to as the final value, 84, 182
  of response of $y(t)$, 84
Steady-state error. The error when the time period is large and the transient response has decayed, leaving the continuous response, 272–275, 325

  - of feedback control system, 344–352
- **Steady-state response.** The constituent of the system response that exists a long time following any signal initiation. 327, 407
- Steel rolling mill, 36, 265, 691–693, 757, 760, 991
- Steering control system, of automobile, 32, 650
  - of mobile robot, 347–350
  - of ship, 748
- Step input, 344–346
  - optimum coefficient of $T(s)$, 357
  - steady-state error, 344
  - test signal equation, 328
- Submarine control system, 242–243, 244–245
- Superposition, principle of, 77
- Symbols, in MATLAB, 1074
  - used in book, 75
- **Synthesis.** The process by which new physical configurations are created. The combining of separate elements or devices to form a coherent whole. 40, 70
- **sys** function, 142, 146
- **System.** An interconnection of elements and devices for a desired purpose. 24, 70
  - bandwidth, 690
  - performance, 378–382
- **System sensitivity.** The ratio of the change in the system transfer function to the change of a process transfer function (or parameter) for a small incremental change. 262, 325
  - to parameters. A measure of the system sensitivity to changes in a parameter defined by $S_\alpha^T = \dfrac{\partial T/T}{\partial \alpha/\alpha}$ where α is the parameter and T is the system transfer function. 934, 1005
- Systems with uncertain parameters, 940–942

- Tables, of differential equations for elements, 74
  - of Laplace transform pairs, 81
  - through- and across-variables for physical systems, 73
  - of transfer function plots, 726–733
  - of transfer functions, 98–101
- Tachometer, 100
- Tacoma Narrows Bridge, 410–412
- **Taylor series.** A power series defined by $g(x) = \sum_{m=0}^{\infty} \frac{g^{(m)}(x_0)}{m!}(x - x_0)^m$. For $m < \infty$, series is an approximation which is used to linearize functions and system models. 78, 182
- **Test input signal.** An input signal used as a standard test of a system's ability to respond adequately. 328–330, 407
- Thermal heating system, 101
- **Through-variable.** A variable that has the same value at both ends of an element. 72, 75
- **Time constant.** The time interval necessary for a system to change from one state to another by a specified percentage. For a first order system, the time constant is the time it takes the output to manifest a 63.2% change due to a step input. 88, 182
- **Time delay.** A time delay, T, so that events occurring at time t at one point in the system occur at another point in the system at a later time $t + T$. 690–695, 764
- **Time domain.** The mathematical domain that incorporates the time response and the description of a system in terms of time t. 184, 255
  - design, 857
- Time-domain specifications, 378–380
- Time response, by a discrete-time evaluation, 211
  - and state transition matrix, 211–214
- **Time-varying system.** A system for which one or more parameters may vary with time. 87, 255
- Tracked vehicle turning control, 426–428, 427–441
- Tracking error. *See* Error signal
- **Trade-off.** The result of making a judgment about how to compromise between conflicting criteria. 23, 39, 70
- **Transfer function.** The ratio of the Laplace transform of the output variable to the Laplace transform of the input variable. 87, 182
  - of complex system, 112
  - of DC motor, 92–96
  - of dynamic elements and networks, 98–101
  - of hydraulic actuator, 96–101
  - of interacting system, 109–110
  - of linear systems, 87
  - in m-file script, 135, 136
  - minimum phase and nonminimum phase, 592–593
  - of multi-loop system, 111–112
  - of op-amp circuit, 89–90
  - from state equation, 209–211
  - of system, 90–92
  - table of dynamic elements and networks, 98–101
- **Transfer function in the frequency domain.** The ratio of the output to the input signal where the input is a sinusoid. It is expressed as $G(j\omega)$. 582, 655
- **Transient response.** The constituent of the system response that disappears with time. 269, 325, 327, 407
  - relationship to root location, 342–344
  - of second-order system, 330
- **Transition matrix $\Phi(t)$.** The matrix exponential function that describes the unforced response of the system. 190, 255
  - evaluation by signal flow graph methods, 212
- Twin lift, 64
- Twin-T network, 592
- **Type number.** The number N of poles of the transfer function, $G_c(s)G(s)$, at the origin. $G_c(s)G(s)$ is the loop transfer function. 345, 407

- **Ultimate gain.** The PID controller proportional gain, K_p, on the border of instability when $K_D = 0$ and $K_I = 0$. 509
- **Ultimate period.** The period of the sustained oscillations when K_p is the ultimate gain and $K_D = 0$ and $K_I = 0$. 509
- Ultra-precision diamond turning machine, 962–965
- Uncertain parameters, 940–942
- **Underdamped.** The case where the damping ratio is $\zeta < 1$. 76, 136, 182

Unit impulse. A test input consisting of an impulse of infinite amplitude and zero width, and having an area of unity. The unit impulse is used to determine the impulse response. 328, 407
Unity feedback. A feedback control system wherein the gain of the feedback loop is one. 143, 182
Unmanned aerial vehicles (UAVs), 38, 39, 306
Unstable system, 409, 410

Variables for physical systems, 73
Vehicle traction control, 1056
Velocity error constant, K_v. The constant evaluated as $\lim_{s \to 0}[sG_c(s)G(s)]$. The steady-state error for a ramp input (of slope A) for a system is equal to A/K_v. 346, 407
Velocity input, 319
Vertical takeoff and landing (VTOL) aircraft, 456, 743, 928
Viscous damper. A type of mechanical damper where the model of the friction force is linearly proportional to the velocity of the mass. 75
Vyshnegradskii, I. A., 28

Water clock, 27
Water level control, 27–28, 63, 119–126, 173
Watt, James, 27, 31
Welding control, 420–421
Wind energy (green engineering), 48
Wind power, 44, 45–46
Wind turbines, 696–699
  rotor speed control, 519–522
Workspace, variables in, 1063
Worktable motion control, 1031–1033

X-Y plotter, 809–811

Zero-order hold. A mathematical model of a sample and data hold operation whose input–output transfer function is represented by $G_0(s) = \frac{1 - e^{-sT}}{s}$. 1011, 1059
Zeros. The roots of the numerator polynomial of the transfer function. 82–83, 182
Ziegler-Nichols PID tuning method. The process of determining the PID controller gains using one of several analytic methods based on open-loop and closed-loop responses to step inputs. 505, 510–513, 574
z-plane. The plane with the vertical axis equal to the imaginary part of z and the horizontal axis equal to the real part of z. 1059
z-plane root locus, 1027–1028
z-transform. A conformal mapping from the s-plane to the z-plane by the relation $z = e^{sT}$. A transform from the s-domain to the z-domain. 1012–1017, 1059