

Contents

Preface xv

About the Companion Website xix

1	Fundamentals	1
1.1	Introduction	1
1.2	What Is a Robot?	2
1.3	Classification of Robots	3
1.4	What Is Robotics?	3
1.5	History of Robotics	3
1.6	Advantages and Disadvantages of Robots	4
1.7	Robot Components	5
1.8	Robot Degrees of Freedom	7
1.9	Robot Joints	9
1.10	Robot Coordinates	9
1.11	Robot Reference Frames	11
1.12	Programming Modes	12
1.13	Robot Characteristics	13
1.14	Robot Workspace	13
1.15	Robot Languages	14
1.16	Robot Applications	17
1.17	Other Robots and Applications	23
1.18	Collaborative Robots	28
1.19	Social Issues	29
1.20	Summary	30
	References	30
	Problems	32
2	Kinematics of Serial Robots: Position Analysis	35
2.1	Introduction	35
2.2	Robots as Mechanisms	35
2.3	Conventions	37
2.4	Matrix Representation	37
	2.4.1 Representation of a Point in Space	37
	2.4.2 Representation of a Vector in Space	38
	2.4.3 Representation of a Frame at the Origin of a Fixed-Reference Frame	40
	2.4.4 Representation of a Frame Relative to a Fixed Reference Frame	41
	2.4.5 Representation of a Rigid Body	42
2.5	Homogeneous Transformation Matrices	45
2.6	Representation of Transformations	46

2.6.1	Representation of a Pure Translation	46
2.6.2	Representation of a Pure Rotation about an Axis	47
2.6.3	Representation of Combined Transformations	50
2.6.4	Transformations Relative to the Current (Moving) Frame	52
2.6.5	Mixed Transformations Relative to Rotating and Reference Frames	53
2.7	Inverse of Transformation Matrices	54
2.8	Forward and Inverse Kinematics of Robots	59
2.9	Forward and Inverse Kinematic Equations: Position	60
2.9.1	Cartesian (Gantry, Rectangular) Coordinates	60
2.9.2	Cylindrical Coordinates	61
2.9.3	Spherical Coordinates	63
2.9.4	Articulated Coordinates	65
2.10	Forward and Inverse Kinematic Equations: Orientation	65
2.10.1	Roll, Pitch, Yaw (RPY) Angles	65
2.10.2	Euler Angles	68
2.10.3	Articulated Joints	70
2.11	Forward and Inverse Kinematic Equations: Position and Orientation	70
2.12	Denavit-Hartenberg Representation of Forward Kinematic Equations of Robots	70
2.13	The Inverse Kinematic Solution of Robots	84
2.13.1	General Solution for Articulated Robot Arms	86
2.14	Inverse Kinematic Programming of Robots	89
2.15	Dual-Arm Cooperating Robots	91
2.16	Degeneracy and Dexterity	92
2.16.1	Degeneracy	92
2.16.2	Dexterity	93
2.17	The Fundamental Problem with the Denavit-Hartenberg Representation	93
2.18	Design Projects	95
2.18.1	Stair-Climbing Robot	96
2.18.2	A 3-DOF Robot	96
2.18.3	A 3-DOF Mobile Robot	98
2.19	Summary	99
	References	99
	Problems	99
3	Robot Kinematics with Screw-Based Mechanics	111
3.1	Introduction	111
3.2	What Is a Screw?	111
3.3	Rotation about a Screw Axis	112
3.4	Homogenous Transformations about a General Screw Axis	115
3.5	Successive Screw-Based Transformations	119
3.6	Forward and Inverse Position Analysis of an Articulated Robot	120
3.7	Design Projects	127
3.8	Summary	127
	Additional Reading	128
	Problems	128
4	Kinematics Analysis of Parallel Robots	133
4.1	Introduction	133
4.2	Physical Characteristics of Parallel Robots	134
4.3	The Denavit-Hartenberg Approach vs. the Direct Kinematic Approach	139

4.4	Forward and Inverse Kinematics of Planar Parallel Robots	140
4.4.1	Kinematic Analysis of a 3-RPR Planar Parallel Robot	141
4.4.2	Kinematic Analysis of a 3-RRR Planar Parallel Robot	143
4.5	Forward and Inverse Kinematics of Spatial Parallel Robots	147
4.5.1	Kinematic Analysis of a Generic 6-6 Stewart-Gough Platform	147
4.5.2	Kinematic Analysis of a Generic 6-3 Stewart-Gough Platform	152
4.5.3	Kinematic Analysis of a 3-Axis RSS-Type Parallel Robot	154
4.5.4	Kinematic Analysis of a 4-Axis RSS-Type Parallel Robot	160
4.5.5	Kinematic Analysis of a 3-Axis PSS-Type Parallel Robot	167
4.6	Other Parallel Robot Configurations	169
4.7	Design Projects	169
4.8	Summary	170
	References	170
	Problems	170
5	Differential Motions and Velocities	173
5.1	Introduction	173
5.2	Differential Relationships	173
5.3	The Jacobian	174
5.4	Differential versus Large-Scale Motions	176
5.5	Differential Motions of a Frame versus a Robot	177
5.6	Differential Motions of a Frame	178
5.6.1	Differential Translations	178
5.6.2	Differential Rotations about Reference Axes	178
5.6.3	Differential Rotation about a General Axis q	179
5.6.4	Differential Transformations of a Frame	181
5.7	Interpretation of the Differential Change	182
5.8	Differential Changes between Frames	183
5.9	Differential Motions of a Robot and Its Hand Frame	185
5.10	Calculation of the Jacobian	185
5.11	How to Relate the Jacobian and the Differential Operator	188
5.12	The Inverse Jacobian	191
5.13	Calculation of the Jacobian with Screw-Based Mechanics	197
5.14	The Inverse Jacobian for the Screw-Based Method	206
5.15	Calculation of the Jacobians of Parallel Robots	206
5.15.1	The Jacobian of a Planar 3-RRR Parallel Robot	207
5.15.2	The Jacobian of a Generic 6-6 Stewart-Gough Parallel Robot	208
5.16	Design Projects	210
5.16.1	The 3-DOF Robot	210
5.16.2	The 3-DOF Mobile Robot	210
5.17	Summary	210
	References	211
	Problems	211
6	Dynamic and Force Analysis	219
6.1	Introduction	219
6.2	Lagrangian Mechanics: A Short Overview	220
6.3	Effective Moments of Inertia	229
6.4	Dynamic Equations for Multiple-DOF Robots	229
6.4.1	Kinetic Energy	229

6.4.2	Potential Energy	234
6.4.3	The Lagrangian	234
6.4.4	Robot's Equations of Motion	234
6.5	Static Force Analysis of Robots	239
6.6	Transformation of Forces and Moments between Coordinate Frames	242
6.7	Design Project	244
6.8	Summary	244
	References	244
	Problems	245
7	Trajectory Planning	247
7.1	Introduction	247
7.2	Path vs. Trajectory	247
7.3	Joint-Space vs. Cartesian-Space Descriptions	248
7.4	Basics of Trajectory Planning	249
7.5	Joint-Space Trajectory Planning	252
7.5.1	Third-Order Polynomial Trajectory Planning	252
7.5.2	Fifth-Order Polynomial Trajectory Planning	255
7.5.3	Linear Segments with Parabolic Blends	257
7.5.4	Linear Segments with Parabolic Blends and Via Points	259
7.5.5	Higher-Order Trajectories	260
7.5.6	Other Trajectories	263
7.6	Cartesian-Space Trajectories	263
7.7	Continuous Trajectory Recording	267
7.8	Design Project	268
7.9	Summary	269
	References	269
	Problems	269
8	Motion Control Systems	273
8.1	Introduction	273
8.2	Basic Components and Terminology	273
8.3	Block Diagrams	274
8.4	System Dynamics	274
8.5	Laplace Transform	278
8.6	Inverse Laplace Transform	281
8.6.1	Partial Fraction Expansion When $F(s)$ Involves Only Distinct Poles	281
8.6.2	Partial Fraction Expansion When $F(s)$ Involves Repeated Poles	282
8.6.3	Partial Fraction Expansion When $F(s)$ Involves Complex Conjugate Poles	283
8.7	Transfer Functions	285
8.8	Block Diagram Algebra	288
8.9	Characteristics of First-Order Transfer Functions	290
8.10	Characteristics of Second-Order Transfer Functions	292
8.11	Characteristic Equation: Pole/Zero Mapping	294
8.12	Steady-State Error	296
8.13	Root Locus Method	298
8.14	Proportional Controllers	303
8.15	Proportional-Plus-Integral Controllers	306
8.16	Proportional-Plus-Derivative Controllers	308

8.17	Proportional-Integral-Derivative Controller (PID)	311
8.18	Lead and Lag Compensators	313
8.19	Bode Diagram and Frequency-Domain Analysis	313
8.20	Open-Loop vs. Closed-Loop Applications	314
8.21	Multiple-Input and Multiple-Output Systems	314
8.22	State-Space Control Methodology	316
8.23	Digital Control	320
8.24	Nonlinear Control Systems	322
8.25	Electromechanical Systems Dynamics: Robot Actuation and Control	323
8.26	Design Projects	326
8.27	Summary	327
	References	327
	Problems	327
9	Actuators and Drive Systems	331
9.1	Introduction	331
9.2	Characteristics of Actuating Systems	331
9.2.1	Nominal Characteristics – Weight, Power-to-Weight Ratio, Operating Pressure, Voltage, and Others	331
9.2.2	Stiffness vs. Compliance	332
9.2.3	Use of Reduction Gears	332
9.3	Comparison of Actuating Systems	335
9.4	Hydraulic Actuators	335
9.5	Pneumatic Devices	337
9.6	Electric Motors	338
9.6.1	Fundamental Differences Between AC- and DC-Type Motors	339
9.6.2	DC Motors	341
9.6.3	AC Motors	344
9.6.4	Brushless DC Motors	345
9.6.5	Direct-Drive Electric Motors	346
9.6.6	Servomotors	346
9.6.7	Stepper Motors	347
9.7	Microprocessor Control of Electric Motors	360
9.7.1	Pulse Width Modulation	361
9.7.2	Direction Control of DC Motors with an H-Bridge	363
9.8	Magnetostrictive Actuators	364
9.9	Shape-Memory Type Metals	364
9.10	Electroactive Polymer Actuators (EAPs)	364
9.11	Speed Reduction	365
9.12	Other Systems	367
9.13	Design Projects	367
9.14	Summary	370
	References	371
	Problems	372
10	Sensors	375
10.1	Introduction	375
10.2	Sensor Characteristics	375
10.3	Sensor Utilization	377

10.4	Position Sensors	378
10.4.1	Potentiometers	378
10.4.2	Encoders	379
10.4.3	Linear Variable Differential Transformer (LVDT)	382
10.4.4	Resolvers	383
10.4.5	(Linear) Magnetostrictive Displacement Transducer (LMDT or MDT)	383
10.4.6	Hall-effect Sensors	384
10.4.7	Global Positioning System (GPS)	384
10.4.8	Other Devices	385
10.5	Velocity Sensors	385
10.5.1	Encoders	385
10.5.2	Tachometers	385
10.5.3	Differentiation of Position Signal	386
10.6	Acceleration Sensors	386
10.7	Force and Pressure Sensors	386
10.7.1	Piezoelectric	386
10.7.2	Force-Sensing Resistor	386
10.7.3	Strain Gauge	387
10.7.4	Antistatic Foam	388
10.8	Torque Sensors	388
10.9	Microswitches	389
10.10	Visible Light and Infrared Sensors	389
10.11	Touch and Tactile Sensors	390
10.12	Proximity Sensors	391
10.12.1	Magnetic Proximity Sensors	391
10.12.2	Optical Proximity Sensors	391
10.12.3	Ultrasonic Proximity Sensors	392
10.12.4	Inductive Proximity Sensors	392
10.12.5	Capacitive Proximity Sensors	393
10.12.6	Eddy Current Proximity Sensors	393
10.13	Range Finders	393
10.13.1	Ultrasonic Range Finders	394
10.13.2	Light-Based Range Finders	395
10.14	Sniff Sensors	396
10.15	Vision Systems	396
10.16	Voice-Recognition Devices	396
10.17	Voice Synthesizers	397
10.18	Remote Center Compliance (RCC) Device	397
10.19	Design Project	400
10.20	Summary	400
	References	401
11	Image Processing and Analysis with Vision Systems	403
11.1	Introduction	403
11.2	Basic Concepts	403
11.2.1	Image Processing vs. Image Analysis	403
11.2.2	Two- and Three-Dimensional Image Types	403
11.2.3	The Nature of an Image	404
11.2.4	Acquisition of Images	405

- 11.2.5 Digital Images 405
- 11.2.6 Frequency Domain vs. Spatial Domain 406
- 11.3 Fourier Transform and Frequency Content of a Signal 406
- 11.4 Frequency Content of an Image: Noise and Edges 409
- 11.5 Resolution and Quantization 410
- 11.6 Sampling Theorem 412
- 11.7 Image-Processing Techniques 415
- 11.8 Histograms of Images 415
- 11.9 Thresholding 418
- 11.10 Spatial Domain Operations Convolution Mask 419
- 11.11 Connectivity 424
- 11.12 Noise Reduction 426
 - 11.12.1 Neighborhood Averaging with Convolution Masks 427
 - 11.12.2 Image Averaging 428
 - 11.12.3 Frequency Domain 429
 - 11.12.4 Median Filters 429
- 11.13 Edge Detection 430
- 11.14 Sharpening an Image 436
- 11.15 Hough Transform 437
- 11.16 Segmentation 440
- 11.17 Segmentation by Region Growing and Region Splitting 441
- 11.18 Binary Morphology Operations 444
 - 11.18.1 Thickening Operation 446
 - 11.18.2 Dilation 446
 - 11.18.3 Erosion 447
 - 11.18.4 Skeletonization 447
 - 11.18.5 Open Operation 448
 - 11.18.6 Close Operation 448
 - 11.18.7 Fill Operation 448
- 11.19 Gray Morphology Operations 449
 - 11.19.1 Erosion 449
 - 11.19.2 Dilation 449
- 11.20 Image Analysis 449
- 11.21 Object Recognition by Features 450
 - 11.21.1 Basic Features Used for Object Identification 450
 - 11.21.2 Moments 451
 - 11.21.3 Template Matching 456
 - 11.21.4 Discrete Fourier Descriptors 456
 - 11.21.5 Computed Tomography (CT) 457
- 11.22 Depth Measurement with Vision Systems 457
 - 11.22.1 Scene Analysis vs. Mapping 457
 - 11.22.2 Range Detection and Depth Analysis 458
 - 11.22.3 Stereo Imaging 458
 - 11.22.4 Scene Analysis with Shading and Sizes 459
- 11.23 Specialized Lighting 459
- 11.24 Image Data Compression 460
 - 11.24.1 Intraframe Spatial Domain Techniques 460
 - 11.24.2 Interframe Coding 461
 - 11.24.3 Compression Techniques 461

11.25	Color Images	462
11.26	Heuristics	462
11.27	Applications of Vision Systems	462
11.28	Design Project	463
11.29	Summary	464
	References	464
	Problems	465
12	Fuzzy Logic Control	475
12.1	Introduction	475
12.2	Fuzzy Control: What Is Needed	476
12.3	Crisp Values vs. Fuzzy Values	476
12.4	Fuzzy Sets: Degrees of Truth and Membership	477
12.5	Fuzzification	477
12.6	Fuzzy Inference Rules	480
12.7	Defuzzification	481
	12.7.1 Center of Gravity Method	481
	12.7.2 Mamdani Inference Method	481
12.8	Simulation of a Fuzzy Logic Controller	485
12.9	Applications of Fuzzy Logic in Robotics	487
12.10	Design Project	488
12.11	Summary	489
	References	489
	Problems	490
	Appendix A	491
	Appendix B	499
	Index	501