
Contents

1	Introduction	1
1.1	Robotics	1
1.2	Robot Mechanical Structure	3
1.2.1	Robot Manipulators	4
1.2.2	Mobile Robots	10
1.3	Industrial Robotics	15
1.4	Advanced Robotics	25
1.4.1	Field Robots	26
1.4.2	Service Robots	27
1.5	Robot Modelling, Planning and Control	29
1.5.1	Modelling	30
1.5.2	Planning	32
1.5.3	Control	32
	Bibliography	33
2	Kinematics	39
2.1	Pose of a Rigid Body	39
2.2	Rotation Matrix	40
2.2.1	Elementary Rotations	41
2.2.2	Representation of a Vector	42
2.2.3	Rotation of a Vector	44
2.3	Composition of Rotation Matrices	45
2.4	Euler Angles	48
2.4.1	ZYZ Angles	49
2.4.2	RPY Angles	51
2.5	Angle and Axis	52
2.6	Unit Quaternion	54
2.7	Homogeneous Transformations	56
2.8	Direct Kinematics	58
2.8.1	Open Chain	60
2.8.2	Denavit–Hartenberg Convention	61

2.8.3	Closed Chain	65
2.9	Kinematics of Typical Manipulator Structures	68
2.9.1	Three-link Planar Arm	69
2.9.2	Parallelogram Arm	70
2.9.3	Spherical Arm	72
2.9.4	Anthropomorphic Arm	73
2.9.5	Spherical Wrist	75
2.9.6	Stanford Manipulator	76
2.9.7	Anthropomorphic Arm with Spherical Wrist	77
2.9.8	DLR Manipulator	79
2.9.9	Humanoid Manipulator	81
2.10	Joint Space and Operational Space	83
2.10.1	Workspace	85
2.10.2	Kinematic Redundancy	87
2.11	Kinematic Calibration	88
2.12	Inverse Kinematics Problem	90
2.12.1	Solution of Three-link Planar Arm	91
2.12.2	Solution of Manipulators with Spherical Wrist	94
2.12.3	Solution of Spherical Arm	95
2.12.4	Solution of Anthropomorphic Arm	96
2.12.5	Solution of Spherical Wrist	99
	Bibliography	100
	Problems	100
3	Differential Kinematics and Statics	105
3.1	Geometric Jacobian	105
3.1.1	Derivative of a Rotation Matrix	106
3.1.2	Link Velocities	108
3.1.3	Jacobian Computation	111
3.2	Jacobian of Typical Manipulator Structures	113
3.2.1	Three-link Planar Arm	113
3.2.2	Anthropomorphic Arm	114
3.2.3	Stanford Manipulator	115
3.3	Kinematic Singularities	116
3.3.1	Singularity Decoupling	117
3.3.2	Wrist Singularities	119
3.3.3	Arm Singularities	119
3.4	Analysis of Redundancy	121
3.5	Inverse Differential Kinematics	123
3.5.1	Redundant Manipulators	124
3.5.2	Kinematic Singularities	127
3.6	Analytical Jacobian	128
3.7	Inverse Kinematics Algorithms	132
3.7.1	Jacobian (Pseudo-)inverse	133
3.7.2	Jacobian Transpose	134

3.7.3	Orientation Error	137
3.7.4	Second-order Algorithms	141
3.7.5	Comparison Among Inverse Kinematics Algorithms	143
3.8	Statics	147
3.8.1	Kineto-Statics Duality	148
3.8.2	Velocity and Force Transformation	149
3.8.3	Closed Chain	151
3.9	Manipulability Ellipsoids	152
	Bibliography	158
	Problems	159
4	Trajectory Planning	161
4.1	Path and Trajectory	161
4.2	Joint Space Trajectories	162
4.2.1	Point-to-Point Motion	163
4.2.2	Motion Through a Sequence of Points	168
4.3	Operational Space Trajectories	179
4.3.1	Path Primitives	181
4.3.2	Position	184
4.3.3	Orientation	187
	Bibliography	188
	Problems	189
5	Actuators and Sensors	191
5.1	Joint Actuating System	191
5.1.1	Transmissions	192
5.1.2	Servomotors	193
5.1.3	Power Amplifiers	197
5.1.4	Power Supply	198
5.2	Drives	198
5.2.1	Electric Drives	198
5.2.2	Hydraulic Drives	202
5.2.3	Transmission Effects	204
5.2.4	Position Control	206
5.3	Proprioceptive Sensors	209
5.3.1	Position Transducers	210
5.3.2	Velocity Transducers	214
5.4	Exteroceptive Sensors	215
5.4.1	Force Sensors	215
5.4.2	Range Sensors	219
5.4.3	Vision Sensors	225
	Bibliography	230
	Problems	231

6	Control Architecture	233
6.1	Functional Architecture	233
6.2	Programming Environment	238
6.2.1	Teaching-by-Showing	240
6.2.2	Robot-oriented Programming	241
6.3	Hardware Architecture	242
	Bibliography	245
	Problems	245
7	Dynamics	247
7.1	Lagrange Formulation	247
7.1.1	Computation of Kinetic Energy	249
7.1.2	Computation of Potential Energy	255
7.1.3	Equations of Motion	255
7.2	Notable Properties of Dynamic Model	257
7.2.1	Skew-symmetry of Matrix $\dot{\mathbf{B}} - 2\mathbf{C}$	257
7.2.2	Linearity in the Dynamic Parameters	259
7.3	Dynamic Model of Simple Manipulator Structures	264
7.3.1	Two-link Cartesian Arm	264
7.3.2	Two-link Planar Arm	265
7.3.3	Parallelogram Arm	277
7.4	Dynamic Parameter Identification	280
7.5	Newton–Euler Formulation	282
7.5.1	Link Accelerations	285
7.5.2	Recursive Algorithm	286
7.5.3	Example	289
7.6	Direct Dynamics and Inverse Dynamics	292
7.7	Dynamic Scaling of Trajectories	294
7.8	Operational Space Dynamic Model	296
7.9	Dynamic Manipulability Ellipsoid	299
	Bibliography	301
	Problems	301
8	Motion Control	303
8.1	The Control Problem	303
8.2	Joint Space Control	305
8.3	Decentralized Control	309
8.3.1	Independent Joint Control	311
8.3.2	Decentralized Feedforward Compensation	319
8.4	Computed Torque Feedforward Control	324
8.5	Centralized Control	327
8.5.1	PD Control with Gravity Compensation	328
8.5.2	Inverse Dynamics Control	330
8.5.3	Robust Control	333
8.5.4	Adaptive Control	338

8.6	Operational Space Control	343
8.6.1	General Schemes	344
8.6.2	PD Control with Gravity Compensation	345
8.6.3	Inverse Dynamics Control	347
8.7	Comparison Among Various Control Schemes	349
	Bibliography	359
	Problems	360
9	Force Control	363
9.1	Manipulator Interaction with Environment	363
9.2	Compliance Control	364
9.2.1	Passive Compliance	366
9.2.2	Active Compliance	367
9.3	Impedance Control	372
9.4	Force Control	378
9.4.1	Force Control with Inner Position Loop	379
9.4.2	Force Control with Inner Velocity Loop	380
9.4.3	Parallel Force/Position Control	381
9.5	Constrained Motion	384
9.5.1	Rigid Environment	385
9.5.2	Compliant Environment	389
9.6	Natural and Artificial Constraints	391
9.6.1	Analysis of Tasks	392
9.7	Hybrid Force/Motion Control	396
9.7.1	Compliant Environment	397
9.7.2	Rigid Environment	401
	Bibliography	403
	Problems	404
10	Visual Servoing	407
10.1	Vision for Control	407
10.1.1	Configuration of the Visual System	409
10.2	Image Processing	410
10.2.1	Image Segmentation	411
10.2.2	Image Interpretation	416
10.3	Pose Estimation	418
10.3.1	Analytical Solution	419
10.3.2	Interaction Matrix	424
10.3.3	Algorithmic Solution	427
10.4	Stereo Vision	433
10.4.1	Epipolar Geometry	433
10.4.2	Triangulation	435
10.4.3	Absolute Orientation	436
10.4.4	3D Reconstruction from Planar Homography	438
10.5	Camera Calibration	440

10.6	The Visual Servoing Problem	443
10.7	Position-based Visual Servoing	445
	10.7.1 PD Control with Gravity Compensation	446
	10.7.2 Resolved-velocity Control	447
10.8	Image-based Visual Servoing	449
	10.8.1 PD Control with Gravity Compensation	449
	10.8.2 Resolved-velocity Control	451
10.9	Comparison Among Various Control Schemes	453
10.10	Hybrid Visual Servoing	460
	Bibliography	465
	Problems	466
11	Mobile Robots	469
11.1	Nonholonomic Constraints	469
	11.1.1 Integrability Conditions	473
11.2	Kinematic Model	476
	11.2.1 Unicycle	478
	11.2.2 Bicycle	479
11.3	Chained Form	482
11.4	Dynamic Model	485
11.5	Planning	489
	11.5.1 Path and Timing Law	489
	11.5.2 Flat Outputs	491
	11.5.3 Path Planning	492
	11.5.4 Trajectory Planning	498
	11.5.5 Optimal Trajectories	499
11.6	Motion Control	502
	11.6.1 Trajectory Tracking	503
	11.6.2 Regulation	510
11.7	Odometric Localization	514
	Bibliography	518
	Problems	518
12	Motion Planning	523
12.1	The Canonical Problem	523
12.2	Configuration Space	525
	12.2.1 Distance	527
	12.2.2 Obstacles	527
	12.2.3 Examples of Obstacles	528
12.3	Planning via Retraction	532
12.4	Planning via Cell Decomposition	536
	12.4.1 Exact Decomposition	536
	12.4.2 Approximate Decomposition	539
12.5	Probabilistic Planning	541
	12.5.1 PRM Method	541

12.5.2	Bidirectional RRT Method	543
12.6	Planning via Artificial Potentials	546
12.6.1	Attractive Potential	546
12.6.2	Repulsive Potential	547
12.6.3	Total Potential	549
12.6.4	Planning Techniques	550
12.6.5	The Local Minima Problem	551
12.7	The Robot Manipulator Case	554
	Bibliography	557
	Problems	557

Appendices

A	Linear Algebra	563
A.1	Definitions	563
A.2	Matrix Operations	565
A.3	Vector Operations	569
A.4	Linear Transformation	572
A.5	Eigenvalues and Eigenvectors	573
A.6	Bilinear Forms and Quadratic Forms	574
A.7	Pseudo-inverse	575
A.8	Singular Value Decomposition	577
	Bibliography	578
B	Rigid-body Mechanics	579
B.1	Kinematics	579
B.2	Dynamics	581
B.3	Work and Energy	584
B.4	Constrained Systems	585
	Bibliography	588
C	Feedback Control	589
C.1	Control of Single-input/Single-output Linear Systems	589
C.2	Control of Nonlinear Mechanical Systems	594
C.3	Lyapunov Direct Method	596
	Bibliography	598
D	Differential Geometry	599
D.1	Vector Fields and Lie Brackets	599
D.2	Nonlinear Controllability	603
	Bibliography	604

E	Graph Search Algorithms	605
E.1	Complexity.....	605
E.2	Breadth-first and Depth-first Search.....	606
E.3	A^* Algorithm.....	607
	Bibliography.....	608
	References	609
	Index	623