

Contents

Preface

page xiii

1 Introduction

- 1.1 Applications of Mobile Robots
- 1.2 Types of Mobile Robots
 - 1.2.1 Automated Guided Vehicles (AGVs)
 - 1.2.2 Service Robots
 - 1.2.3 Cleaning and Lawn Care Robots
 - 1.2.4 Social Robots
 - 1.2.5 Field Robots
 - 1.2.6 Inspection, Reconnaissance, Surveillance,
and Exploration Robots
- 1.3 Mobile Robot Engineering
 - 1.3.1 Mobile Robot Subsystems
 - 1.3.2 Overview of the Text
 - 1.3.3 Fundamentals of Wheeled Mobile Robots
 - 1.3.4 References and Further Reading
 - 1.3.5 Exercise

2 Math Fundamentals

- 2.1 Conventions and Definitions
 - 2.1.1 Notational Conventions
 - 2.1.2 Embedded Coordinate Frames
 - 2.1.3 References and Further Reading
- 2.2 Matrices
 - 2.2.1 Matrix Operations
 - 2.2.2 Matrix Functions
 - 2.2.3 Matrix Inversion
 - 2.2.4 Rank-Nullity Theorem
 - 2.2.5 Matrix Algebra
 - 2.2.6 Matrix Calculus
 - 2.2.7 Leibnitz' Rule
 - 2.2.8 References and Further Reading
 - 2.2.9 Exercises

1
2
2
2
3
4
4
5
6
7
7
8
9
11
11
12
12
13
17
21
21
21
24
25
28
29
31
39
40
40

2.3	Fundamentals of Rigid Transforms	41
2.3.1	Definitions	41
2.3.2	Why Homogeneous Transforms	42
2.3.3	Semantics and Interpretations	43
2.3.4	References and Further Reading	55
2.3.5	Exercises	56
2.4	Kinematics of Mechanisms	57
2.4.1	Forward Kinematics	57
2.4.2	Inverse Kinematics	61
2.4.3	Differential Kinematics	66
2.4.4	References and Further Reading	69
2.4.5	Exercises	69
2.5	Orientation and Angular Velocity	70
2.5.1	Orientation in Euler Angle Form	70
2.5.2	Angular Rates and Small Angles	75
2.5.3	Angular Velocity and Orientation Rates in Euler Angle Form	77
2.5.4	Angular Velocity and Orientation Rates in Angle-Axis Form	79
2.5.5	References and Further Reading	81
2.5.6	Exercises	81
2.6	Kinematic Models of Sensors	82
2.6.1	Kinematics of Video Cameras	82
2.6.2	Kinematics of Laser Rangefinders	83
2.6.3	References and Further Reading	89
2.6.4	Exercises	90
2.7	Transform Graphs and Pose Networks	90
2.7.1	Transforms as Relationships	90
2.7.2	Solving Pose Networks	93
2.7.3	Overconstrained Networks	95
2.7.4	Differential Kinematics Applied to Frames in General Position	97
2.7.5	References and Further Reading	102
2.7.6	Exercises	103
2.8	Quaternions	103
2.8.1	Representations and Notation	104
2.8.2	Quaternion Multiplication	105
2.8.3	Other Quaternion Operations	107
2.8.4	Representing 3D Rotations	109
2.8.5	Attitude and Angular Velocity	111
2.8.6	References and Further Reading	114
2.8.7	Exercises	114
3	Numerical Methods	116
3.1	Linearization and Optimization of Functions of Vectors	116
3.1.1	Linearization	117
3.1.2	Optimization of Objective Functions	120
3.1.3	Constrained Optimization	124
3.1.4	References and Further Reading	130
3.1.5	Exercises	130
3.2	Systems of Equations	131
3.2.1	Linear Systems	131
3.2.2	Nonlinear Systems	136

3.2.3	References and Further Reading	138
3.2.4	Exercises	139
3.3	Nonlinear and Constrained Optimization	140
3.3.1	Nonlinear Optimization	140
3.3.2	Constrained Optimization	146
3.3.3	References and Further Reading	150
3.3.4	Exercises	150
3.4	Differential Algebraic Systems	151
3.4.1	Constrained Dynamics	151
3.4.2	First- and Second-Order Constrained Kinematic Systems	154
3.4.3	Lagrangian Dynamics	157
3.4.4	Constraints	162
3.4.5	References and Further Reading	166
3.4.6	Exercises	167
3.5	Integration of Differential Equations	168
3.5.1	Dynamic Models in State Space	168
3.5.2	Integration of State Space Models	168
3.5.3	References and Further Reading	172
3.5.4	Exercises	172
4	Dynamics	173
4.1	Moving Coordinate Systems	173
4.1.1	Context of Measurement	174
4.1.2	Change of Reference Frame	175
4.1.3	Example: Attitude Stability Margin Estimation	180
4.1.4	Recursive Transformations of State of Motion	182
4.1.5	References and Further Reading	186
4.1.6	Exercises	186
4.2	Kinematics of Wheeled Mobile Robots	187
4.2.1	Aspects of Rigid Body Motion	187
4.2.2	WMR Velocity Kinematics for Fixed Contact Point	191
4.2.3	Common Steering Configurations	195
4.2.4	References and Further Reading	200
4.2.5	Exercises	201
4.3	Constrained Kinematics and Dynamics	201
4.3.1	Constraints of Disallowed Direction	202
4.3.2	Constraints of Rolling Without Slipping	207
4.3.3	Lagrangian Dynamics	211
4.3.4	Terrain Contact	217
4.3.5	Trajectory Estimation and Prediction	220
4.3.6	References and Further Reading	224
4.3.7	Exercises	225
4.4	Aspects of Linear Systems Theory	226
4.4.1	Linear Time-Invariant Systems	227
4.4.2	State Space Representation of Linear Dynamical Systems	234
4.4.3	Nonlinear Dynamical Systems	239
4.4.4	Perturbative Dynamics of Nonlinear Dynamical Systems	240
4.4.5	References and Further Reading	244
4.4.6	Exercises	244

4.5	Predictive Modeling and System Identification	245
4.5.1	Braking	245
4.5.2	Turning	247
4.5.3	Vehicle Rollover	250
4.5.4	Wheel Slip and Yaw Stability	253
4.5.5	Parameterization and Linearization of Dynamic Models	256
4.5.6	System Identification	259
4.5.7	References and Further Reading	268
4.5.8	Exercises	269
5	Optimal Estimation	270
5.1	Random Variables, Processes, and Transformation	270
5.1.1	Characterizing Uncertainty	270
5.1.2	Random Variables	272
5.1.3	Transformation of Uncertainty	279
5.1.4	Random Processes	289
5.1.5	References and Further Reading	294
5.1.6	Exercises	295
5.2	Covariance Propagation and Optimal Estimation	296
5.2.1	Variance of Continuous Integration and Averaging Processes	296
5.2.2	Stochastic Integration	301
5.2.3	Optimal Estimation	307
5.2.4	References and Further Reading	315
5.2.5	Exercises	315
5.3	State Space Kalman Filters	316
5.3.1	Introduction	316
5.3.2	Linear Discrete Time Kalman Filter	319
5.3.3	Kalman Filters for Nonlinear Systems	321
5.3.4	Simple Example: 2D Mobile Robot	327
5.3.5	Pragmatic Information for Kalman Filters	338
5.3.6	Other Forms of the Kalman Filter	344
5.3.7	References and Further Reading	344
5.3.8	Exercises	345
5.4	Bayesian Estimation	346
5.4.1	Definitions	346
5.4.2	Bayes' Rule	349
5.4.3	Bayes' Filters	353
5.4.4	Bayesian Mapping	358
5.4.5	Bayesian Localization	365
5.4.6	References and Further Reading	369
5.4.7	Exercises	369
6	State Estimation	370
6.1	Mathematics of Pose Estimation	370
6.1.1	Pose Fixing versus Dead Reckoning	371
6.1.2	Pose Fixing	372
6.1.3	Error Propagation in Triangulation	376
6.1.4	Real Pose Fixing Systems	384
6.1.5	Dead Reckoning	385
6.1.6	Real Dead Reckoning Systems	396
6.1.7	References and Further Reading	396
6.1.8	Exercises	397

6.2	Sensors for State Estimation	398
6.2.1	Articulation Sensors	398
6.2.2	Ambient Field Sensors	400
6.2.3	Inertial Frames of Reference	401
6.2.4	Inertial Sensors	403
6.2.5	References and Further Reading	409
6.2.6	Exercises	410
6.3	Inertial Navigation Systems	410
6.3.1	Introduction	410
6.3.2	Mathematics of Inertial Navigation	411
6.3.3	Errors and Aiding in Inertial Navigation	416
6.3.4	Example: Simple Odometry-Aided Attitude and Heading Reference System	420
6.3.5	References and Further Reading	423
6.3.6	Exercises	424
6.4	Satellite Navigation Systems	425
6.4.1	Introduction	425
6.4.2	Implementation	425
6.4.3	State Measurement	426
6.4.4	Performance	430
6.4.5	Modes of Operation	431
6.4.6	References and Further Reading	433
6.4.7	Exercises	434
7	Control	435
7.1	Classical Control	435
7.1.1	Introduction	435
7.1.2	Virtual Spring-Damper	439
7.1.3	Feedback Control	441
7.1.4	Model Referenced and Feedforward Control	447
7.1.5	References and Further Reading	452
7.1.6	Exercises	452
7.2	State Space Control	453
7.2.1	Introduction	453
7.2.2	State Space Feedback Control	454
7.2.3	Example: Robot Trajectory Following	458
7.2.4	Perception Based Control	463
7.2.5	Steering Trajectory Generation	466
7.2.6	References and Further Reading	472
7.2.7	Exercises	472
7.3	Optimal and Model Predictive Control	473
7.3.1	Calculus of Variations	473
7.3.2	Optimal Control	476
7.3.3	Model Predictive Control	482
7.3.4	Techniques for Solving Optimal Control Problems	484
7.3.5	Parametric Optimal Control	487
7.3.6	References and Further Reading	492
7.3.7	Exercises	492

7.4 Intelligent Control	493
7.4.1 Introduction	493
7.4.2 Evaluation	496
7.4.3 Representation	499
7.4.4 Search	507
7.4.5 References and Further Reading	512
7.4.6 Exercises	513
8 Perception	514
8.1 Image Processing Operators and Algorithms	514
8.1.1 Taxonomy of Computer Vision Algorithms	515
8.1.2 High-Pass Filtering Operators	517
8.1.3 Low-Pass Operators	523
8.1.4 Matching Signals and Images	524
8.1.5 Feature Detection	526
8.1.6 Region Processing	529
8.1.7 References and Further Reading	532
8.1.8 Exercises	533
8.2 Physics and Principles of Radiative Sensors	534
8.2.1 Radiative Sensors	534
8.2.2 Techniques for Range Sensing	535
8.2.3 Radiation	539
8.2.4 Lenses, Filters, and Mirrors	545
8.2.5 References and Further Reading	550
8.2.6 Exercises	551
8.3 Sensors for Perception	551
8.3.1 Laser Rangefinders	551
8.3.2 Ultrasonic Rangefinders	555
8.3.3 Visible Wavelength Cameras	557
8.3.4 Mid to Far Infrared Wavelength Cameras	560
8.3.5 Radars	562
8.3.6 References and Further Reading	564
8.3.7 Exercises	565
8.4 Aspects of Geometric and Semantic Computer Vision	565
8.4.1 Pixel Classification	565
8.4.2 Computational Stereo Vision	568
8.4.3 Obstacle Detection	572
8.4.4 References and Further Reading	576
8.4.5 Exercises	576
9 Localization and Mapping	579
9.1 Representation and Issues	580
9.1.1 Introduction	580
9.1.2 Representation	580
9.1.3 Timing and Motion Issues	583
9.1.4 Related Localization Issues	585
9.1.5 Structural Aspects	586
9.1.6 Example: Unmanned Ground Vehicle (UGV) Terrain Mapping	588
9.1.7 References and Further Reading	592
9.1.8 Exercises	593

9.2	Visual Localization and Motion Estimation	593
9.2.1	Introduction	593
9.2.2	Aligning Signals for Localization and Motion Estimation	600
9.2.3	Matching Features for Localization and Motion Estimation	606
9.2.4	Searching for the Optimal Pose	612
9.2.5	References and Further Reading	621
9.2.6	Exercises	622
9.3	Simultaneous Localization and Mapping	623
9.3.1	Introduction	623
9.3.2	Global Consistency in Cyclic Maps	624
9.3.3	Revisiting	630
9.3.4	EKF SLAM for Discrete Landmarks	632
9.3.5	Example: Autosurveying of Laser Reflectors	636
9.3.6	References and Further Reading	638
9.3.7	Exercises	639
10	Motion Planning	640
10.1	Introduction	640
10.1.1	Introducing Path Planning	641
10.1.2	Formulation of Path Planning	642
10.1.3	Obstacle-Free Motion Planning	643
10.1.4	References and Further Reading	646
10.1.5	Exercises	646
10.2	Representation and Search for Global Path Planning	646
10.2.1	Sequential Motion Planning	647
10.2.2	Big Ideas in Optimization and Search	653
10.2.3	Uniform Cost Sequential Planning Algorithms	656
10.2.4	Weighted Sequential Planning	661
10.2.5	Representation for Sequential Motion Planning	669
10.2.6	References and Further Reading	672
10.2.7	Exercises	672
10.3	Real-Time Global Motion Planning: Moving in Unknown and Dynamic Environments	673
10.3.1	Introduction	673
10.3.2	Depth-Limited Approaches	674
10.3.3	Anytime Approaches	677
10.3.4	Plan Repair Approach: D* Algorithm	678
10.3.5	Hierarchical Planning	686
10.3.6	References and Further Reading	689
10.3.7	Exercise	690
<i>Index</i>		691