Contents

Acknowledgments xiii

Preface xv

1 Introduction 1
- 1.1 Introduction 1
- 1.2 An Overview of the Book 11

2 Locomotion 13
- 2.1 Introduction 13
  - 2.1.1 Key issues for locomotion 16
- 2.2 Legged Mobile Robots 17
  - 2.2.1 Leg configurations and stability 18
  - 2.2.2 Consideration of dynamics 21
  - 2.2.3 Examples of legged robot locomotion 25
- 2.3 Wheeled Mobile Robots 35
  - 2.3.1 Wheeled locomotion: The design space 35
  - 2.3.2 Wheeled locomotion: Case studies 43
- 2.4 Aerial Mobile Robots 50
  - 2.4.1 Introduction 50
  - 2.4.2 Aircraft configurations 52
  - 2.4.3 State of the art in autonomous VTOL 52
- 2.5 Problems 56

3 Mobile Robot Kinematics 57
- 3.1 Introduction 57
- 3.2 Kinematic Models and Constraints 58

3.2.1 Representing robot position 58
3.2.2 Forward kinematic models 61
3.2.3 Wheel kinematic constraints 63
3.2.4 Robot kinematic constraints 71
3.2.5 Examples: Robot kinematic models and constraints 73
3.3 Mobile Robot Maneuverability 77
3.3.1 Degree of mobility 77
3.3.2 Degree of steerability 81
3.3.3 Robot maneuverability 82
3.4 Mobile Robot Workspace 84
3.4.1 Degrees of freedom 84
3.4.2 Holonomic robots 85
3.4.3 Path and trajectory considerations 87
3.5 Beyond Basic Kinematics 90
3.6 Motion Control (Kinematic Control) 91
3.6.1 Open loop control (trajectory-following) 91
3.6.2 Feedback control 92
3.7 Problems 99

4 Perception 101
4.1 Sensors for Mobile Robots 101
4.1.1 Sensor classification 101
4.1.2 Characterizing sensor performance 103
4.1.3 Representing uncertainty 109
4.1.4 Wheel/motor sensors 115
4.1.5 Heading sensors 116
4.1.6 Accelerometers 119
4.1.7 Inertial measurement unit (IMU) 121
4.1.8 Ground beacons 122
4.1.9 Active ranging 125
4.1.10 Motion/speed sensors 140
4.1.11 Vision sensors 142
4.2 Fundamentals of Computer Vision 142
4.2.1 Introduction 142
4.2.2 The digital camera 142
4.2.3 Image formation 148
4.2.4 Omnidirectional cameras 159
4.2.5 Structure from stereo 169
4.2.6 Structure from motion 180

4.2.7 Motion and optical flow 189
4.2.8 Color tracking 192
4.3 Fundamentals of Image Processing 195
4.3.1 Image filtering 196
4.3.2 Edge detection 199
4.3.3 Computing image similarity 207
4.4 Feature Extraction 208
4.5 Image Feature Extraction: Interest Point Detectors 212
4.5.1 Introduction 212
4.5.2 Properties of the ideal feature detector 213
4.5.3 Corner detectors 215
4.5.4 Invariance to photometric and geometric changes 220
4.5.5 Blob detectors 227
4.6 Place Recognition 234
4.6.1 Introduction 234
4.6.2 From bag of features to visual words 235
4.6.3 Efficient location recognition by using an inverted file 236
4.6.4 Geometric verification for robust place recognition 237
4.6.5 Applications 237
4.6.6 Other image representations for place recognition 238
4.7 Feature Extraction Based on Range Data (Laser, Ultrasonic) 242
4.7.1 Line fitting 243
4.7.2 Six line-extraction algorithms 248
4.7.3 Range histogram features 259
4.7.4 Extracting other geometric features 260
4.8 Problems 262

5 Mobile Robot Localization 265
5.1 Introduction 265
5.2 The Challenge of Localization: Noise and Aliasing 266
5.2.1 Sensor noise 267
5.2.2 Sensor aliasing 268
5.2.3 Effector noise 269
5.2.4 An error model for odometric position estimation 270
5.3 To Localize or Not to Localize: Localization-Based Navigation Versus Programmed Solutions 275
5.4 Belief Representation 278
5.4.1 Single-hypothesis belief 278
5.4.2 Multiple-hypothesis belief 280

5.5 Map Representation 284
5.5.1 Continuous representations 284
5.5.2 Decomposition strategies 287
5.5.3 State of the art: Current challenges in map representation 294
5.6 Probabilistic Map-Based Localization 296
5.6.1 Introduction 296
5.6.2 The robot localization problem 297
5.6.3 Basic concepts of probability theory 299
5.6.4 Terminology 302
5.6.5 The ingredients of probabilistic map-based localization 304
5.6.6 Classification of localization problems 306
5.6.7 Markov localization 307
5.6.8 Kalman filter localization 322
5.7 Other Examples of Localization Systems 342
5.7.1 Landmark-based navigation 344
5.7.2 Globally unique localization 345
5.7.3 Positioning beacon systems 346
5.7.4 Route-based localization 347
5.8 Autonomous Map Building 348
5.8.1 Introduction 348
5.8.2 SLAM: The simultaneous localization and mapping problem 349
5.8.3 Mathematical definition of SLAM 351
5.8.4 Extended Kalman Filter (EKF) SLAM 353
5.8.5 Visual SLAM with a single camera 356
5.8.6 Discussion on EKF SLAM 359
5.8.7 Graph-based SLAM 361
5.8.8 Particle filter SLAM 363
5.8.9 Open challenges in SLAM 364
5.8.10 Open source SLAM software and other resources 365
5.9 Problems 366

6 Planning and Navigation 369
6.1 Introduction 369
6.2 Competences for Navigation: Planning and Reacting 370
6.3 Path Planning 371
6.3.1 Graph search 373
6.3.2 Potential field path planning 386
6.4 Obstacle avoidance 393
6.4.1 Bug algorithm 393

6.4.2 Vector field histogram 397
6.4.3 The bubble band technique 399
6.4.4 Curvature velocity techniques 401
6.4.5 Dynamic window approaches 402
6.4.6 The Schlegel approach to obstacle avoidance 404
6.4.7 Nearness diagram 405
6.4.8 Gradient method 405
6.4.9 Adding dynamic constraints 406
6.4.10 Other approaches 406
6.4.11 Overview 406
6.5 Navigation Architectures 409
6.5.1 Modularity for code reuse and sharing 410
6.5.2 Control localization 410
6.5.3 Techniques for decomposition 411
6.5.4 Case studies: tiered robot architectures 416
6.6 Problems 423

Bibliography **425**
Books 425
Papers 427
Referenced Webpages 444

Index **447**