

Contents

Preface *xi*

About the Authors *xiii*

Introduction *1*

- 1 Kinematic Models for Mobile Robots** *5*
 - 1.1 Introduction *5*
 - 1.2 Vehicles with Front-Wheel Steering *5*
 - 1.3 Vehicles with Differential-Drive Steering *8*
 - Exercises *11*
 - References *12*
- 2 Mobile Robot Control** *13*
 - 2.1 Introduction *13*
 - 2.2 Front-Wheel Steered Vehicle, Heading Control *13*
 - 2.3 Front-Wheel Steered Vehicle, Speed Control *22*
 - 2.4 Heading and Speed Control for the Differential-Drive Robot *23*
 - 2.5 Reference Trajectory and Incremental Control, Front-Wheel Steered Robot *26*
 - 2.6 Heading Control of Front-Wheel Steered Robot Using the Nonlinear Model *31*
 - 2.7 Computed Control for Heading and Velocity, Front-Wheel Steered Robot *34*
 - 2.8 Heading Control of Differential-Drive Robot Using the Nonlinear Model *36*
 - 2.9 Computed Control for Heading and Velocity, Differential-Drive Robot *37*
 - 2.10 Steering Control Along a Path Using a Local Coordinate Frame *38*
 - 2.11 Optimal Steering of Front-Wheel Steered Vehicle *49*
 - 2.12 Optimal Steering of Front-Wheel Steered Vehicle, Free Final Heading Angle *67*

Exercises 68
References 69

3 Robot Attitude 71

- 3.1 Introduction 71
- 3.2 Definition of Yaw, Pitch, and Roll 71
- 3.3 Rotation Matrix for Yaw 72
- 3.4 Rotation Matrix for Pitch 74
- 3.5 Rotation Matrix for Roll 75
- 3.6 General Rotation Matrix 77
- 3.7 Homogeneous Transformation 78
- 3.8 Rotating a Vector 82
- Exercises 83
- References 84

4 Robot Navigation 85

- 4.1 Introduction 85
- 4.2 Coordinate Systems 85
- 4.3 Earth-Centered Earth-Fixed Coordinate System 85
- 4.4 Associated Coordinate Systems 88
- 4.5 Universal Transverse Mercator Coordinate System 91
- 4.6 Global Positioning System 93
- 4.7 Computing Receiver Location Using GPS, Numerical Methods 97
 - 4.7.1 Computing Receiver Location Using GPS via Newton's Method 97
 - 4.7.2 Computing Receiver Location Using GPS via Minimization of a Performance Index 105
- 4.8 Array of GPS Antennas 111
- 4.9 Gimbaled Inertial Navigation Systems 114
- 4.10 Strap-Down Inertial Navigation Systems 118
- 4.11 Dead Reckoning or Deduced Reckoning 123
- 4.12 Inclinator/Compass 125
- Exercises 127
- References 131

5 Application of Kalman Filtering 133

- 5.1 Introduction 133
- 5.2 Estimating a Fixed Quantity Using Batch Processing 133
- 5.3 Estimating a Fixed Quantity Using Recursive Processing 134
- 5.4 Estimating the State of a Dynamic System Recursively 139
- 5.5 Estimating the State of a Nonlinear System via the Extended Kalman Filter 150
- Exercises 165
- References 169

6 Remote Sensing 171

- 6.1 Introduction 171
- 6.2 Camera-Type Sensors 171
- 6.3 Stereo Vision 181
- 6.4 Radar Sensing: Synthetic Aperture Radar 185
- 6.5 Pointing of Range Sensor at Detected Object 190
- 6.6 Detection Sensor in Scanning Mode 195
 - Exercises 199
 - References 200

7 Target Tracking Including Multiple Targets with Multiple Sensors 203

- 7.1 Introduction 203
- 7.2 Regions of Confidence for Sensors 203
- 7.3 Model of Target Location 211
- 7.4 Inventory of Detected Targets 215
 - Exercises 220
 - References 221

8 Obstacle Mapping and Its Application to Robot Navigation 223

- 8.1 Introduction 223
- 8.2 Sensors for Obstacle Detection and Geo-Registration 223
- 8.3 Dead Reckoning Navigation 225
- 8.4 Use of Previously Detected Obstacles for Navigation 229
- 8.5 Simultaneous Corrections of Coordinates of Detected Obstacles and of the Robot 233
 - Exercises 236
 - References 237

9 Operating a Robotic Manipulator 239

- 9.1 Introduction 239
- 9.2 Forward Kinematic Equations 239
- 9.3 Path Specification in Joint Space 242
- 9.4 Inverse Kinematic Equations 242
- 9.5 Path Specification in Cartesian Space 248
- 9.6 Velocity Relationships 249
- 9.7 Forces and Torques 255
 - Exercises 261
 - References 262

10 Remote Sensing via UAVs 263

- 10.1 Introduction 263
- 10.2 Mounting of Sensors 263

| | | |
|-----------|--|------------|
| 10.3 | Resolution of Sensors | 264 |
| 10.4 | Precision of Vehicle Instrumentation | 264 |
| 10.5 | Overall Geo-Registration Precision | 265 |
| | Exercise | 267 |
| | References | 267 |
| 11 | Dynamics Modeling of AUVs | 269 |
| 11.1 | Introduction | 269 |
| 11.2 | Motivation | 269 |
| 11.3 | Full Dynamic Model | 270 |
| 11.4 | Hydrodynamic Model | 273 |
| 11.5 | Reduced-Order Longitudinal Dynamics | 274 |
| 11.6 | Computation of Steady Gliding Path in the Longitudinal Plane | 276 |
| 11.7 | Scaling Analysis | 279 |
| 11.8 | Spiraling Dynamics | 281 |
| 11.9 | Computation of Spiral Path | 286 |
| | Exercises | 288 |
| | References | 289 |
| 12 | Control of AUVs | 291 |
| 12.1 | Introduction | 291 |
| 12.2 | Longitudinal Gliding Stabilization | 291 |
| 12.2.1 | Longitudinal Dynamic Model Reduction | 292 |
| 12.2.2 | Passivity-Based Controller Design | 295 |
| 12.2.3 | Simulation Results | 297 |
| 12.3 | Yaw Angle Regulation | 298 |
| 12.3.1 | Problem Statement | 298 |
| 12.3.2 | Sliding Mode Controller Design | 300 |
| 12.3.3 | Simulation Results | 303 |
| 12.4 | Spiral Path Tracking | 307 |
| 12.4.1 | Steady Spiral and Its Differential Geometric Parameters | 307 |
| 12.4.2 | Two Degree-of-Freedom Control Design | 310 |
| 12.4.3 | Simulation Results | 314 |
| | Exercises | 321 |
| | References | 322 |

| | | |
|-------------------|---|------------|
| Appendix A | Demonstrations of Undergraduate Student Robotic Projects | 323 |
|-------------------|---|------------|

| | |
|--------------|------------|
| Index | 327 |
|--------------|------------|