## Contents

Preface xv

1 Introduction 1
   1.1 Intelligence and Embodiment 1
   1.2 A Roboticists’ Problem 2
   1.3 Ratslife: An Example of Autonomous Mobile Robotics 3
   1.4 Autonomous Mobile Robots: Some Core Challenges 5
   1.5 Autonomous Manipulation: Some Core Challenges 5

I MECHANISMS 9

2 Locomotion, Manipulation, and Their Representations 11
   2.1 Locomotion and Manipulation Examples 11
   2.2 Static and Dynamic Stability 13
   2.3 Degrees of Freedom 14
   2.4 Coordinate Systems and Frames of Reference 18
       2.4.1 Matrix Notation 19
       2.4.2 Mapping from One Frame to Another 21
       2.4.3 Concatenation of Transformations 23
       2.4.4 Other Representations for Orientation 24

3 Kinematics 27
   3.1 Forward Kinematics 28
       3.1.1 Forward Kinematics of a Simple Robot Arm 28
       3.1.2 The Denavit-Hartenberg Notation 30
   3.2 Inverse Kinematics 33
       3.2.1 Solvability 33
       3.2.2 Inverse Kinematics of a Simple Manipulator Arm 34
<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>3.3 Differential Kinematics</td>
<td>35</td>
</tr>
<tr>
<td>3.3.1 Forward Differential Kinematics</td>
<td>36</td>
</tr>
<tr>
<td>3.3.2 Forward Kinematics of a Differential-Wheel Robot</td>
<td>37</td>
</tr>
<tr>
<td>3.3.3 Forward Kinematics of Carlike Steering</td>
<td>43</td>
</tr>
<tr>
<td>3.4 Inverse Differential Kinematics</td>
<td>44</td>
</tr>
<tr>
<td>3.4.1 Inverse Kinematics of Mobile Robots</td>
<td>46</td>
</tr>
<tr>
<td>3.4.2 Feedback Control for Mobile Robots</td>
<td>48</td>
</tr>
<tr>
<td>3.4.3 Under-actuation and Over-actuation</td>
<td>49</td>
</tr>
<tr>
<td>4 Forces</td>
<td>53</td>
</tr>
<tr>
<td>4.1 Statics</td>
<td>54</td>
</tr>
<tr>
<td>4.2 Kineto-Statics Duality</td>
<td>56</td>
</tr>
<tr>
<td>4.3 Manipulability</td>
<td>56</td>
</tr>
<tr>
<td>4.3.1 Manipulability Ellipsoid in Velocity Space</td>
<td>56</td>
</tr>
<tr>
<td>4.3.2 Manipulability Ellipsoid in Force Space</td>
<td>57</td>
</tr>
<tr>
<td>4.3.3 Manipulability Considerations</td>
<td>58</td>
</tr>
<tr>
<td>5 Grasping</td>
<td>61</td>
</tr>
<tr>
<td>5.1 The Theory of Grasping</td>
<td>61</td>
</tr>
<tr>
<td>5.1.1 Friction</td>
<td>62</td>
</tr>
<tr>
<td>5.1.2 Multiple Contacts and Deformation</td>
<td>63</td>
</tr>
<tr>
<td>5.1.3 Suction</td>
<td>64</td>
</tr>
<tr>
<td>5.2 Simple Grasping Mechanisms</td>
<td>65</td>
</tr>
<tr>
<td>5.2.1 1-DoF Scissorlike Gripper</td>
<td>65</td>
</tr>
<tr>
<td>5.2.2 Parallel Jaw</td>
<td>66</td>
</tr>
<tr>
<td>5.2.3 4-Bar Linkage Parallel Gripper</td>
<td>67</td>
</tr>
<tr>
<td>5.2.4 Multifingered Hands</td>
<td>68</td>
</tr>
<tr>
<td>II Sensing and Actuation</td>
<td>71</td>
</tr>
<tr>
<td>6 Actuators</td>
<td>73</td>
</tr>
<tr>
<td>6.1 Electric Motors</td>
<td>73</td>
</tr>
<tr>
<td>6.1.1 AC and DC Motors</td>
<td>74</td>
</tr>
<tr>
<td>6.1.2 Stepper Motor</td>
<td>75</td>
</tr>
<tr>
<td>6.1.3 Brushless DC Motor</td>
<td>76</td>
</tr>
<tr>
<td>6.1.4 Servo Motor</td>
<td>76</td>
</tr>
<tr>
<td>6.1.5 Motor Controllers</td>
<td>77</td>
</tr>
<tr>
<td>6.2 Hydraulic and Pneumatic Actuators</td>
<td>77</td>
</tr>
<tr>
<td>6.2.1 Hydraulic Actuators</td>
<td>78</td>
</tr>
<tr>
<td>6.2.2 Pneumatic Actuators and Soft Robotics</td>
<td>78</td>
</tr>
<tr>
<td>6.3 Safety Considerations</td>
<td>79</td>
</tr>
</tbody>
</table>
7 Sensors
  7.1 Terminology
    7.1.1 Proprioception versus Exteroception
  7.2 Sensors That Measure the Robot’s Joint Configuration
  7.3 Sensors That Measure Ego-Motion
    7.3.1 Accelerometers
    7.3.2 Gyroscopes
  7.4 Measuring Force
    7.4.1 Measuring Pressure or Touch
  7.5 Sensors to Measure Distance
    7.5.1 Reflection
    7.5.2 Phase Shift
    7.5.3 Time of Flight
  7.6 Sensors to Sense Global Pose

III COMPUTATION

8 Vision
  8.1 Images as Two-Dimensional Signals
  8.2 From Signals to Information
  8.3 Basic Image Operations
    8.3.1 Threshold-Based Operations
    8.3.2 Convolution-Based Filters
    8.3.3 Morphological Operations
  8.4 Extracting Structure from Vision
  8.5 Computer Vision and Machine Learning

9 Feature Extraction
  9.1 Feature Detection as an Information-Reduction Problem
  9.2 Features
  9.3 Line Recognition
    9.3.1 Line Fitting Using Least Squares
    9.3.2 Split-and-Merge Algorithm
    9.3.3 RANSAC: Random Sample and Consensus
    9.3.4 The Hough Transform
  9.4 Scale-Invariant Feature Transforms
    9.4.1 Overview
    9.4.2 Object Recognition Using Scale-Invariant Features
  9.5 Feature Detection and Machine Learning
10 Artificial Neural Networks

10.1 The Simple Perceptron
   10.1.1 Geometric Interpretation of the Simple Perceptron
   10.1.2 Training the Simple Perceptron

10.2 Activation Functions

10.3 From the Simple Perceptron to Multilayer Neural Networks
   10.3.1 Formal Description of Artificial Neural Networks
   10.3.2 Training a Multilayer Neural Network

10.4 From Single Outputs to Higher Dimensional Data

10.5 Objective Functions and Optimization
   10.5.1 Loss Functions for Regression Tasks
   10.5.2 Loss Functions for Classification Tasks
   10.5.3 Binary and Categorical Cross-Entropy

10.6 Convolutional Neural Networks
   10.6.1 From Convolutions to 2D Neural Networks
   10.6.2 Padding and Striding
   10.6.3 Pooling
   10.6.4 Flattening
   10.6.5 A Sample CNN
   10.6.6 Convolutional Networks beyond 2D Image Data

10.7 Recurrent Neural Networks

11 Task Execution

11.1 Reactive Control
   11.1.1 Limitations of Reactive Control

11.2 Finite State Machines
   11.2.1 Implementation

11.3 Hierarchical Finite State Machines
   11.3.1 Implementation

11.4 Behavior Trees
   11.4.1 Node Definition and Status
   11.4.2 Node Types
   11.4.3 Behavior Tree Execution
   11.4.4 Implementation

11.5 Mission Planning
   11.5.1 The General Problem Solver and STRIPS

12 Mapping

12.1 Map Representations
12.2 Iterative Closest Point for Sparse Mapping
12.3 Octomap: Dense Mapping of Voxels 160
12.4 RGB-D Mapping: Dense Mapping of Surfaces 160

13 Path Planning 165
13.1 The Configuration Space 165
13.2 Graph-Based Planning Algorithms 166
   13.2.1 Dijkstra’s Algorithm 166
   13.2.2 A* 168
13.3 Sampling-Based Path Planning 169
   13.3.1 Rapidly Exploring Random Trees 170
13.4 Planning at Different Length Scales 173
13.5 Coverage Path Planning 175
13.6 Summary and Outlook 175

14 Manipulation 179
14.1 Nonprehensile Manipulation 179
14.2 Choosing the Right Grasp 180
   14.2.1 Finding Good Grasps for Simple Grippers 181
   14.2.2 Finding Good Grasps for Multifingered Hands 183
14.3 Pick and Place 184
14.4 Peg-in-Hole Problems 185

IV UNCERTAINTY 189

15 Uncertainty and Error Propagation 191
15.1 Uncertainty in Robotics as a Random Variable 191
15.2 Error Propagation 192
   15.2.1 Example: Line Fitting 194
   15.2.2 Example: Odometry 195
15.3 Optimal Sensor Fusion 196
   15.3.1 The Kalman Filter 197

16 Localization 201
16.1 Motivating Example 201
16.2 Markov Localization 203
   16.2.1 Perception Update 203
   16.2.2 Action Update 204
   16.2.3 Example: Markov Localization on a Topological Map 205
16.3 The Bayes Filter 207
   16.3.1 Example: Bayes Filter on a Grid 209
16.4 Particle Filter 211
16.5 Extended Kalman Filter

16.5.1 Odometry Using the Kalman Filter

16.6 Summary: Probabilistic Map-Based Localization

17 Simultaneous Localization and Mapping

17.1 Introduction

17.1.1 Landmarks

17.1.2 Special Case I: One Landmark

17.1.3 Special Case II: Two Landmarks

17.2 The Covariance Matrix

17.3 EKF SLAM

17.3.1 Algorithm

17.3.2 Multiple Sensors

17.4 Graph-Based SLAM

17.4.1 SLAM as a Maximum-Likelihood Estimation Problem

17.4.2 Numerical Techniques for Graph-Based SLAM

V APPENDIXES

A Trigonometry

A.1 Inverse Trigonometry

A.2 Trigonometric Identities

B Linear Algebra

B.1 Dot Product

B.2 Cross Product

B.3 Matrix Product

B.4 Matrix Inversion

B.5 Principal Component Analysis

C Statistics

C.1 Random Variables and Probability Distributions

C.1.1 The Normal Distribution

C.1.2 Normal Distribution in Two Dimensions

C.2 Conditional Probabilities and Bayes’ Rule

C.3 Sum of Two Random Processes

C.4 Linear Combinations of Independent Gaussian Random Variables

C.5 Testing Statistical Significance

C.5.1 Null Hypothesis on Distributions

C.5.2 Testing Whether Two Distributions Are Independent

C.5.3 Statistical Significance of True-False Tests

C.5.4 Summary
D Backpropagation 247
  D.1 Backward Propagation of Error 249
  D.2 Backpropagation Algorithm 251

E How to Write a Research Paper 253
  E.1 Original Research 253
  E.2 Hypothesis: Or, What Do We Learn from This Work? 255
  E.3 Survey and Tutorial 256
  E.4 Writing It Up! 256

F Sample Curricula 257
  F.1 An Introduction to Autonomous Mobile Robots 257
    F.1.1 Overview 257
    F.1.2 Content 258
    F.1.3 Implementation Suggestions 259
  F.2 An Introduction to Robotic Manipulation 260
    F.2.1 Overview 260
    F.2.2 Content 261
    F.2.3 Implementation Suggestions 261
  F.3 An Introduction to Robotic Systems 262
    F.3.1 Overview 262
    F.3.2 Content 262
    F.3.3 Implementation Suggestions 263
  F.4 Class Debates 263

References 265
Index 269