

Brief Contents

I Basics 1

- 1 *Introduction* 3
- 2 *Recursive State Estimation* 13
- 3 *Gaussian Filters* 39
- 4 *Nonparametric Filters* 85
- 5 *Robot Motion* 117
- 6 *Robot Perception* 149

II Localization 189

- 7 *Mobile Robot Localization: Markov and Gaussian* 191
- 8 *Mobile Robot Localization: Grid And Monte Carlo* 237

III Mapping 279

- 9 *Occupancy Grid Mapping* 281
- 10 *Simultaneous Localization and Mapping* 309
- 11 *The GraphSLAM Algorithm* 337
- 12 *The Sparse Extended Information Filter* 385
- 13 *The FastSLAM Algorithm* 437

IV Planning and Control 485

- 14 *Markov Decision Processes* 487
- 15 *Partially Observable Markov Decision Processes* 513

Contents

Preface xvii

Acknowledgments xix

I Basics 1

1 Introduction 3

- 1.1 Uncertainty in Robotics 3
- 1.2 Probabilistic Robotics 4
- 1.3 Implications 9
- 1.4 Road Map 10
- 1.5 Teaching Probabilistic Robotics 11
- 1.6 Bibliographical Remarks 11

2 Recursive State Estimation 13

- 2.1 Introduction 13
- 2.2 Basic Concepts in Probability 14
- 2.3 Robot Environment Interaction 19
 - 2.3.1 State 20
 - 2.3.2 Environment Interaction 22
 - 2.3.3 Probabilistic Generative Laws 24
 - 2.3.4 Belief Distributions 25
- 2.4 Bayes Filters 26
 - 2.4.1 The Bayes Filter Algorithm 26
 - 2.4.2 Example 28
 - 2.4.3 Mathematical Derivation of the Bayes Filter 31
 - 2.4.4 The Markov Assumption 33

2.5	Representation and Computation	34
2.6	Summary	35
2.7	Bibliographical Remarks	36
2.8	Exercises	36
3	<i>Gaussian Filters</i>	39
3.1	Introduction	39
3.2	The Kalman Filter	40
3.2.1	Linear Gaussian Systems	40
3.2.2	The Kalman Filter Algorithm	43
3.2.3	Illustration	44
3.2.4	Mathematical Derivation of the KF	45
3.3	The Extended Kalman Filter	54
3.3.1	Why Linearize?	54
3.3.2	Linearization Via Taylor Expansion	56
3.3.3	The EKF Algorithm	59
3.3.4	Mathematical Derivation of the EKF	59
3.3.5	Practical Considerations	61
3.4	The Unscented Kalman Filter	65
3.4.1	Linearization Via the Unscented Transform	65
3.4.2	The UKF Algorithm	67
3.5	The Information Filter	71
3.5.1	Canonical Parameterization	71
3.5.2	The Information Filter Algorithm	73
3.5.3	Mathematical Derivation of the Information Filter	74
3.5.4	The Extended Information Filter Algorithm	75
3.5.5	Mathematical Derivation of the Extended Information Filter	76
3.5.6	Practical Considerations	77
3.6	Summary	79
3.7	Bibliographical Remarks	81
3.8	Exercises	81
4	<i>Nonparametric Filters</i>	85
4.1	The Histogram Filter	86
4.1.1	The Discrete Bayes Filter Algorithm	86
4.1.2	Continuous State	87
4.1.3	Mathematical Derivation of the Histogram Approximation	89

4.1.4	Decomposition Techniques	92
4.2	Binary Bayes Filters with Static State	94
4.3	The Particle Filter	96
4.3.1	Basic Algorithm	96
4.3.2	Importance Sampling	100
4.3.3	Mathematical Derivation of the PF	103
4.3.4	Practical Considerations and Properties of Particle Filters	104
4.4	Summary	113
4.5	Bibliographical Remarks	114
4.6	Exercises	115
5	<i>Robot Motion</i>	117
5.1	Introduction	117
5.2	Preliminaries	118
5.2.1	Kinematic Configuration	118
5.2.2	Probabilistic Kinematics	119
5.3	Velocity Motion Model	121
5.3.1	Closed Form Calculation	121
5.3.2	Sampling Algorithm	122
5.3.3	Mathematical Derivation of the Velocity Motion Model	125
5.4	Odometry Motion Model	132
5.4.1	Closed Form Calculation	133
5.4.2	Sampling Algorithm	137
5.4.3	Mathematical Derivation of the Odometry Motion Model	137
5.5	Motion and Maps	140
5.6	Summary	143
5.7	Bibliographical Remarks	145
5.8	Exercises	145
6	<i>Robot Perception</i>	149
6.1	Introduction	149
6.2	Maps	152
6.3	Beam Models of Range Finders	153
6.3.1	The Basic Measurement Algorithm	153
6.3.2	Adjusting the Intrinsic Model Parameters	158
6.3.3	Mathematical Derivation of the Beam Model	162

6.3.4	Practical Considerations	167	
6.3.5	Limitations of the Beam Model	168	
6.4	Likelihood Fields for Range Finders	169	
6.4.1	Basic Algorithm	169	
6.4.2	Extensions	172	
6.5	Correlation-Based Measurement Models	174	
6.6	Feature-Based Measurement Models	176	
6.6.1	Feature Extraction	176	
6.6.2	Landmark Measurements	177	
6.6.3	Sensor Model with Known Correspondence	178	178
6.6.4	Sampling Poses	179	
6.6.5	Further Considerations	180	
6.7	Practical Considerations	182	
6.8	Summary	183	
6.9	Bibliographical Remarks	184	
6.10	Exercises	185	

II Localization 189

7	<i>Mobile Robot Localization: Markov and Gaussian</i>	191	
7.1	A Taxonomy of Localization Problems	193	
7.2	Markov Localization	197	
7.3	Illustration of Markov Localization	200	
7.4	EKF Localization	201	
7.4.1	Illustration	201	
7.4.2	The EKF Localization Algorithm	203	
7.4.3	Mathematical Derivation of EKF Localization	205	205
7.4.4	Physical Implementation	210	
7.5	Estimating Correspondences	215	
7.5.1	EKF Localization with Unknown Correspondences	215	
7.5.2	Mathematical Derivation of the ML Data Association	216	
7.6	Multi-Hypothesis Tracking	218	
7.7	UKF Localization	220	
7.7.1	Mathematical Derivation of UKF Localization	220	220
7.7.2	Illustration	223	
7.8	Practical Considerations	229	

7.9	Summary	232
7.10	Bibliographical Remarks	233
7.11	Exercises	234
8	<i>Mobile Robot Localization: Grid And Monte Carlo</i>	237
8.1	Introduction	237
8.2	Grid Localization	238
8.2.1	Basic Algorithm	238
8.2.2	Grid Resolutions	239
8.2.3	Computational Considerations	243
8.2.4	Illustration	245
8.3	Monte Carlo Localization	250
8.3.1	Illustration	250
8.3.2	The MCL Algorithm	252
8.3.3	Physical Implementations	253
8.3.4	Properties of MCL	253
8.3.5	Random Particle MCL: Recovery from Failures	256
8.3.6	Modifying the Proposal Distribution	261
8.3.7	KLD-Sampling: Adapting the Size of Sample Sets	263
8.4	Localization in Dynamic Environments	267
8.5	Practical Considerations	273
8.6	Summary	274
8.7	Bibliographical Remarks	275
8.8	Exercises	276

III Mapping 279

9	<i>Occupancy Grid Mapping</i>	281
9.1	Introduction	281
9.2	The Occupancy Grid Mapping Algorithm	284
9.2.1	Multi-Sensor Fusion	293
9.3	Learning Inverse Measurement Models	294
9.3.1	Inverting the Measurement Model	294
9.3.2	Sampling from the Forward Model	295
9.3.3	The Error Function	296
9.3.4	Examples and Further Considerations	298
9.4	Maximum A Posteriori Occupancy Mapping	299
9.4.1	The Case for Maintaining Dependencies	299

9.4.2	Occupancy Grid Mapping with Forward Models	301
9.5	Summary	304
9.6	Bibliographical Remarks	305
9.7	Exercises	307
10	<i>Simultaneous Localization and Mapping</i>	309
10.1	Introduction	309
10.2	SLAM with Extended Kalman Filters	312
10.2.1	Setup and Assumptions	312
10.2.2	SLAM with Known Correspondence	313
10.2.3	Mathematical Derivation of EKF SLAM	317
10.3	EKF SLAM with Unknown Correspondences	323
10.3.1	The General EKF SLAM Algorithm	323
10.3.2	Examples	324
10.3.3	Feature Selection and Map Management	328
10.4	Summary	330
10.5	Bibliographical Remarks	332
10.6	Exercises	334
11	<i>The GraphSLAM Algorithm</i>	337
11.1	Introduction	337
11.2	Intuitive Description	340
11.2.1	Building Up the Graph	340
11.2.2	Inference	343
11.3	The GraphSLAM Algorithm	346
11.4	Mathematical Derivation of GraphSLAM	353
11.4.1	The Full SLAM Posterior	353
11.4.2	The Negative Log Posterior	354
11.4.3	Taylor Expansion	355
11.4.4	Constructing the Information Form	357
11.4.5	Reducing the Information Form	360
11.4.6	Recovering the Path and the Map	361
11.5	Data Association in GraphSLAM	362
11.5.1	The GraphSLAM Algorithm with Unknown Correspondence	363
11.5.2	Mathematical Derivation of the Correspondence Test	366
11.6	Efficiency Consideration	368
11.7	Empirical Implementation	370

11.8	Alternative Optimization Techniques	376
11.9	Summary	379
11.10	Bibliographical Remarks	381
11.11	Exercises	382
12	<i>The Sparse Extended Information Filter</i>	385
12.1	Introduction	385
12.2	Intuitive Description	388
12.3	The SEIF SLAM Algorithm	391
12.4	Mathematical Derivation of the SEIF	395
12.4.1	Motion Update	395
12.4.2	Measurement Updates	398
12.5	Sparsification	398
12.5.1	General Idea	398
12.5.2	Sparsification in SEIFs	400
12.5.3	Mathematical Derivation of the Sparsification	401
12.6	Amortized Approximate Map Recovery	402
12.7	How Sparse Should SEIFs Be?	405
12.8	Incremental Data Association	409
12.8.1	Computing Incremental Data Association Probabilities	409
12.8.2	Practical Considerations	411
12.9	Branch-and-Bound Data Association	415
12.9.1	Recursive Search	416
12.9.2	Computing Arbitrary Data Association Probabilities	416
12.9.3	Equivalence Constraints	419
12.10	Practical Considerations	420
12.11	Multi-Robot SLAM	424
12.11.1	Integrating Maps	424
12.11.2	Mathematical Derivation of Map Integration	427
12.11.3	Establishing Correspondence	429
12.11.4	Example	429
12.12	Summary	432
12.13	Bibliographical Remarks	434
12.14	Exercises	435
13	<i>The FastSLAM Algorithm</i>	437
13.1	The Basic Algorithm	439

13.2	Factoring the SLAM Posterior	439
13.2.1	Mathematical Derivation of the Factored SLAM Posterior	442
13.3	FastSLAM with Known Data Association	444
13.4	Improving the Proposal Distribution	451
13.4.1	Extending the Path Posterior by Sampling a New Pose	451
13.4.2	Updating the Observed Feature Estimate	454
13.4.3	Calculating Importance Factors	455
13.5	Unknown Data Association	457
13.6	Map Management	459
13.7	The FastSLAM Algorithms	460
13.8	Efficient Implementation	460
13.9	FastSLAM for Feature-Based Maps	468
13.9.1	Empirical Insights	468
13.9.2	Loop Closure	471
13.10	Grid-based FastSLAM	474
13.10.1	The Algorithm	474
13.10.2	Empirical Insights	475
13.11	Summary	479
13.12	Bibliographical Remarks	481
13.13	Exercises	482
IV	Planning and Control	485
14	<i>Markov Decision Processes</i>	487
14.1	Motivation	487
14.2	Uncertainty in Action Selection	490
14.3	Value Iteration	495
14.3.1	Goals and Payoff	495
14.3.2	Finding Optimal Control Policies for the Fully Observable Case	499
14.3.3	Computing the Value Function	501
14.4	Application to Robot Control	503
14.5	Summary	507
14.6	Bibliographical Remarks	509
14.7	Exercises	510

15	<i>Partially Observable Markov Decision Processes</i>	513
15.1	Motivation	513
15.2	An Illustrative Example	515
15.2.1	Setup	515
15.2.2	Control Choice	516
15.2.3	Sensing	519
15.2.4	Prediction	523
15.2.5	Deep Horizons and Pruning	526
15.3	The Finite World POMDP Algorithm	527
15.4	Mathematical Derivation of POMDPs	531
15.4.1	Value Iteration in Belief Space	531
15.4.2	Value Function Representation	532
15.4.3	Calculating the Value Function	533
15.5	Practical Considerations	536
15.6	Summary	541
15.7	Bibliographical Remarks	542
15.8	Exercises	544
16	<i>Approximate POMDP Techniques</i>	547
16.1	Motivation	547
16.2	QMDPs	549
16.3	Augmented Markov Decision Processes	550
16.3.1	The Augmented State Space	550
16.3.2	The AMDP Algorithm	551
16.3.3	Mathematical Derivation of AMDPs	553
16.3.4	Application to Mobile Robot Navigation	556
16.4	Monte Carlo POMDPs	559
16.4.1	Using Particle Sets	559
16.4.2	The MC-POMDP Algorithm	559
16.4.3	Mathematical Derivation of MC-POMDPs	562
16.4.4	Practical Considerations	563
16.5	Summary	565
16.6	Bibliographical Remarks	566
16.7	Exercises	566
17	<i>Exploration</i>	569
17.1	Introduction	569
17.2	Basic Exploration Algorithms	571
17.2.1	Information Gain	571

17.2.2	Greedy Techniques	572	
17.2.3	Monte Carlo Exploration	573	
17.2.4	Multi-Step Techniques	575	
17.3	Active Localization	575	
17.4	Exploration for Learning Occupancy Grid Maps		580
17.4.1	Computing Information Gain	580	
17.4.2	Propagating Gain	585	
17.4.3	Extension to Multi-Robot Systems		587
17.5	Exploration for SLAM	593	
17.5.1	Entropy Decomposition in SLAM		593
17.5.2	Exploration in FastSLAM	594	
17.5.3	Empirical Characterization	598	
17.6	Summary	600	
17.7	Bibliographical Remarks	602	
17.8	Exercises	604	
	Bibliography	607	
	Index	639	