

# Contents

Preface	xvii
Acknowledgments	xix

## CHAPTER 1

Introduction	1
1.1 Fundamental Concepts	1
1.2 Dead Reckoning	5
1.3 Position Fixing	7
1.3.1 Position-Fixing Methods	7
1.3.2 Signal-Based Positioning	12
1.3.3 Environmental Feature Matching	14
1.4 The Navigation System	15
1.4.1 Requirements	16
1.4.2 Context	17
1.4.3 Integration	18
1.4.4 Aiding	18
1.4.5 Assistance and Cooperation	19
1.4.6 Fault Detection	20
1.5 Overview of the Book	20
References	22

## CHAPTER 2

Coordinate Frames, Kinematics, and the Earth	23
2.1 Coordinate Frames	23
2.1.1 Earth-Centered Inertial Frame	25
2.1.2 Earth-Centered Earth-Fixed Frame	26
2.1.3 Local Navigation Frame	27
2.1.4 Local Tangent-Plane Frame	28
2.1.5 Body Frame	28
2.1.6 Other Frames	29
2.2 Attitude, Rotation, and Resolving Axes Transformations	30
2.2.1 Euler Attitude	33
2.2.2 Coordinate Transformation Matrix	35
2.2.3 Quaternion Attitude	40
2.2.4 Rotation Vector	42
2.3 Kinematics	43

2.3.1	Angular Rate	44
2.3.2	Cartesian Position	46
2.3.3	Velocity	48
2.3.4	Acceleration	50
2.3.5	Motion with Respect to a Rotating Reference Frame	51
2.4	Earth Surface and Gravity Models	53
2.4.1	The Ellipsoid Model of the Earth's Surface	54
2.4.2	Curvilinear Position	57
2.4.3	Position Conversion	61
2.4.4	The Geoid, Orthometric Height, and Earth Tides	64
2.4.5	Projected Coordinates	65
2.4.6	Earth Rotation	66
2.4.7	Specific Force, Gravitation, and Gravity	67
2.5	Frame Transformations	72
2.5.1	Inertial and Earth Frames	73
2.5.2	Earth and Local Navigation Frames	74
2.5.3	Inertial and Local Navigation Frames	75
2.5.4	Earth and Local Tangent-Plane Frames	76
2.5.5	Transposition of Navigation Solutions	77
	References	78
<b>CHAPTER 3</b>		
	<b>Kalman Filter-Based Estimation</b>	<b>81</b>
3.1	Introduction	82
3.1.1	Elements of the Kalman Filter	82
3.1.2	Steps of the Kalman Filter	84
3.1.3	Kalman Filter Applications	86
3.2	Algorithms and Models	87
3.2.1	Definitions	87
3.2.2	Kalman Filter Algorithm	91
3.2.3	System Model	96
3.2.4	Measurement Model	100
3.2.5	Kalman Filter Behavior and State Observability	103
3.2.6	Closed-Loop Kalman Filter	106
3.2.7	Sequential Measurement Update	107
3.3	Implementation Issues	109
3.3.1	Tuning and Stability	109
3.3.2	Algorithm Design	111
3.3.3	Numerical Issues	113
3.3.4	Time Synchronization	114
3.3.5	Kalman Filter Design Process	117
3.4	Extensions to the Kalman Filter	117
3.4.1	Extended and Linearized Kalman Filter	118
3.4.2	Unscented Kalman Filter	121
3.4.3	Time-Correlated Noise	123
3.4.4	Adaptive Kalman Filter	124

3.4.5	Multiple-Hypothesis Filtering	125
3.4.6	Kalman Smoothing	129
3.5	The Particle Filter	131
	References	135

## CHAPTER 4

	Inertial Sensors	137
4.1	Accelerometers	139
	4.1.1 Pendulous Accelerometers	140
	4.1.2 Vibrating-Beam Accelerometers	142
4.2	Gyroscopes	142
	4.2.1 Optical Gyroscopes	143
	4.2.2 Vibratory Gyroscopes	146
4.3	Inertial Measurement Units	149
4.4	Error Characteristics	151
	4.4.1 Biases	152
	4.4.2 Scale Factor and Cross-Coupling Errors	154
	4.4.3 Random Noise	155
	4.4.4 Further Error Sources	157
	4.4.5 Vibration-Induced Errors	159
	4.4.6 Error Models	160
	References	161

## CHAPTER 5

	Inertial Navigation	163
5.1	Introduction to Inertial Navigation	164
5.2	Inertial-Frame Navigation Equations	168
	5.2.1 Attitude Update	168
	5.2.2 Specific-Force Frame Transformation	170
	5.2.3 Velocity Update	171
	5.2.4 Position Update	172
5.3	Earth-Frame Navigation Equations	172
	5.3.1 Attitude Update	173
	5.3.2 Specific-Force Frame Transformation	174
	5.3.3 Velocity Update	174
	5.3.4 Position Update	175
5.4	Local-Navigation-Frame Navigation Equations	176
	5.4.1 Attitude Update	176
	5.4.2 Specific-Force Frame Transformation	178
	5.4.3 Velocity Update	179
	5.4.4 Position Update	179
	5.4.5 Wander-Azimuth Implementation	180
5.5	Navigation Equations Optimization	183
	5.5.1 Precision Attitude Update	183
	5.5.2 Precision Specific-Force Frame Transformation	187
	5.5.3 Precision Velocity and Position Updates	188



5.5.4	Effects of Sensor Sampling Interval and Vibration	189
5.5.5	Design Tradeoffs	195
5.6	Initialization and Alignment	195
5.6.1	Position and Velocity Initialization	196
5.6.2	Attitude Initialization	196
5.6.3	Fine Alignment	200
5.7	INS Error Propagation	203
5.7.1	Short-Term Straight-Line Error Propagation	204
5.7.2	Medium- and Long-Term Error Propagation	209
5.7.3	Maneuver-Dependent Errors	212
5.8	Indexed IMU	214
5.9	Partial IMU	215
	References	216

## CHAPTER 6

	Dead Reckoning, Attitude, and Height Measurement	217
6.1	Attitude Measurement	217
6.1.1	Magnetic Heading	218
6.1.2	Marine Gyrocompass	222
6.1.3	Strapdown Yaw-Axis Gyro	223
6.1.4	Heading from Trajectory	225
6.1.5	Integrated Heading Determination	226
6.1.6	Accelerometer Leveling and Tilt Sensors	226
6.1.7	Horizon Sensing	227
6.1.8	Attitude and Heading Reference System	228
6.2	Height and Depth Measurement	229
6.2.1	Barometric Altimeter	230
6.2.2	Depth Pressure Sensor	231
6.2.3	Radar Altimeter	232
6.3	Odometry	233
6.3.1	Linear Odometry	234
6.3.2	Differential Odometry	238
6.3.3	Integrated Odometry and Partial IMU	239
6.4	Pedestrian Dead Reckoning Using Step Detection	240
6.5	Doppler Radar and Sonar	245
6.6	Other Dead-Reckoning Techniques	249
6.6.1	Correlation-Based Velocity Measurement	249
6.6.2	Air Data	249
6.6.3	Ship's Speed Log	250
	References	250

## CHAPTER 7

	Principles of Radio Positioning	255
7.1	Radio Positioning Configurations and Methods	255
7.1.1	Self-Positioning and Remote Positioning	255
7.1.2	Relative Positioning	257

7.1.3	Proximity	258
7.1.4	Ranging	260
7.1.5	Angular Positioning	269
7.1.6	Pattern Matching	271
7.1.7	Doppler Positioning	274
7.2	Positioning Signals	276
7.2.1	Modulation Types	276
7.2.2	Radio Spectrum	277
7.3	User Equipment	279
7.3.1	Architecture	279
7.3.2	Signal Timing Measurement	280
7.3.3	Position Determination from Ranging	282
7.4	Propagation, Error Sources, and Positioning Accuracy	287
7.4.1	Ionosphere, Troposphere, and Surface Propagation Effects	287
7.4.2	Attenuation, Reflection, Multipath, and Diffraction	288
7.4.3	Resolution, Noise, and Tracking Errors	290
7.4.4	Transmitter Location and Timing Errors	292
7.4.5	Effect of Signal Geometry	292
	References	297

## CHAPTER 8

	GNSS: Fundamentals, Signals, and Satellites	299
8.1	Fundamentals of Satellite Navigation	300
8.1.1	GNSS Architecture	300
8.1.2	Signals and Range Measurement	303
8.1.3	Positioning	307
8.1.4	Error Sources and Performance Limitations	309
8.2	The Systems	312
8.2.1	Global Positioning System	312
8.2.2	GLONASS	313
8.2.3	Galileo	313
8.2.4	Beidou	314
8.2.5	Regional Systems	314
8.2.6	Augmentation Systems	314
8.2.7	System Compatibility	316
8.3	GNSS Signals	317
8.3.1	Signal Types	318
8.3.2	Global Positioning System	320
8.3.3	GLONASS	323
8.3.4	Galileo	324
8.3.5	Beidou	326
8.3.6	Regional Systems	326
8.3.7	Augmentation Systems	327
8.4	Navigation Data Messages	327
8.4.1	GPS	327
8.4.2	GLONASS	328



8.4.3	Galileo	329
8.4.4	SBAS	329
8.4.5	Time Base Synchronization	329
8.5	Satellite Orbits and Geometry	330
8.5.1	Satellite Orbits	330
8.5.2	Satellite Position and Velocity	332
8.5.3	Range, Range Rate, and Line of Sight	339
8.5.4	Elevation and Azimuth	344
	References	345

## CHAPTER 9

	GNSS: User Equipment Processing and Errors	349
9.1	Receiver Hardware and Antenna	350
9.1.1	Antennas	350
9.1.2	Reference Oscillator	351
9.1.3	Receiver Front End	352
9.1.4	Baseband Signal Processor	355
9.2	Ranging Processor	367
9.2.1	Acquisition	367
9.2.2	Code Tracking	372
9.2.3	Carrier Tracking	377
9.2.4	Tracking Lock Detection	384
9.2.5	Navigation-Message Demodulation	385
9.2.6	Carrier-Power-to-Noise-Density Measurement	386
9.2.7	Pseudo-Range, Pseudo-Range-Rate, and Carrier-Phase Measurements	387
9.3	Range Error Sources	389
9.3.1	Ephemeris Prediction and Satellite Clock Errors	390
9.3.2	Ionosphere and Troposphere Propagation Errors	391
9.3.3	Tracking Errors	395
9.3.4	Multipath, Nonline-of-Sight, and Diffraction	401
9.4	Navigation Processor	407
9.4.1	Single-Epoch Navigation Solution	409
9.4.2	Filtered Navigation Solution	413
9.4.3	Signal Geometry and Navigation Solution Accuracy	424
9.4.4	Position Error Budget	429
	References	431

## CHAPTER 10

	GNSS: Advanced Techniques	437
10.1	Differential GNSS	437
10.1.1	Spatial and Temporal Correlation of GNSS Errors	438
10.1.2	Local and Regional Area DGNSS	439
10.1.3	Wide Area DGNSS and Precise Point Positioning	440
10.1.4	Relative GNSS	441

10.2	Real-Time Kinematic Carrier-Phase Positioning and Attitude Determination	442
10.2.1	Principles of Accumulated Delta Range Positioning	443
10.2.2	Single-Epoch Navigation Solution Using Double-Differenced ADR	446
10.2.3	Geometry-Based Integer Ambiguity Resolution	447
10.2.4	Multifrequency Integer Ambiguity Resolution	449
10.2.5	GNSS Attitude Determination	450
10.3	Interference Rejection and Weak Signal Processing	451
10.3.1	Sources of Interference, Jamming, and Attenuation	452
10.3.2	Antenna Systems	452
10.3.3	Receiver Front-End Filtering	453
10.3.4	Extended Range Tracking	454
10.3.5	Receiver Sensitivity	455
10.3.6	Combined Acquisition and Tracking	456
10.3.7	Vector Tracking	456
10.4	Mitigation of Multipath Interference and Nonline-of-Sight Reception	458
10.4.1	Antenna-Based Techniques	459
10.4.2	Receiver-Based Techniques	460
10.4.3	Navigation-Processor-Based Techniques	461
10.5	Aiding, Assistance, and Orbit Prediction	462
10.5.1	Acquisition and Velocity Aiding	463
10.5.2	Assisted GNSS	464
10.5.3	Orbit Prediction	465
10.6	Shadow Matching	465
	References	467

## CHAPTER 11

	Long- and Medium-Range Radio Navigation	473
11.1	Aircraft Navigation Systems	473
11.1.1	Distance Measuring Equipment	474
11.1.2	Range-Bearing Systems	479
11.1.3	Nondirectional Beacons	480
11.1.4	JTIDS/MIDS Relative Navigation	481
11.1.5	Future Air Navigation Systems	481
11.2	Enhanced Loran	481
11.2.1	Signals	482
11.2.2	User Equipment and Positioning	484
11.2.3	Error Sources	487
11.2.4	Differential Loran	488
11.3	Phone Positioning	488
11.3.1	Proximity and Pattern Matching	489
11.3.2	Ranging	490
11.4	Other Systems	491
11.4.1	Iridium Positioning	491



11.4.2	Marine Radio Beacons	492
11.4.3	AM Radio Broadcasts	492
11.4.4	FM Radio Broadcasts	493
11.4.5	Digital Television and Radio	493
11.4.6	Generic Radio Positioning	494
	References	495

## CHAPTER 12

	Short-Range Positioning	499
12.1	Pseudolites	499
12.1.1	In-Band Pseudolites	500
12.1.2	Locata and Terralite XPS	500
12.1.3	Indoor Messaging System	501
12.2	Ultrawideband	501
12.2.1	Modulation Schemes	502
12.2.2	Signal Timing	503
12.2.3	Positioning	504
12.3	Short-Range Communications Systems	506
12.3.1	Wireless Local Area Networks (Wi-Fi)	506
12.3.2	Wireless Personal Area Networks	507
12.3.3	Radio Frequency Identification	508
12.3.4	Bluetooth Low Energy	508
12.3.5	Dedicated Short-Range Communication	509
12.4	Underwater Acoustic Positioning	509
12.5	Other Positioning Technologies	512
12.5.1	Radio	512
12.5.2	Ultrasound	512
12.5.3	Infrared	512
12.5.4	Optical	513
12.5.5	Magnetic	513
	References	513

## CHAPTER 13

	Environmental Feature Matching	517
13.1	Map Matching	519
13.1.1	Digital Road Maps	520
13.1.2	Road Link Identification	521
13.1.3	Road Positioning	526
13.1.4	Rail Map Matching	527
13.1.5	Pedestrian Map Matching	528
13.2	Terrain-Referenced Navigation	530
13.2.1	Sequential Processing	531
13.2.2	Batch Processing	532
13.2.3	Performance	535
13.2.4	Laser TRN	535



	13.2.5	Sonar TRN	536
	13.2.6	Barometric TRN	537
	13.2.7	Terrain Database Height Aiding	537
13.3		Image-Based Navigation	538
	13.3.1	Imaging Sensors	539
	13.3.2	Image Feature Comparison	541
	13.3.3	Position Fixing Using Individual Features	543
	13.3.4	Position Fixing by Whole-Image Matching	546
	13.3.5	Visual Odometry	546
	13.3.6	Feature Tracking	548
	13.3.7	Stellar Navigation	548
13.4		Other Feature-Matching Techniques	550
	13.4.1	Gravity Gradiometry	551
	13.4.2	Magnetic Field Variation	552
	13.4.3	Celestial X-Ray Sources	552
		References	552

## CHAPTER 14

		INS/GNSS Integration	559
14.1		Integration Architectures	560
	14.1.1	Correction of the Inertial Navigation Solution	562
	14.1.2	Loosely Coupled Integration	566
	14.1.3	Tightly Coupled Integration	567
	14.1.4	GNSS Aiding	569
	14.1.5	Deeply Coupled Integration	571
14.2		System Model and State Selection	573
	14.2.1	State Selection and Observability	574
	14.2.2	INS State Propagation in an Inertial Frame	577
	14.2.3	INS State Propagation in an Earth Frame	582
	14.2.4	INS State Propagation Resolved in a Local Navigation Frame	584
	14.2.5	Additional IMU Error States	589
	14.2.6	INS System Noise	590
	14.2.7	GNSS State Propagation and System Noise	593
	14.2.8	State Initialization	594
14.3		Measurement Models	596
	14.3.1	Loosely Coupled Integration	598
	14.3.2	Tightly Coupled Integration	602
	14.3.3	Deeply Coupled Integration	606
	14.3.4	Estimation of Attitude and Instrument Errors	614
14.4		Advanced INS/GNSS Integration	615
	14.4.1	Differential GNSS	615
	14.4.2	Carrier-Phase Positioning	616
	14.4.3	GNSS Attitude	618
	14.4.4	Large Heading Errors	619

14.4.5	Advanced IMU Error Modeling	621
14.4.6	Smoothing	622
	References	622

## CHAPTER 15

	INS Alignment, Zero Updates, and Motion Constraints	627
15.1	Transfer Alignment	627
15.1.1	Conventional Measurement Matching	629
15.1.2	Rapid Transfer Alignment	631
15.1.3	Reference Navigation System	633
15.2	Quasi-Stationary Alignment	634
15.2.1	Coarse Alignment	634
15.2.2	Fine Alignment	637
15.3	Zero Updates	638
15.3.1	Stationary-Condition Detection	638
15.3.2	Zero Velocity Update	639
15.3.3	Zero Angular Rate Update	640
15.4	Motion Constraints	641
15.4.1	Land Vehicle Constraints	641
15.4.2	Pedestrian Constraints	643
15.4.3	Ship and Boat Constraint	644
	References	644

## CHAPTER 16

	Multisensor Integrated Navigation	647
16.1	Integration Architectures	647
16.1.1	Cascaded Single-Epoch Integration	648
16.1.2	Centralized Single-Epoch Integration	651
16.1.3	Cascaded Filtered Integration	652
16.1.4	Centralized Filtered Integration	654
16.1.5	Federated Filtered Integration	655
16.1.6	Hybrid Integration Architectures	658
16.1.7	Total-State Kalman Filter Employing Prediction	659
16.1.8	Error-State Kalman Filter	661
16.1.9	Primary and Reversionary Moding	663
16.1.10	Context-Adaptive Moding	665
16.2	Dead Reckoning, Attitude, and Height Measurement	666
16.2.1	Attitude	667
16.2.2	Height and Depth	673
16.2.3	Odometry	674
16.2.4	Pedestrian Dead Reckoning Using Step Detection	677
16.2.5	Doppler Radar and Sonar	680
16.2.6	Visual Odometry and Terrain-Referenced Dead Reckoning	682
16.3	Position-Fixing Measurements	682
16.3.1	Position Measurement Integration	683
16.3.2	Ranging Measurement Integration	685



16.3.3	Angular Measurement Integration	690
16.3.4	Line Fix Integration	694
16.3.5	Handling Ambiguous Measurements	695
16.3.6	Feature Tracking and Mapping	697
16.3.7	Aiding of Position-Fixing Systems	698
	References	699

## CHAPTER 17

	Fault Detection, Integrity Monitoring, and Testing	701
17.1	Failure Modes	702
17.1.1	Inertial Navigation	702
17.1.2	Dead Reckoning, Attitude, and Height Measurement	702
17.1.3	GNSS	703
17.1.4	Terrestrial Radio Navigation	703
17.1.5	Environmental Feature Matching and Tracking	704
17.1.6	Integration Algorithm	704
17.1.7	Context	705
17.2	Range Checks	705
17.2.1	Sensor Outputs	705
17.2.2	Navigation Solution	706
17.2.3	Kalman Filter Estimates	706
17.3	Kalman Filter Measurement Innovations	706
17.3.1	Innovation Filtering	707
17.3.2	Innovation Sequence Monitoring	709
17.3.3	Remedying Biased State Estimates	711
17.4	Direct Consistency Checks	712
17.4.1	Measurement Consistency Checks and RAIM	713
17.4.2	Parallel Solutions	715
17.5	Infrastructure-Based Integrity Monitoring	719
17.6	Solution Protection and Performance Requirements	720
17.7	Testing	724
17.7.1	Field Trials	724
17.7.2	Recorded Data Testing	725
17.7.3	Laboratory Testing	725
17.7.4	Software Simulation	725
	References	726

## CHAPTER 18

	Applications and Future Trends	729
18.1	Design and Development	729
18.2	Aviation	731
18.3	Guided Weapons and Small UAVs	733
18.4	Land Vehicle Applications	733
18.5	Rail Navigation	734
18.6	Marine Navigation	735
18.7	Underwater Navigation	737

---

18.8	Spacecraft Navigation	737
18.9	Pedestrian Navigation	738
18.10	Other Applications	739
18.11	Future Trends	740
	References	741
	List of Symbols	743
	Acronyms and Abbreviations	751
	About the Author	757
	DVD Contents	759
	Index	763