

MEMS-Based Integrated Navigation

Priyanka Aggarwal
Zainab Syed
Aboelmagd Noureldin
Naser El-Sheimy



**ARTECH
H O U S E**

BOSTON | LONDON
artechhouse.com

Fachbereich 13
(TU Darmstadt)



62516070

Contents

Preface	xi
<hr/>	<hr/>
1 Microelectromechanical Systems (MEMS)	1
1.1 Introduction	1
1.2 Different Applications of MEMS Devices	3
1.2.1 Electric Wheelchairs	3
1.2.2 Personnel Tracking and Navigation	3
1.2.3 Agriculture	4
1.2.4 Event Data Recorder	4
1.2.5 Wildlife and Livestock Tracking	5
1.2.6 Patient Monitoring	5
1.2.7 Electronic Stability Control	6
1.2.8 Supplemental/Secondary Restraint System	6
1.2.9 Land Vehicle Navigation	6
1.3 Aided MEMS-Based Inertial Navigation	7
1.3.1 Aiding Sources in Coordinate Domain	7
1.3.2 Aiding Sources in Velocity Domain	10
1.3.3 Aiding Sources in Attitude Domain	11
References	12
<hr/>	<hr/>
2 MEMS Inertial Sensors	15
2.1 Introduction	15
2.2 Accelerometers	16
2.2.1 Working Principle for MEMS Accelerometers	17
2.2.2 Classifications of Accelerometers	19

2.3 Gyroscopes	21
2.3.1 Principle of MEMS Gyroscopes	21
2.3.2 Classification of MEMS Gyroscopes	22
2.4 MEMS Inertial Sensors for the Most Economical Land Navigation	24
2.5 Method to Compute Minimum Sensors	26
2.6 Results and Analysis	29
2.6.1 Drift Errors Without NHC	29
2.6.2 Drift Errors with NHC	31
References	32

3 MEMS Inertial Sensors Errors	35
3.1 Introduction	35
3.2 Systematic Errors	36
3.2.1 Bias	37
3.2.2 Input Sensitivity or Scale Factor	38
3.2.3 Nonorthogonality/Misalignment Errors	39
3.2.4 Run-to-Run (Repeatability) Bias/Scale Factor	41
3.2.5 In Run (Stability) Bias/Scale Factor	42
3.2.6 Temperature-Dependent Bias/Scale Factor	43
3.3 Calibration of Systematic Sensor Errors	43
3.3.1 6-Position Static Test	44
3.3.2 Angular Rate Test	45
3.3.3 Thermal Calibration Test	46
3.4 Random/Stochastic Errors	53
3.4.1 Examples of Random Processes	53
3.5 Stochastic Modeling	57
3.5.1 Autocorrelation Function	58
3.5.2 Allan Variance Methodology	58

3.6 Sensors Measurement Models	60
3.6.1 Accelerometer Measurement Model	61
3.6.2 Gyroscope Measurement Model	61
References	62
4 Initial Alignment of MEMS Sensors	63
4.1 Introduction	63
4.2 Considerations for MEMS Sensor Navigation	65
4.3 Portable Navigation System	66
4.4 Economical Considerations	68
4.4.1 Economically Desirable Configuration	68
4.4.2 Complete Six DOF IMU—Economically Less Desirable	74
4.5 Absolute Alignment	77
4.5.1 Static Alignment for MEMS Sensors	77
4.5.2 Static Alignment Example	78
4.6 Velocity Matching Alignment	79
4.6.1 GPS Derived Heading Example	80
4.7 Transfer Alignment	80
References	81
5 Navigation Equations	83
5.1 Introduction—Mathematical Relations and Transformations Between Frames	84
5.1.1 e -Frame to i -Frame	84
5.1.2 ENU l -Frame to e -Frame	85
5.1.3 NED l -Frame to e -Frame	87
5.1.4 b -Frame to ENU l -Frame	88
5.1.5 b -Frame to NED l -Frame	89

5.2 Motion Modeling in the <i>l</i> -Frame	90
5.2.1 ENU Realization	90
5.2.2 NED Realization	95
5.3 Solving Mechanization Equations	96
5.3.1 Classical Method	96
5.3.2 Half-Interval Method	97
References	97
6 Aiding MEMS-Based INS	99
6.1 Introduction	99
6.1.1 Loosely Coupled Mode of Integration	101
6.1.2 Tightly Coupled Integration	101
6.2 Introduction to Kalman Filter	102
6.2.1 Dynamic Model	103
6.2.2 Measurement Model	105
6.3 Kalman Filter Algorithm	105
6.3.1 The Prediction Stage	105
6.3.2 The Update Stage	106
6.4 Introduction to Extended Kalman Filter	106
6.4.1 Linearization	107
6.4.2 EKF Limitations	110
References	112
7 Artificial Neural Networks	115
7.1 Introduction	115
7.2 Types of ANNs	117
7.2.1 Multilayer Perception Neural Network (MLPNN)	118
7.2.2 Radial Basis Function Neural Network (RBFNN)	120
7.2.3 Adaptive Neuro Fuzzy Inference System (ANFIS)	124

7.3 Whole Navigation States Architecture	126
7.3.1 Example of Position Update Architecture	127
7.3.2 Example of Position and Velocity Update Architecture	128
7.4 Navigation Error States Architecture	128
7.4.1 Architecture for INS/GPS Integration	130
7.4.2 System Implementation	132
7.4.3 The Combined $P - \delta P$ and $V - \delta V$ Architecture for INS/GPS Integration	133
7.4.4 ANN/KF Augmented Module for INS/GPS Integration	135
References	137

8 Particle Filters	139
8.1 Introduction	139
8.2 The Monte Carlo Principle	144
8.3 Importance Sampling Method	144
8.4 Resampling Methods	146
8.4.1 Simple Random Resampling	148
8.4.2 Systematic Resampling (SR)	148
8.4.3 Stratified Resampling	149
8.4.4 Residual Resampling	149
8.5 Basic Particle Filters	149
8.6 Types of Particle Filters	150
8.6.1 Extended Particle Filter (EPF) and Unscented Particle (UPF) Filters	150
8.6.2 Rao-Blackwellized Particle Filter (RBPF)	156
8.6.3 Likelihood Particle Filter (LPF)	156
8.6.4 Regularized Particle Filter (RPF)	157
8.6.5 Gaussian Particle Filter (GPE) and Gaussian Sum Particle Filter (GSPF)	157
8.7 Hybrid Extended Particle Filter	158

8.7.1 Zero Velocity Condition Detection Algorithm	159
8.7.2 Algorithm of the Hybrid Extended Particle Filter	160
8.7.3 HEPF Results	162
8.7.4 Partial Sensor Configuration	167
References	169

**Appendix: Linearization Process for the EKF
for Low-Cost Navigation****173**

A.1 System Model for Loosely Coupled Approach	173
A.1.1 Attitude Errors	174
A.1.2 Velocity Linearization	175
A.1.3 Position Linearization	177
A.1.4 Sensor Errors	177
A.2 GPS Measurement Model	178
A.3 System Model for the Tightly Coupled Approach	178
A.4 The Update Stage	183
A.5 Pseudorange and Doppler Corrections	184
References	184

About the Authors**187**

Index**189**