

Contents

	<i>Preface</i>	<i>page xv</i>
	<i>List of Acronyms</i>	<i>xvii</i>
1	Introduction to Autonomous Space Vehicles and Robotics	1
	1.1 Space Exploration: The Unmanned Spacecraft That Ventured into Space	1
	1.2 Exploring Mars	7
	1.3 Robotic Spacecraft for Planetary Landing and Exploration	9
	1.4 Exploring a Comet	10
	1.5 Grabbing an Asteroid	11
	1.6 Routing Space Debris	13
	1.7 Venturing into Deep Space: Spacecraft with Endurance	15
	1.8 Planetary Rovers and Robot Walkers, Hoppers, and Crawlers for Exploration	15
	1.9 Underwater Rovers and Aquanauts	16
	1.10 Humanoid Space Robots and Robonauts	16
	1.11 Robot Arms for Tele-Robotic Servicing	18
	1.12 Tumbling Cubes	23
	1.13 Collaborative Robotic Systems	23
	1.14 The Meaning of Autonomy	24
	1.15 Dynamics and Control of Space Vehicles	26
	1.16 The Future	26
	References	27
2	Space Vehicle Orbit Dynamics	28
	2.1 Orbit Dynamics: An Introduction	28
	2.2 Planetary Motion: The Two-Body Problem	28
	2.2.1 Kepler's Laws	28
	2.2.2 Keplerian Motion of Two Bodies	29
	2.2.3 Orbital Elements	34
	2.2.4 Two-Body Problem in a Plane: Position and Velocity in an Elliptic Orbit	35
	2.2.5 Orbital Energy: The Visa-Viva Equation	39
	2.2.6 Position and Time in Elliptic Orbit	41
	2.2.7 Lambert's Theorem	42
		vii

2.2.8	Orbit Inclination, Argument of the Ascending Node, Argument of the Perigee, and True Anomaly	43
2.2.9	The f and g Functions	46
2.3	Types of Orbits	47
2.3.1	Geosynchronous Earth Orbits	47
2.3.2	Geostationary Orbits	47
2.3.3	Geosynchronous Transfer Orbit	47
2.3.4	Polar Orbits	48
2.3.5	Walking Orbits	48
2.3.6	Sun Synchronous Orbits	48
2.4	Impulsive Orbit Transfer	48
2.4.1	Co-Planar Hohmann Transfer	49
2.4.2	Non-Planar Hohmann Transfer	51
2.5	Preliminary Orbit Determination	53
2.5.1	Two Position Vectors of the Satellite	53
2.5.2	Three Position Vectors of the Satellite	54
2.5.3	Two Sets of Observations of the Range at Three Locations	55
2.5.4	Range and Range Rates Measured at Three Locations	56
2.6	Lambert's Problem	56
2.7	Third Body and Other Orbit Perturbations	58
2.7.1	Circular Restricted Three-Body Problem	59
2.8	Lagrange Planetary Equations	62
2.8.1	Geostationary Satellites	65
2.9	Gauss' Planetary Equations: Force Perturbations	65
2.9.1	Effect of Atmospheric Drag	67
2.9.2	Space Shuttle in a Low Earth Orbit	68
2.9.3	Lunar Orbits	69
2.9.4	Third-Body Perturbation and Orbital Elements in Earth Orbit	71
2.10	Spacecraft Relative Motion	71
2.10.1	Hill-Clohessy-Wiltshire Equations	71
2.10.2	Linear Orbit Theory with Perturbations	74
2.10.3	Nonlinear Equations of Relative Motion with Perturbations	75
2.10.4	Nonlinear Equations of Relative Motion with Reference to an Elliptic Orbit	77
2.10.5	The Extended Nonlinear Tschauner-Hempel Equations	81
2.11	Orbit Control	85
2.11.1	Delaunay Elements	86
2.11.2	Non-Singular Element Sets	86
2.11.3	Equinoctial Elements	87
2.11.4	Orbital Elements with the Orbit Plane Quaternion Replacing the Euler Angles in the 3–1–3 Sequence	88
2.11.5	Gauss Planetary Equations in Terms of Orbit Quaternion Parameters	91
2.11.6	Other Nonclassical Elements	92

2.12	Orbit Maneuvers	93
2.12.1	Feedback Control Laws for Low-Thrust Transfers Based on the GPE	94
2.12.2	Feedback Control Laws with Constraints on the Control Accelerations	98
2.13	Interception and Rendezvous	100
2.14	Advanced Orbit Perturbations	102
2.14.1	Gravitational Potential of a Perfect Oblate Spheroid Model of the Central Body	102
2.14.2	Gravitational Potential due to a Central Body's Real Geometry	103
2.14.3	Real Drag Acceleration Acting on the Actual Satellite	104
2.14.4	Third-Body Perturbations	105
2.14.5	Solar Radiation Pressure	106
2.15	Launch Vehicle Dynamics: Point Mass Model	107
2.15.1	Systems with Varying Mass	107
2.15.2	Basic Rocket Thrust Equation	108
2.16	Applications of the Rocket Equation	109
2.16.1	Time to Burnout, Velocity, and Altitude in the Boost Phase	109
2.16.2	Time and Altitude in the Coast Phase	110
2.16.3	Delta-Vee Solution	110
2.16.4	Mass-Ratio Decay	110
2.16.5	Gravity Loss	111
2.16.6	Specific Impulse	111
2.17	Effects of Mass Expulsion	111
2.17.1	Staging and Payloads	112
2.18	Electric Propulsion	112
2.18.1	Application to Mission Design	114
	References	115
3	Space Vehicle Attitude Dynamics and Control	118
3.1	Fundamentals of Satellite Attitude Dynamics	118
3.2	Rigid Body Kinematics and Kinetics	118
3.2.1	Coordinate Frame Definitions and Transformations	118
3.2.2	Definition of Frames/ Rotations	118
3.2.3	The Inertial (<i>i</i>) Frame <i>X–Y–Z</i>	119
3.2.4	The Local Rotating (<i>r</i>) or Orbiting Frame <i>x–y–z</i>	119
3.2.5	The Body (<i>b</i>) Frame <i>b₁– b₂–b₃</i>	119
3.2.6	Defining the Body Frame	120
3.2.7	Three- and Four-Parameter Attitude Representations	120
3.3	Spacecraft Attitude Dynamics	121
3.4	Environmental Disturbances	123
3.4.1	Gravity Gradient Torques	123
3.4.2	Aerodynamic Disturbance Torques	125
3.4.3	Solar Wind and Radiation Pressure	126

3.4.4	Thruster Misalignments	126
3.4.5	Magnetic Disturbance Torques	126
3.4.6	Control Torques	129
3.5	Numerical Simulation	129
3.6	Spacecraft Stability	129
3.6.1	Linearized Attitude Dynamic Equation for Spacecraft in Low Earth Orbit	129
3.6.2	Gravity-Gradient Stabilization	130
3.6.3	Stability Analysis of the Spacecraft	131
3.6.4	Influence of Dissipation of Energy on Stability	133
3.7	Introduction and Overview of Spacecraft Attitude Control Concepts	133
3.7.1	Objectives of Attitude Active Stabilization and Control	134
3.7.2	Actuators and Thrusters for Spacecraft Attitude Control	134
3.7.3	Active and Passive Stabilization Techniques	135
3.7.4	Use of Thrusters on Spinning Satellites	136
3.8	Momentum and Reaction Wheels	136
3.8.1	Stabilization of Spacecraft	137
3.8.2	Passive Control with a Gravity-Gradient Boom or a Yo-Yo Device	139
3.8.3	Reaction Wheel Stabilization	143
3.8.4	Momentum Wheel and Dual-Spin Stabilization	145
3.8.5	Momentum Wheel Approximation with MW along Axis 1	148
3.8.6	Control Moment Gyroscopes	149
3.8.7	Example of Control System Based on Reaction Wheels	149
3.8.8	Quaternion Representation of Attitude	152
3.8.9	The Relations between the Quaternion Rates and Angular Velocities	154
3.8.10	The Gravity Gradient Stability Equations in Terms of the Quaternion	157
3.9	Definition of the General Control Problem with CMG Actuation	158
3.9.1	Nonlinear Attitude Control Laws	162
3.9.2	Minimum Time Maneuvers	163
3.9.3	Passive Damping Systems	163
3.9.4	Spin Rate Damping	164
3.10	Magnetic Actuators	164
3.10.1	Active Control with Magnetic Actuators	165
	References	165
4	Manipulators on Space Platforms: Dynamics and Control	167
4.1	Review of Robot Kinematics	167
4.1.1	The Total Moment of Momentum and Translational Momentum	167
4.1.2	The Screw Vector and the Generalized Jacobian Matrix of the Manipulator	169

4.2	Fundamentals of Robot Dynamics: The Lagrangian Approach	170
4.3	Other Approaches to Robot Dynamics Formulation	178
4.4	Fundamentals of Manipulator Deployment and Control	179
4.5	Free-Flying Multi-Link Serial Manipulator in Three Dimensions	183
4.6	Application of the Principles of Momentum Conservation to Satellite-Manipulator Dynamics	185
4.7	Application of the Lagrangian Approach to Satellite-Manipulator Dynamics	185
4.8	Gravity-Gradient Forces and Moments on an Orbiting Body	187
	4.8.1 Gravity-Gradient Moment Acting on the Satellite Body and Manipulator Combined	188
4.9	Application to Satellite-Manipulator Dynamics	189
4.10	Dynamic Stability of Satellite-Manipulator Dynamics with Gravity-Gradient Forces and Moment	191
4.11	Three-Axis Control of a Satellite's Attitude with an Onboard Robot Manipulator	196
	4.11.1 Rotation Rate Synchronization Control	196
	References	203
5	Kinematics, Dynamics, and Control of Mobile Robot Manipulators	206
5.1	Kinematics of Wheeled Mobile Manipulators: Non-Holonomic Constraints	206
5.2	Dynamics of Manipulators on a Moving Base	209
5.3	Dynamics of Wheeled Mobile Manipulators	209
	5.3.1 Manipulability	211
	5.3.2 Tip Over and Dynamic Stability Issues	212
5.4	Dynamic Control for Path Tracking by Wheeled Mobile Manipulators	215
5.5	Decoupled Control of the Mobile Platform and Manipulator	222
5.6	Motion Planning for Mobile Manipulators	223
5.7	Non-Holonomic Space Manipulators	224
	References	227
6	Planetary Rovers and Mobile Robotics	229
6.1	Planetary Rovers: Architecture	229
	6.1.1 Vehicle Dynamics and Control	230
	6.1.2 Mission Planning	231
	6.1.3 Propulsion and Locomotion	232
	6.1.4 Planetary Navigation	233
6.2	Dynamic Modeling of Planetary Rovers	233
	6.2.1 Non-Holonomic Constraints	233
	6.2.2 Vehicle Generalized Forces	235
	6.2.3 Modeling the Suspension System and Limbs	235
	6.2.4 Platform Kinetic and Potential Energies	240

6.2.5	Assembling the Vehicle's Kinetic and Potential Energies	242
6.2.6	Deriving the Dynamic Equations of Motion	243
6.2.7	Considerations of Slip and Traction	243
6.3	Control of Planetary Rovers	248
6.3.1	Path Following Control: Kinematic Modeling	248
6.3.2	Estimating Slip	251
6.3.3	Slip-Compensated Path Following Control Law Synthesis	251
6.3.4	The Focused D^* Algorithm	254
	References	254
7	Navigation and Localization	257
7.1	Introduction to Navigation	257
7.1.1	Basic Navigation Activities	257
7.2	Localization, Mapping, and Navigation	258
7.2.1	Introduction to Localization	259
7.3	Random Processes	264
7.3.1	Basics of Probability	269
7.3.2	The Kalman Filter	272
7.3.3	Probabilistic Methods and Essentials of Bayesian Inference	275
7.4	Probabilistic Representation of Uncertain Motion Using Particles	277
7.4.1	Monte Carlo Integration, Normalization, and Resampling	277
7.4.2	The Particle Filter	278
7.4.3	Application to Rover Localization	282
7.4.4	Monte Carlo Localization	284
7.4.5	Probabilistic Localization within a Map, Using Odometry and Range Measurements	285
7.5	Place Recognition and Occupancy Mapping: Advanced Sensing Techniques and Ranging	286
7.5.1	Place Recognition Using Ranging Signatures: Occupancy Mapping of Free Space and Obstacles	287
7.6	The Extended Kalman Filter	287
7.6.1	The Unscented Kalman Filter (UKF)	290
7.7	Nonlinear Least Squares, Maximum Likelihood (ML), Maximum A Posteriori (MAP) Estimation	292
7.7.1	Nonlinear Least Squares Problems Solution Using Gauss-Newton and Levenberg Marquardt Optimization Algorithms	296
7.8	Simultaneous Localization and Mapping (SLAM)	298
7.8.1	Introduction to the Essential Principles and Method of SLAM	298
7.8.2	Multi-Sensor Fusion and SLAM	303
7.8.3	Large-Scale Map Building via Sub-Maps	304
7.8.4	Vision-Based SLAM	305
7.9	Localization in Space and Mobile Robotics	305
	References	306

8	Sensing and Estimation of Spacecraft Dynamics	308
8.1	Introduction	308
8.2	Spacecraft Attitude Sensors	308
8.2.1	The Principle of Operation of Accelerometers and Gyroscopes	308
8.2.2	Magnetic Field Sensor	311
8.2.3	Sun Sensors	312
8.2.4	Earth Horizon Sensors	312
8.2.5	Star Sensors	313
8.2.6	Use of Navigation Satellite as a Sensor for Attitude Determination	313
8.3	Attitude Determination	315
8.4	Spacecraft Large Attitude Estimation	319
8.4.1	Attitude Kinematics Process Modeling	320
8.4.2	Codeless Satellite Navigation Attitude Sensor Model	322
8.4.3	Application of Nonlinear Kalman Filtering to Attitude Estimation	324
8.5	Nonlinear State Estimation for Spacecraft Rotation Rate Synchronization with an Orbiting Body	328
8.5.1	Chaser Spacecraft's Attitude Dynamics	330
8.5.2	Relative Attitude Dynamics	332
8.5.3	Nonlinear State Estimation	334
8.5.4	The Measurements	336
8.5.5	The Controller Synthesis	338
8.6	Sensors for Localization	339
8.7	Sensors for Navigation	341
8.7.1	Imaging Sensors and Cameras	342
	References	344
	<i>Index</i>	349