

Dynamics and Control of Autonomous Space Vehicles and Robotics

This book presents the established principles underpinning space robotics (conservation of momentum and energy, stability) in a thorough and modern fashion. Chapters build from general physical foundations through an extensive treatment of kinematics of multi-body systems, and then to conservation principles in dynamics. The latter part of the book focuses on real-life applications related to space systems.

Drawing upon years of practical experience and using numerous solved examples, illustrative applications, and MATLAB, Ranjan Vepa discusses:

- Basic space mechanics and the dynamics of space vehicles.
- Conservation and variational principles in dynamics and in control theory that can be applied to a range of space vehicles and robotic systems.
- A systematic presentation of the application of dynamics and control theory to real spacecraft systems.

Dr. Ranjan Vepa is currently a senior lecturer at Queen Mary University of London. He is the author of five books: *Biomimetic Robotics*; *Dynamics of Smart Structures*; *Dynamic Modeling, Simulation and Control of Energy Generation*; *Flight Dynamics Simulation and Control of Aircraft*; and *Nonlinear Control of Robots and UAVs*. His research interests include applications in space robotics, electric aircraft, and autonomous vehicles. He teaches advanced courses on robotics, aeroelasticity, advanced flight control and simulation, and spacecraft design, maneuvering, and orbital mechanics.

Cambridge University Press

978-1-108-42284-0 — Dynamics and Control of Autonomous Space Vehicles and Robotics

Ranjan Vepa

Frontmatter

[More Information](#)

Dynamics and Control of Autonomous Space Vehicles and Robotics

RANJAN VEPA

Queen Mary University of London



CAMBRIDGE UNIVERSITY PRESS

University Printing House, Cambridge CB2 8BS, United Kingdom
One Liberty Plaza, 20th Floor, New York, NY 10006, USA
477 Williamstown Road, Port Melbourne, VIC 3207, Australia
314–321, 3rd Floor, Plot 3, Splendor Forum, Jasola District Centre, New Delhi – 110025, India
79 Anson Road, #06-04/06, Singapore 079906

Cambridge University Press is part of the University of Cambridge.

It furthers the University's mission by disseminating knowledge in the pursuit of education, learning, and research at the highest international levels of excellence.

www.cambridge.org
Information on this title: www.cambridge.org/9781108422840
DOI: 10.1017/9781108525404

© Ranjan Vepa 2019

This publication is in copyright. Subject to statutory exception and to the provisions of relevant collective licensing agreements, no reproduction of any part may take place without the written permission of Cambridge University Press.

First published 2019

Printed in the United Kingdom by TJ International Ltd. Padstow Cornwall

A catalogue record for this publication is available from the British Library.

Library of Congress Cataloging-in-Publication Data

Names: Vepa, Ranjan, author.

Title: Dynamics and control of autonomous space vehicles and robotics / Ranjan Vepa.

Description: Cambridge, United Kingdom ; New York, NY, USA : University Printing House, 2019. |

Includes bibliographical references and index.

Identifiers: LCCN 2018046546 | ISBN 9781108422840 (hardback)

Subjects: LCSH: Roving vehicles (Astronautics) | Autonomous robots. | Space vehicles—Dynamics. | Space vehicles—Control systems.

Classification: LCC TL475 .V47 2019 | DDC 629.43—dc23

LC record available at <https://lcn.loc.gov/2018046546>

ISBN 978-1-108-42284-0 Hardback

Cambridge University Press has no responsibility for the persistence or accuracy of URLs for external or third-party internet websites referred to in this publication and does not guarantee that any content on such websites is, or will remain, accurate or appropriate.

Cambridge University Press

978-1-108-42284-0 — Dynamics and Control of Autonomous Space Vehicles and Robotics

Ranjan Vepa

Frontmatter

[More Information](#)

To my parents, Narasimha Row and Annapurna, and to my family

Cambridge University Press

978-1-108-42284-0 — Dynamics and Control of Autonomous Space Vehicles and Robotics

Ranjan Vepa

Frontmatter

[More Information](#)

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

Cambridge University Press

978-1-108-42284-0 — Dynamics and Control of Autonomous Space Vehicles and Robotics

Ranjan Vepa

Frontmatter

[More Information](#)

Preface

This book is about the stability and control of satellites carrying robotic manipulators as well as the stability and control of the manipulators themselves. The book also addresses the issues related to the stability and control of planetary rovers that are used to explore the environment of a planet's surface. The book begins with an introduction to "Autonomous Space Vehicles and Robotics," followed by a chapter on "Space Vehicle Orbit Dynamics." Chapter 3 is entitled "Space Vehicle Attitude Dynamics and Control." The next chapter is about the dynamics of manipulators on board a spacecraft and is entitled "Manipulators on Space Platforms: Dynamics and Control." In particular, the focus of this chapter is on establishing the dynamic models of the robotic manipulators with a finite number of degrees of freedom operating on board a space vehicle. The dynamic stability and control of the coupled manipulator and satellite dynamics are also discussed in this chapter. "Kinematics, Dynamics, and Control of Mobile Robot Manipulators" is discussed in the next chapter, while Chapter 6 is devoted to the dynamics and control of planetary rovers. This chapter deals with mobile robots and is entitled "Planetary Rovers and Mobile Robotics."

The focus of the penultimate chapter is on "Navigation and Localization," and deals with specialized issues related to autonomous navigation and the issue of localization in mobile robotics, including triangulation, trilateration, dead reckoning, localization based on significant environmental characteristics, odometry, statistical and probabilistic approaches, Markov localization, and the use of Kalman filters for localization. Chapter 8 is about "Sensing and Estimation of Spacecraft Dynamics." In particular, the various types of sensors that are typical to the space environment and the problems associated with the estimation of the spacecraft's position and orientation will be discussed here.

I would like to thank my colleagues, in the School of Engineering and Material Science, at Queen Mary University of London, and Professor V. V. Toropov, in particular, for his support in this endeavor. I would also like to express my special thanks to Steven Elliot, Senior Editor, Aeronautical, Biomedical, Chemical, and Mechanical Engineering, Cambridge University Press, New York, for his enthusiastic support for this project.

I would like to thank my wife, Sudha, for her love, understanding, and patience. Her encouragement was a principal factor that provided the motivation to complete the

project. I would like to thank my brother Dr. Kosla Vepa, who was always willing to discuss issues related to astronautics and space mechanics. Finally, I must add that my interest in the kinematics of mechanisms and in robotics was inherited from my late father many years ago. To him I owe my deepest debt of gratitude. This book is dedicated to his memory.

Acronyms

AC	Alternating current
AKM	Apogee kick motor
AUV	Autonomous underwater vehicle
BLF	Barrier Lyapunov function
CDM	Code division multiplexing
CG	Center of gravity
CM	Center of mass
CP	Center of (aerodynamic) pressure
DC	Direct current
DOP	Dilution of precision
ECEF	Earth centered earth fixed
ECI	Earth centered inertial
EDM	Enhanced disturbance map
EKF	Extended Kalman filter
ESA	European space agency
FDMA	Frequency division multiple access
GDOP	Geometric dilution of precision
GEO	Geostationary earth orbit
GPE	Gauss planetary equations
GPS	Global positioning system
GTO	Geosynchronous transfer orbit
HCW	Hill Clohessy Wiltshire
HDOP	Horizontal dilution of precision
IAGA	International association of geomagnetism and aeronomy
IGRF	International geomagnetic reference field
IR	Infra-red
ISS	<i>International space station</i>
JAXA	Japan aerospace exploration agency
JPL	Jet propulsion laboratory
LADAR	LASER detection and ranging
LASER	Light amplification by stimulated emission of radiation
LEO	Low earth orbit
LERM	Linear equations of relative motion
LIDAR	Light detection and ranging

LORAN	Long range navigation
LPE	Lagrange planetary equations
LQR	Linear-quadratic regulator
LVLH	Local vertical local horizontal
MER	Mars exploration rover
NASA	National aeronautics and space administration
NERM	Nonlinear equations of relative motion
PF	Particle filter
RAAN	Right ascension of the ascending node
RADAR	Radio detection and ranging
ROSCOSMOS	Russian federal space agency
ROV	Remotely operated vehicle
RTG	Radio-isotope thermoelectric generator
SI	Système internationale
SLAM	Simultaneous localization and navigation
SONAR	Sound navigation and ranging
SRP	Solar radiation pressure
SSO	Sun synchronous orbit
SSRMS	Space shuttle remote manipulator system
TDOP	Time dilution of precision
TLE	Two line elements
TVC	Thruster vectoring control
UKF	Unscented Kalman filter
VDOP	Vertical dilution of precision