## WHO CAN USE THIS BOOK?

This book reads more as a research monograph than a graduate textbook. Hence, it is intended for university researchers (graduate and post-graduate level) in automatic control systems and especially those who work at the intersection of two critical and rapidly developing fields: control theory and network analysis. It could also be used as a supplementary text in an advanced graduate course in network control systems, or as an independent resource.

Moreover, it will also be handy to practitioners in industry, since several instances of NCSs exist in the automotive industry (the authors of the book have worked closely with Jaguar and Land Rover research), the aerospace industry, and in process control. It can also be useful to engineers working with chemical processes, industrial control, and nuclear engineering.

## REVIEWER INFORMATION

***Kyriakos G. Vamvoudakis*** (kyriakos@ece.ucsb.edu) received the Diploma (five-year degree) in electronic and computer engineering from the Technical University of Crete, Greece, in 2006 with highest honors and the M.Sc. and Ph.D. degrees in electrical engineering from the University of Texas in 2008 and 2011, respectively. From May 2011 to January 2012, he was an adjunct professor and faculty research associate at The University of Texas at Arlington and at the Automation and Robotics Research Institute. He is currently working as a project research scientist at the Center for Control, Dynamical Systems, and Computation at the University of California, Santa Barbara. His research focuses on optimal control, adaptive control, neural network feedback control, game-theory-based network security, multiagent optimization, and approximate dynamic programming. He is the coauthor of one patent, 12 book chapters, 75 technical publications, and the book *Optimal Adaptive Control and Differential Games by Reinforcement Learning Principles*. He is the recipient of several international awards, including the Best Paper Award for Autonomous/Unmanned Vehicles at the 27th Army Science Conference in 2010, the Best Presentation Award at the World Congress of Computational Intelligence in 2010, and the Best Researcher Award from the Automation and Robotics Research Institute in 2011. He is currently a member of the IEEE Control Systems Society Technical Committee on Intelligent Control, a member of the IEEE Computational Intelligence Society Technical Committee on Approximate Dynamic Programming and Reinforcement Learning, editor-in-chief for the Communications in Control Science and Engineering, an associate editor of the *Journal of Optimization Theory and Applications*, an associate editor on the IEEE Control Systems Society Conference Editorial Board, a registered electrical/computer engineer (PE), and a member of the Technical Chamber of Greece.

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## Spacecraft Dynamics and Control: An Introduction


by ANTON H.J. DE RUITER, CHRISTOPHER J. DAMAREN, and JAMES R. FORBES

Reviewed by MARCO B. QUADRELLI


When I accepted the task of writing a review for this book, I welcomed it as an opportunity to read a clear and unifying exposition of the basic theory of spacecraft dynamics and control. The more I delved into the book, the more I felt that it needed to be evaluated carefully and put into perspective relative to the several other excellent books on this subject. A few of these books have stood the test of time and will continue to be used in the field by teachers, students, and practitioners. Reference [1] was the first to treat this topic in a unifying manner. Reference [2] uses the attitude control problem as a running example throughout to motivate and illustrate the analysis of dynamic systems. Reference [3] covers orbital dynamics, spacecraft dynamics, and orbital and spacecraft control. The handbook [4] is the first comprehensive presentation of data, theory, and practice in spacecraft attitude analysis.

Reference [5] popularized the "vectrix calculus" approach, where a "vectrix" is an operational technique used to manipulate vectorial quantities that distinguishes


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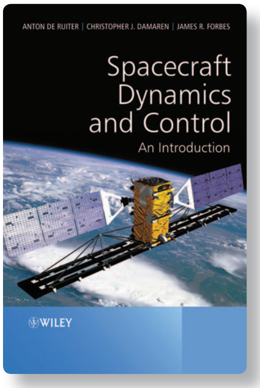


Wiley, 2013, ISBN: 978-1-1183-4236-7, 592 pages, US$105.00.

between the components of a vector and the coordinate basis. Vectrices provide a very useful analysis tool by which results can first be stated in coordinate-free form and then later be projected into appropriate coordinate systems for numerical simulation. Hughes also covers environmental torques encountered in space, energy dissipation analysis, motion equations for several practical spacecraft configurations, rotation matrices and rotational kinematics, on-orbit flight data, and typical attitude control system hardware. Reference [6] describes attitude control of rigid and flexible spacecraft using momentum wheels, spin stabilization, fixed thrusters, and gimbaled engines with a strong emphasis on the mathematical modeling necessary for designing a good feedback control system. Reference [7] provides a comprehensive treatment of orbital mechanics, including orbital estimation, maneuvering, and perturbation analysis. Reference [8] provides a succinct treatment of many topics in spacecraft dynamics including orbital dynamics, entry dynamics, and attitude dynamics. Reference [9] provides a solid foundation in dynamic modeling, analysis, and control of space vehicles. Reference [10] explains the basic theory of spacecraft dynamics and control, as well as practical aspects of controlling a satellite. Reference [11] is a pedagogically clear exposition of the two-body problem, calculating orbital elements from observations, orbital maneuvers, orbital rendezvous, interplanetary missions, and an introduction to spacecraft and rocket dynamics. Reference [12] combines, in a unified manner, a broad coverage of atmospheric and space flight dynamics. Reference [13] presents a unified approach to aircraft, rocket, and spacecraft flight control systems, including chapters on nonlinear and optimal control techniques, numerical solution methods, robust and adaptive guidance and navigation, and attitude control for atmospheric and space flight vehicles. References [14] and [15] present a unified treatment of guidance, dynamics, estimation, and control for surface and subsurface vessels.

*Spacecraft Dynamics and Control: An Introduction* is written, appropriately enough, at an introductory level and covers the basics of spacecraft orbital dynamics, attitude dynamics, and attitude control. The entire treatment of both orbital and attitude dynamics uses vectrix notation [5]. This textbook is written for engineering students and practicing engineers who are equipped with the standard background in mathematics and mechanics, and it is suitable for upper-year undergraduate courses, first-year graduate courses, as well as self-study. I consider this text a valuable addition to the library of both the student and the practitioner. I know of no other text that follows the unique and innovative approach of treating introductory spacecraft dynamics and control by means of vectrix calculus. This book can be considered as a prequel to those wishing to study the more advanced graduate-level text of Hughes [5]. In that it attempts to cover and unify the very broad topic of spacecraft dynamics and control in a single volume, this book is similar in scope to the treatment covered in [3] and [9] but presents the material in a more accessible and pedagogical way. Although the book does contain a few worked examples, it is notably missing exercises at the end of each chapter. In the words of the authors: "…This was a decision made in order to keep the page count down." However, exercises for each chapter are available for download from http://www.wiley.com//legacy/wileychi/deRuiter/index.html. Instructors who plan to use this book to teach a course can also request the solutions manual through the Wiley Web site.

## CONTENTS

This book consists of 26 chapters and two appendices. The exposition is divided into roughly five parts:

- basic kinematics and dynamics of particles and rigid bodies
- orbital mechanics of point mass objects
- spacecraft attitude dynamics
- feedback control theory
- practical applications of the above four to spacecraft control.

Chapter 1, which is on kinematics, covers the basics of vectrix calculus and rotational kinematics. Chapter 2 covers the kinetics of a particles and rigid bodies and makes the distinction between translational and rotational kinetics. Once the kinematics and kinetics of particles and rigid bodies have been described, Chapters 3–10 cover the dynamics of a point mass spacecraft in a Keplerian orbit around a primary gravitational body. Chapter 3 is an introductory treatment of the Keplerian two-body problem and covers the integrals of the motion, Kepler's laws, the time-of-flight equation, and the orbital elements. Chapter 4 addresses the basics of orbital determination, including Lambert's problem. Chapter 5 illustrates how the orbit can be changed by planar and nonplanar impulsive maneuvers and covers the Hohmann and bielliptic transfers. Chapter 6 addresses interplanetary trajectories, the sphere of influence, and the method of patched conics. Chapter 7 introduces orbital perturbation techniques to deal with non-Keplerian orbits. Special orbit types such as the Molniya and sun-synchronous orbits are also covered, and the Gauss variational equations are derived. Chapter 8 is a concise treatment of low-thrust trajectory analysis and design, including how planar and noncoplanar orbit changes can be achieved. Chapter 9 is an introductory treatment of spacecraft formation flying and covers the relative motion between two point masses in different orbits and derives Hill's equations of relative motion. The treatment in this chapter also includes the proximity elliptical and circular orbits, which are used as reference for maneuvering between a chaser and a target spacecraft. Chapter 10 discusses the restricted three-body problem (in the context of the Earth-moon-spacecraft system), including the derivation of the Lagrange points, their stability, and the Jacobi integral.

Chapters 11–17 describe the dynamics and control of a spacecraft modeled as a rigid body. Chapter 11 introduces the spacecraft attitude control problem as the benchmark problem to be analyzed in the sequel. Chapter 12 lists various sources of disturbance torques affecting the attitude of the spacecraft: magnetic, solar radiation pressure, aerodynamic, and gravity-gradient. Chapter 13 discusses the properties of spacecraft motion and its stability under zero external torques, including a discussion of the space and body cones. Chapter 14 considers spin stabilization and the effect of energy dissipation on spin using the energy sink approximation. Chapter 15 introduces the topic of dual-spin spacecraft and the effect of internal energy dissipation on stability. The dual-spin equations of motion are derived, the stability of the equilibrium solutions is analyzed, and the effect of damping on stability is considered. Chapter 16 discusses gravity gradient stabilization of spacecraft.

Chapters 17–23 cover the topic of feedback control theory for linear systems. Chapter 17 addresses the attitude dynamics of a spacecraft. Both a frequency-domain and a time-domain representation of this system under feedback are introduced. System transient behavior is described, and typical control laws are presented, together with how the addition of poles and zeros to the closed-loop transfer function can modify the response. Steady-state response specifications are introduced, and the effect of disturbances and actuator dynamics are also discussed. Chapters 18 and 19 introduce the Routh stability criterion and discuss the stability criterion for a feedback-stabilized spacecraft under proportional-derivative control with actuator dynamics. Chapter 20 describes how the root-locus technique can be used for control design. It covers root-locus shaping due to the poles and zeros introduced by a lead, lag, proportional-derivative, and proportional-integral compensator. The design of the proportional-integral-derivative controller of a spacecraft is discussed as an application. Chapter 21 deals with the frequency-domain representation and frequency response of linear systems. Chapter 22 addresses the concept of relative stability in the frequency domain, polar plots, the Nyquist stability criterion, and the definitions of stability margins. Chapter 23 describes how to synthesize a feedback controller of a linear dynamic system in the frequency domain using fundamental concepts such as the tracking error and control effort. An example is then given of spacecraft feedback control using a proportional-integral-derivative controller. Chapter 24 addresses linear control of a spacecraft considered as a nonlinear system, the nonlinearity arising from its rotational kinematics. The state-space representation and stability analysis based on Lyapunov functions and LaSalle's theorem are introduced. An example of stabilizing a spacecraft's attitude using quaternion and angular rate feedback is then presented.

Chapter 25 covers the topic of spacecraft attitude estimation. It assumes that the trajectory estimation of the vehicle's center of mass is decoupled from its attitude. After a brief review of probability theory, the authors discuss batch approaches to attitude estimation. The Wahba problem, Davenport's q-method, the QUEST algorithm, and the TRIAD algorithm are discussed at length. The discrete-time Kalman filter and the extended Kalman filter are also discussed in detail.

Chapter 26 deals with practical spacecraft attitude control design issues. Various types of attitude sensors and actuators are discussed, including their functional and operational limitations. Analog and digital sun sensors, three-axis magnetometers, Earth sensors, star trackers, and rate sensors are discussed at length. Actuators, including thrusters, magnetic torque rods, reaction wheels, momentum wheels, and control moment gyroscopes, are also covered. A very interesting section on control law implementation follows. This chapter covers practical topics, including how to convert a control law from the frequency domain to the time domain, control law digitization, stability analysis of the resulting digital system, and the effects of sampling and aliasing. The influence of unmodeled dynamics on the system closed-loop stability is discussed, and an example of a spacecraft with flexibility is discussed in detail. The effect of structural damping and flexibility on the open-loop and closed-loop system response is described. Finally, a section on the effects of propellant sloshing on stability closes the chapter.

Appendix A is a review of the basic elements of complex variables and the Laplace transform. Appendix B is a very useful summary of the coupled translational and rotational equations of motion of a space vehicle under a gravitational field, written in a form ready to be implemented in a computer program for simulation.

## SUMMARY

Overall, I consider this book an excellent pedagogical exposition of spacecraft dynamics and control, valuable for a student or professional who has never before been exposed to this material and wants to come up to speed with the basics of orbital mechanics, attitude kinematics and dynamics, and feedback control theory. A very notable feature of this book lies in the successful unifying treatment of spacecraft orbital dynamics, attitude dynamics, and control using the vectrix calculus. For these reasons, I not only strongly recommend this book for students and practitioners, as well as academic and company libraries, but also have no doubt that this book will earn its place amongst the other excellent treatments of the subject mentioned above.

## REVIEWER INFORMATION

***Marco B. Quadrelli*** (Marco.B.Quadrelli@jpl.nasa.gov) has been at the Jet Propulsion Laboratory, California Institute of

Technology, since 1997, where he has worked as research technologist in the Mobility and Robotic Systems Section and in the Guidance and Control Section. He received an M.S. in aeronautics and astronautics from the Massachusetts Institute of Technology and a Ph.D. in aerospace engineering from Georgia Tech in 1996. He has been a visiting scientist at the Harvard-Smithsonian Center for Astrophysics, did post-doctoral work in computational micromechanics at the Institute of Paper Science and Technology in Atlanta, and has been a lecturer in aerospace engineering at the Caltech Graduate Aeronautical Laboratories. His flight project experience includes the Cassini-Huygens Probe Decelerator Design; Deep Space One dynamics analysis and testing; the Mars Aerobot Test Program; the design of the Mars Exploration Rover entry, descent, and landing; the Space Interferometry Mission; the Autonomous Rendezvous Experiment; and the Mars Science Laboratory. He has been involved in spacecraft stability, dynamics, and control of tethered space systems; formation flying; distributed spacecraft and robots; inflatable apertures; hypersonic entry; aeromaneuvering; precision landing with controlled decelerators; adaptive systems for planetary sampling; guidance, navigation, and control of spacecraft swarms; and granular media dynamics and control. His current research interest is exploring innovative dynamics and control concepts for distributed space-robotic systems. He is an AIAA associate fellow and associate editor of the *Journal of Guidance, Control, and Dynamics*.

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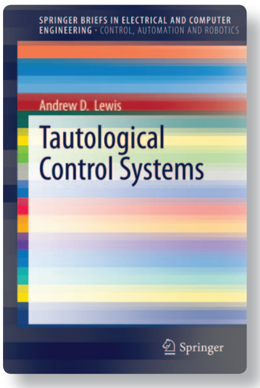
# Book Announcements




Springer, 2014, ISBN: 978-3319086378, 118 pages, US$54.99.

## Tautological Control Systems

by ANDREW D. LEWIS

This monograph presents a description of a new modeling framework for nonlinear and geometric control theory. The framework is intended, and shown, to be feedback invariant. As such, *Tautological Control Systems* provides a platform for understanding fundamental structural problems in geometric control theory. This text discusses a variety of regularity classes (such as Lipschitz, finitely differentiable, smooth, and real analytic) in a unified manner. The treatment of the real-analytic class reflects recent work on real-analytic topologies by the author. Applied mathematicians and graduate students in control theory interested in nonlinear and geometric control theory will find this book of interest.

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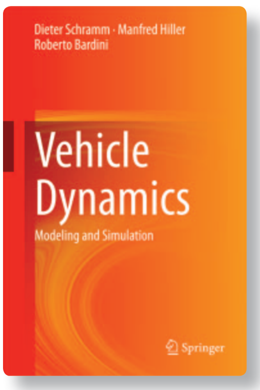


Springer, 2014, ISBN: 978-3-540-36044-5
405 pages, US$139.00.

## Vehicle Dynamics: Modeling and Simulation

by DIETER SCHRAMM, MANFRED HILLER, and ROBERTO BARDINI

The authors examine the fundamentals and mathematical descriptions of the dynamics of automobiles. In this context, different levels of complexity will be presented, starting with basic single-track models up to complex three-dimensional multibody models. A particular focus is on the process of establishing