Introduction

In recent years, an unprecedented interest in novel and revolutionary space missions has risen out of new NASA and ESA programs. Astrophysicists, astronomers, space systems engineers, mathematicians, and scientists have been cooperating to develop and implement novel, ground-breaking space missions. Recent progress in mathematical dynamics has enabled development of low-energy spacecraft orbits; significant progress in the research and development of electric and propellantless propulsion system promises revolutionary, energy-efficient spacecraft trajectories; and the idea of flying several spacecraft in formation will break the boundaries of mass and size by creating virtual space-borne platforms.

The growing interest in the astrodynamical sciences at large creates a sound need for a new book series solely devoted to astrodynamics. The purpose of the *Elsevier Astrodynamics Series* is, therefore, to give scientists and engineers worldwide an opportunity to publish their works utilizing the high professional and editorial standards of Elsevier Science under the supervision and guidance of a superb editorial board comprised of world-renowned scientists, engineers, and mathematicians.

The first volume in the series, *Modern Astrodynamics*, reviews emerging topics in astrodynamics. The book is designed as a stepping stone for the exposition of modern astrodynamics to students, researchers, engineers, and scientists, and covers the main constituents of the astrodynamical sciences in a comprehensive and rigorous manner.

Modern Astrodynamics deals with the following key topics: Orbital dynamics and perturbations; low-energy orbits, chaos, and Hamiltonian methods; trajectory optimization; novel propulsion systems and spacecraft formation flying.

This volume will be of value to research and graduate students, for its clear and comprehensive portrayal of state-of-the-art astrodynamics; to aerospace and mechanical engineers, for its discussion of advanced trajectory optimization and control techniques, spacecraft formation flying and solar sail design; for mathematicians, for its discussion of Hamiltonian dynamics, chaos and numerical methods; for astronomers, for its presentation of perturbation methods and orbit determination schemes; and for astrophysicists, for its discussion of deep-space and libration point orbits suitable for observational science missions. It is also a must-read for commercial and economic policymakers, as it presents the forefront of space technology from the broad perspective of astrodynamics.

Modern Astrodynamics is a multi-authored volume comprising invited technical contributions written by some of the world's leading researchers: David Vallado (Analytical Graphics Inc., USA), Michael Efroimsky (United States Naval Observatory), Vincent Guibout and Daniel Scheeres (University of Michigan, USA), Edward Belbruno (Princeton University, USA), Oliver Junge and Michael Dellnitz (Paderborn University, Germany), Michael Ross (Naval Postgraduate School, USA), Colin McInnes and Matthew Cartmell

(University of Strathclyde, UK), and Louis Breger, Gokhan Inalhan, Michael Tillerson, and Jonathan How (Massachusetts Institute of Technology, USA).

David Vallado opens this volume with an informative chapter on orbital dynamics and perturbations, including the classical distinction between secular, short- and long-periodic motions, Keplerian orbits, and the quantitative and qualitative effects of gravitational and non-gravitational perturbations on satellite orbits.

Michael Efroimsky continues the discussion on orbital dynamics by presenting one of the most remarkable recent discoveries of theoretical astrodynamics: Gauge freedom. If the inertial Keplerian solution in a non-perturbed setting is expressed via time and some six adjustable constants called elements, then under perturbations this expression is used as *ansatz* and the 'constants' are endowed with time dependence. The perturbed velocity will consist of a partial derivative with respect to time and a so-called convective term, one that includes the time derivatives of the variable 'constants'. Out of sheer convenience, the so-called Lagrange constraint is often imposed. It nullifies the convective term and, thereby, guarantees that the functional dependence of the velocity upon the time and 'constants' stays, under perturbation, the same as it used to be in the undisturbed setting. The variable 'constants' obeying this condition are called osculating elements. Efroimsky shows that it is sometimes convenient, however, to deliberately permit deviation from osculation, by substituting the Lagrange constraint with an essentially arbitrary condition. Moreover, each such condition will then give birth to an appropriate family of non-osculating elements, and the freedom of choosing such conditions will be analogous to the gauge freedom in electrodynamics.

Vincent Guibout and Daniel Scheeres embark on a quest for solving well-known mathematical problems, with important applications in astrodynamics: Two-point boundary value problems. The Hamilton–Jacobi theory for dynamical systems predicts the existence of functions that transform Hamiltonian systems to ones with trivial solutions. These functions, called generating functions, have been widely used to solve a variety of problems in fields ranging from geometric optics to dynamical systems. Guibout and Scheeres' recent work has applied generating functions to solve problems in astrodynamics, with applications to targeting, formation flight, and optimal control. Their chapter defines an algorithm which solves the Hamilton–Jacobi equation for the generating functions associated with the canonical transformation induced by the phase flow. A new algorithm for computing the generating functions, specialized to two-point boundary value problems, is developed.

Ed Belbruno discusses, from the theoretical standpoint, the fascinating applications of Chaos Theory in astrodynamics. Prior to 1985, the Hohmann transfer was viewed as the only way to get a spacecraft from Earth to another planet of the solar system, e.g., the Moon. Is there a better way? Belbruno shows that, indeed, the answer is positive: Have the spacecraft arrive at the Moon with a lesser velocity than the Hohmann transfer, and let the subtle interactions of the gravitational fields of the Earth and Moon gradually slow it down with no fuel required. This theory is called *weak stability boundary theory*. It estimates a region about the Moon where the motion of a spacecraft is chaotic in nature and approximately feels the gravitational pulls of the Earth and Moon almost equally—so that, like a surfer trying to ride a wave, the spacecraft can arrive at the Moon balancing itself on the transition boundaries of the gravity fields of the Earth and the Moon. This yields a capture of the spacecraft into lunar orbit requiring no fuel at all.

Oliver Junge and Michael Dellnitz continue the study of chaos and low-energy orbits by dwelling upon pertinent numerical aspects. They extend recent studies of energy-efficient trajectories for space missions based on the circular restricted three-body problem model. In their chapter, Junge and Dellnitz develop numerical methods for computing approximations to invariant manifolds, which are important for the design of low-energy trajectories. They show how to detect connecting orbits as well as pseudo-trajectories that might serve as initial guesses for the solution of more complex optimal control problems.

Michael Ross continues the quest for energy-efficient orbits by considering spacecraft trajectory optimization problems, or, stated differently, Ross is developing methods for enabling new space missions by reducing the amount of consumed fuel. This problem, as well as its concomitant mathematical modelling and solution, are of prime importance to modern space missions. In particular, Ross provides a well-thought distinction among several options for defining what is meant by "optimal" and "energy efficient", and concludes that these terms are dependent on the particular propulsion system in use.

Colin McInnes and Matthew Cartmell complete the discussion of efficient space travel by a comprehensive study of propellantless mass systems, enabling the breaking of boundaries of currently conceived space missions. Conventional spacecraft are limited in their ability to deliver high-energy missions by a fundamental reliance on reaction mass. However, this basic constraint can be overcome by a class of propulsion systems which either extract momentum from the environment (solar sails), or balance momentum through payload exchanges (tethers). This chapter provides an introduction to the physics of solar sail and tether propulsion systems, along with a review of the recent development of the technologies. This chapter also suggests an outlook for future innovation, including some practical applications of highly non-Keplerian orbits for solar sails and performance optimization for interplanetary tether transfers using motorized momentum exchange principles.

Louis Breger, Gokhan Inalhan, Michael Tillerson, and Jonathan How conclude this volume by addressing an important emerging topic in space systems: Spacecraft formation flying. Efficient execution of precise spacecraft formation flying relies on having accurate descriptions of the fleet dynamics and accurate knowledge of the relative states. However, there are numerous sources of error that exist in real-time as a result of perturbations and differential disturbances. Breger, Inhalan, Tillerson and How analyze the impact of key perturbations on formation flying control. The main point is that analyzing the closed-loop system gives a common framework for comparing both navigation and modeling errors.

Finally, a few debts of gratitude. I would like to acknowledge the dedicated members of the Editorial Board, who diligently and professionally reviewed the contributed chapters for this volume. Special thanks to Professor Terry Alfriend, member of the National Academy of Engineering, for his encouragement, endorsement and support. Finally, great many thanks to Isabelle Kandler, who prepared the infrastructure for this project, and Graham Hart and Jonathan Simpson, the Commissioning Editors, for their professionalism, far-reaching vision and good will.

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