Weiduo Hu

FUNDAMENTAL SPACECRAFT DYNAMICS AND CONTROL

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This edition first published 2015

Registered office
John Wiley & Sons Singapore Pte. Ltd., 1 Fusionopolis Walk, #07-01 Solaris South Tower, Singapore 138628.

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Library of Congress Cataloging-in-Publication Data applied for.

ISBN: 9781118753538

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

Typeset in 10/12pt TimesLTStd by SPi Global, Chennai, India

Printed and bound in Singapore by Markono Print Media Pte Ltd

1 2015

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Preface

I have taught orbital mechanics for international students since 2006 at Beihang University, and have found that many Chinese students are also interested in learning this course in English. But a lot of these students whose mother language is not English have told me that most present English textbooks use long and complicated English descriptions, which means that they find it difficult to understand the basic materials of this course at the beginning.

One of the major objectives of this book is therefore to use simple and concise English to introduce orbital theory and applications, which other textbooks may already contain. Of course, some augmentations and extensions are also included, such as the orbital motion around asteroids, which are closely related to my Ph.D. dissertation at the University of Michigan; and satellite full attitude capture, which I studied in my work at the Beijing Institute of Control Engineering. Moreover many special simulation figures are made for this book. Finally, the organization of the content is different from similar books to allow it to be read easily, step by step.

To realize this special objective, detailed derivations of theories, a large number of illustrations and many practical application examples are given, making this textbook especially suitable for students whose mother language is not English when they begin to learn spacecraft dynamics in English.

Spacecraft dynamics in this book is concerned with the description of the motion of bodies in space. This subject is divided into two parts, one of which is termed orbital mechanics, while the other is referred to as attitude dynamics. As we know, spacecraft orbital motion is the motion of its mass center, whereas attitude motion is the spacecraft motion about its center of mass.

This book focuses mainly on the *orbital mechanics* course, which has been taught for the past 10 years by the author. It is also intended as a reference for other courses such as *spacecraft attitude dynamics and control*. Hence some fundamental information on attitude dynamics has also been included. In the first part of this book from Chapter 1 to 7, orbital related topics are discussed, such as Keplerian motion, orbital maneuvers, CW-equations, the Lambert problem, orbital determination and optimal control, the three body problem, perturbed orbits, asteroid exploration, orbital applications etc. In the second part, from Chapter 8 to 10, attitude kinematics, dynamics, stabilization and determination are introduced. The two parts can be treated independently, but they are related. For example, attitude determination and gravity gradient stabilization are based on knowledge of both orbital mechanics and attitude dynamics. Spacecraft control is not discussed independently, but general speaking, orbital maneuver, attitude stabilization, etc., are in the category of spacecraft control which are all included in this book. Although in this book, fundamental knowledge is mainly described, some relatively new definitions and methods or complicated problems are also introduced, such as periodic orbit, chaotic motion, f, g expansion, Lagrange bracket, resonant orbit, elliptic expansion, three body problem, orbital determination and optimization, CW equation, Lambert problem, Poincaré map, liquid sloshing model, two line element, GPS RINEX, inertia tensor, spherical geometry etc. All these materials could be interested not only by beginners but for experienced aerospace engineers.

Though I try to correct mistakes in the book very hard, there must be some errors left. If you find any questions, please tell me by email: weiduo.hu@buaa.edu.cn. All comments are grateful.

Weiduo Hu

Acknowledgments

Some of the material in this book originate from my class notes, handouts, and homework of different courses at the University of Michigan where I pursued my Ph.D. and also from discussions and exchanges with my friends in the USA, and also my students at Beihang. Here I wish to thank all of those who have contributed to this book, including Professors Scheeres, McClamours, Kambaber, Kuo, C. Hall, P. Lu, Chen, Bernstein, Greenwood, and also my friends FY Hsiao, B.F. Villac, Dan, David, Z. Shen, Z. Wu, L.Tian, as well as several reviewers such as K. Anupama whose suggestions have been helpful.

Many thanks are given to Beihang International School and Astronautics School for their support and encouragement.

Special thanks go to my family for their love, blessing, inspiration and patience.

About the Author

Weiduo Hu obtained his bachelor, masters and Ph.D. degrees in the Department of Automatic Control at Beihang in 1986, 1989, 1993 respectively. He then worked as an engineer and senior engineer at Beijing Institute of Control Engineering, where he was in charge of fault detection of a satellite control system. In 1998, he went to the USA, in pursuit of a second Ph.D. in the Department of Aerospace Engineering at the University of Michigan, supported by NASA JPL, focusing on research on spacecraft orbital motions around asteroids. In 2005, he joined the School of Astronautics at Beihang University (BUAA).

He has published many research papers on spacecraft dynamics and control in journals such as *Planetary and Space Science*, *AIAA Journal of GCD*, *Celestial Mechanics and Dynamical Astronomy*, *IEEE Trans. on Aero. and Elec. Sys.*, *Chinese Journal of Astronomy and Astrophysics*, *Acta Mechanica Sinica*, etc. He is currently an editor of the *Journal of Aerospace Science and Technology* at Hans Publishers Inc. USA. His research interests are spacecraft attitude and orbit determination, control and dynamics. He teaches courses such as Orbital Mechanics, Spacecraft Control, Integrated Navigation, Modern Control Theory etc. for undergraduate, graduate and international students.

Contents

Part One

Orbital Mechanics

1

Introduction

Spacecraft dynamics in this book means the study of motion of man-made objects in space, subject to both natural and artificially induced forces, which includes orbital mechanics and attitude dynamics.

Orbital mechanics is the science concerned with the trajectory motion of a spacecraft, whereas attitude dynamics is concerned with the orientation motion of a spacecraft.

This text book mainly focuses on trajectory motion, that is, the motion of mass center of a man-made spacecraft or a natural body. Natural body's motion is also within the scope of celestial mechanics. A basic introduction to attitude dynamics is given in this book.

Since dynamics are closely related to GNC (guidance, navigation and control), a brief discussion about its meaning is given here. Simply speaking, guidance answers the question where to go, navigation tells us where you are, and control is concerned with how to go. In this book, orbit and attitude determination belong to the category of navigation, while orbit maneuver, attitude stabilization and control are in the category of control. Dynamics form the foundation in analyzing a GNC system. Very little discussion is given to guidance in this book, and it can be simply regarded as a reference. Figure 1.1 shows the basic relations between these definitions using the classical feedback control diagram.

Many sub-systems of a spacecraft are closely related to GNC, including attitude control, communication, power supply, thermal control, structure, propulsion subsystem, etc.

1.1 History

The scientists who have made great contributions to the development of orbital mechanics include Aristotle, Ptolemy, Copernicus, Tycho Brahe, Kepler, Galileo, Newton, Euler, Lagrange, ...

1.1.1 Kepler's Laws

The Danish astronomer Tycho Brahe (1546–1601) gathered extremely accurate observational data on planetary motion. He developed and maintained detailed and precise records. But he

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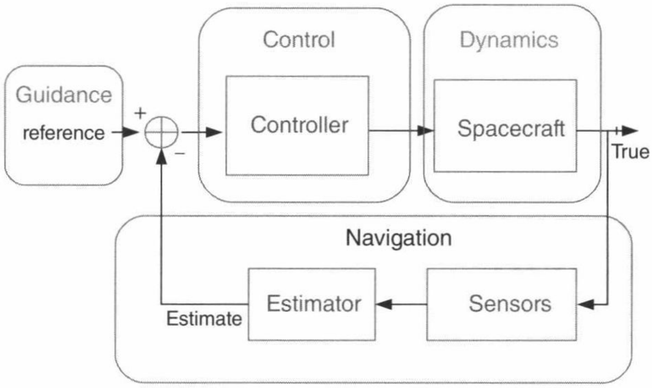

Figure 1.1 Basic relations between GNC and dynamics

didn't capitalize on observations, as he lacked the vision and mathematical skills. And he kept the Earth at the center of the planets.

Johannes Kepler (1571–1630), a gifted mathematician and astronomer, distilled Brahe's observation data to provide the first quantitative statements about orbital mechanics, which is known as Kepler's three Laws:

Law of ellipse: The orbits of the planets are ellipses with the Sun at one focus.
Law of equal area: The line joining a planet to the Sun sweeps out equal areas at equal times.
Law of harmony: The square of the orbital period (time to complete one orbit) is directly proportional to the cube of the average distance between the Sun and the planet.

Kepler's Laws are descriptive, which answer how the planets move around the Sun. But they can not explain why planetary motion satisfies these three laws. It was Isaac Newton (1642–1727), who established the mathematical foundation from which Kepler's Laws can be derived.

1.1.2 Newton's Laws

Newton is arguably the greatest physicist ever. His major discoveries and developments were differential and integral calculus, the gravitational laws, and also contributions in optics.

Isaac Newton (1642–1727) established the fundamentals of celestial mechanics based on the earlier work of Tycho and Kepler. Newton formulated the basic concepts of the Laws of Motion and Law of Gravitation around 1666, but it was not until 1687, at the urging of Edmund Halley, the Principia was published. It originally presented the three laws of motion.

Law of inertia: Every body continues in its state of rest or of uniform motion in a straight line unless it is compelled to change that state by forces impressed upon it.
Law of momentum: The rate of change of momentum ($m\mathbf{v}$) is proportional to the force ($\mathbf{F}$) impressed and is in the same direction as that force.

$$\mathbf{F} = \frac{\mathrm{d}}{\mathrm{d}t}(m\mathbf{v}).$$

This law is also sometimes called *the first principle*.