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Optimal Space Flight Navigation

An Analytical Approach

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Preface

This book is primarily written to consolidate optimal space flight navigation theory as a discipline. There are several excellent textbooks on optimal control theory and equally good books on orbital space mechanics, but the application of optimal control theory to orbital mechanics is mainly confined to research articles. Over the last several decades, the research literature on optimal space flight navigation has become voluminous and has fragmented into many esoteric subdisciplines. However, a monograph which organizes this content and vitalizes it for contemporary application is hitherto lacking.

Optimal space flight navigation is a problem of practical interest and has been so ever since humans imagined journeying into space. While visionaries such as Tsiolkovsky and Goddard helped in taking the first steps by developing rocketry, it required enthusiasts to devise fuel-optimal trajectories for practical space missions. The vision of Walter Hohmann, a civil engineer, revealed in his 1925 book *Die Erreichbarkeit der Himmelskörper* (*The Accessibility of Celestial Bodies*) is one of the most useful and commonly applied space flight maneuvers—the Hohmann transfer. As recently as in 2014, the Hohmann transfer was successfully applied to efficiently send India's first mission to Mars. While arising as an elegant idea in Hohmann's mind, the optimality of the Hohmann transfer can now be rigorously proved in various ways, including by optimal control theory. Similarly, the straightforward and insightful application by D.F. Lawden of the erstwhile nascent optimal control theory to the space navigation problem produced in 1963 in the monograph entitled *Optimal Trajectories for Space Navigation* has guided many researchers since then. The first footsteps on the Moon would not have appeared if NASA's engineers (including Richard Battin who passed away in 2014) had not devised simple but efficient techniques to guide the lunar module on a flat thrusting trajectory to a safe landing. Battin in his treatise *An Introduction to the Mathematics and Methods of Astrodynamics* reminisces about how he came up with the velocity-to-be-gained and cross-product steering as simple but practical guidance strategies for space flight in the era of primitive computer technology. He writes of the enormous buildings required to house the computer mainframes of the day with only very modest computing power. Perhaps the total computational resources present on board *Apollo 11* could be surpassed by those of today's pocket calculator. The feat performed by those pioneering guidance engineers can only be appreciated by the complexity of their task—to send people to the Moon and to bring them successfully back to the Earth. The design and analysis of practical lunar and interplanetary trajectories could be conducted in the analytical framework established by Victor Szebehely in his 1967 masterpiece, *Theory of Orbits: The Restricted Problem of Three Bodies*.

Rather than highlighting the computational (and often unrealizable) solutions of mathematically complex problems, this book emphasizes the analytical approach to optimal space navigation. The need for simplicity and practicability of guidance methods is to be contrasted with the unfortunate emphasis which has been placed these days on increasing the complexity of control schemes. Multilevel iterative algorithms must be solved in real-time computations and therefore have unresolved convergence issues which prevent applications to actual missions. It should thus be asked: Is more sophistication always better, and does it lead to any advantage in the practical sense? I think a simpler guidance solution must be sought, wherever possible, due to its reliable implementation in a realistic situation, which has been amply demonstrated by the analytical guidance methods. That is why even the latest space flight missions are based upon analytical techniques.

The complex interplanetary and asteroid (or comet) flyby and rendezvous missions are analytically derived from the application of optimal control theory to multi-body dynamics, such as the optimal transfers between halo and quasi-halo orbits and Lissajous trajectories using the stable and unstable manifolds of the restricted three-body problem. Studying such optimal paths often imparts new insights into the problem of multi-body transfers, which would be lacking in a purely numerical search for suboptimal solutions. In a similar vein, the problem of orbiting and landing on an irregularly shaped body with an uncertain gravity field (such as an asteroid or a comet) can be solved out by time-optimal and fuel-optimal methods, as has been demonstrated in many practical missions.

The thought of writing this book arose from the course AE-777 (Optimal Space Flight Control), which I have taught for the past several years and for which a single textbook containing all the relevant material was unavailable. Therefore, the book is designed to be used as a textbook in a course on optimal space flight at the graduate and senior undergraduate levels. The first three chapters give a basic introduction to the topic, namely, optimal control theory (Chaps. 1 and 2) and orbital mechanics with impulsive transfers (Chap. 3). Chapter 4 covers optimal transfers in a spherical gravity field with continuous, unconstrained acceleration inputs, whereas Chap. 5 extends the treatment to trajectory optimization with bounded acceleration inputs. Finally, Chap. 6 introduces the reader to the advanced topics of optimal transfer in time-varying gravity fields, including multi-body transfers. Unfortunately, due to the vast scope of these topics, it is not possible to do them full justice in an introductory text. Hence, references to research articles are provided for the advanced topics. The end-of-chapter exercises test the understanding of the basic concepts, whereas several references are provided for undertaking research and for advanced applications. A basic knowledge of control systems and dynamics is assumed of the reader, which can be supplemented by textbooks on these topics, such as those previously published by me (e.g., *Modern Control Design*, *and Atmospheric and Space Flight Dynamics*, *Automatic Control of Atmospheric and Space Flight Vehicles*).

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