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A Mathematical Perspective on Flight Dynamics and Control

Springer

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Foreword

One of the remarkable aspects that distinguished the Wright brothers from other flight enthusiasts at the time was their careful analysis of flight dynamics. This included developing the first wind tunnel to quantify the aerodynamic forces as a function of wing shape. Their systematic, scientific approach eventually led to the first successful powered flight under human control. Since the time of the Wright brothers, the development of novel flight strategies has required a solid understanding of flight dynamics and control. The need for scientist and engineers who understand flight at a deep level has become even more critical with the advent and rapid development of autonomous unmanned aerial systems (UAS). In the future, even more sophisticated and agile aerial platforms will be developed, and the design of successful flight control strategies will require knowledge of attitude representations that can capture the entire flight envelop, even though these representations require the designer to employ sophisticated mathematical tools. It will also require the best available control design strategies.

There currently exist a wide variety of excellent teaching and resource materials focused on helping scientists and engineers master the mathematical prerequisites to work on UAS and other flight control areas. To this body of material, the current monograph is a welcome addition. The monograph focuses on mathematical aspects of flight dynamics and control. The list of topics include attitude representation using Tait–Bryan (Euler 321) angles, and quaternions, a nice derivation of the equations of motion of a rigid body, a careful analysis of the common flight modes, and a mathematically rigorous discussion of common strategies used for flight control. The material is self-contained and highly readable. This monograph will be helpful for students and practitioners who are looking for a mathematically rigorous development of the dynamics and control of fixed wing aircraft.

July 2016

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Preface

Flight dynamics is a fascinating topic in aerospace sciences, since it requires competences in several branches of engineering, ranging from aerodynamics to structures and ergonomics. Understanding flight dynamics is a prerequisite to design effective controls for aircraft and, in particular, unmanned vehicles. In many cases of practical interest, the dynamics of aircraft can be considered as linear and the literature on the control of linear-dynamical systems is extremely vast, to say the least. Nowadays, flight control engineers can rely on 'classic' control techniques, such as the notorious proportional-integral-derivative feedback control and $\mathcal{H}_2$ and $\mathcal{H}_\infty$ control theories. Nonlinear control techniques are becoming preponderant, especially in advanced applications, such as the design of military aircraft. For example, adaptive control, sliding mode control, model predictive control, and backstepping are still open fields of research in aeronautics.

This brief comprises a selection of the complementary material I present in my flight controls course at The University of Oklahoma. For brevity, many of the numerical examples I provide in class have been omitted, since herein, I prefer giving more emphasis to theoretical notions. This monograph does *not* intend to be a textbook: I leave this daunting duty to the many excellent books in flight dynamics currently available. The scope of this brief is to present in a concise, self-contained, and rigorous manner several aspects of flight dynamics and control, which are usually omitted or briefly mentioned in textbooks. As a matter of fact, this monograph has been written for graduate students and practitioners with strong interest in control theory and applied mathematics, who desire to have a deeper and *different* insight into flight dynamics and control.

This brief is characterized by a few distinguished features, such as the definition of angular velocity, which I borrowed from Prof. T.R. Kane. This definition leaves no room to ambiguities, in spite of more traditional ones based on infinitesimal variations. Moreover, in Chap. 1 I endeavored discussing in detail intrinsic rotations and Tait–Bryan angles, which are commonly used, though very briefly examined, in numerous books on flight dynamics. In Chap. 1, a section is dedicated to quaternion algebra and Euler parameters. Specifically, starting from the definition of imaginary basis units, the most relevant properties of quaternions are discussed, so that the reader can fully appreciate every detail about the relations between Euler parameters, rotations, and angular velocity. Although most of the books on dynamics successfully explain the notion of axis of rotation and the role it plays in the definition of the Euler parameters, the derivation of the relation between the angular velocity of a rigid body and the time derivatives of the Euler parameters is often omitted for brevity or proved starting from some nonintuitive result.

The equations of motion of an aircraft are presented in Chap. 2 both as functions of the Tait–Bryan angles and the Euler parameters. Since the equations of motion of an aircraft are a set of *implicit* nonlinear differential equations, the linearization of these equations is a delicate process that requires some machinery, which is discussed in detail in this brief. Chapter 2 is also dedicated to the analysis of the longitudinal- and lateral- directional dynamics of a vehicle without relying on any intuition or observation of the physical behavior of aircraft, but dissecting the properties of the linearized equations of motion.

The proportional-integral-derivative control technique, the linear-quadratic Gaussian regulator, the optimal state feedback $\mathcal{H}_\infty$ control, and the model reference adaptive control are presented in Chap. 3 and applied through meaningful numerical examples to the problem of controlling the attitude of an aircraft. Lastly, Appendix A is a brief compendium of the mathematical tools needed to comprehend the material presented in this brief. Appendix A presents also some advanced topics, such as the notion of semistability, the Smith–McMillan form of a transfer function, and the differentiation of complex functions; these concepts are usually omitted in most reference books for engineers, but are fundamental to appreciate several details on the dynamics and control design of linear-dynamical systems.

This brief does not pretend to be complete. For instance, stability derivatives are merely mentioned and aircrafts are modeled as six degrees-of-freedom rigid bodies, in which center of mass moves at Mach number less than or equal to 3. Moreover, the results presented in this brief apply only if we assume that the Earth is fixed in space and locally flat. Lastly, this brief does not pretend to exhaustively illustrate all the control techniques that can be applied to aircraft. The reader is referred through this monograph to relevant books and publications for further reading on all the topics covered herein. Hopefully, at the end of this brief, the readers will be able to better appreciate the work of the scholars who preceded and will follow us.

Writing a monograph while serving as a first year assistant professor has been a unique experience. The vibrant enthusiasm of the graduate and undergraduate students I am proudly advising, as well as of those students attending my AME 4513/5513 ‘Flight Controls’ class, has strongly motivated me; I am indebted to them for their comments, questions, and suggestions. I also wish to express my deep gratitude to Prof. R.W. Beard, who provided his invaluable comments and considerably improved the quality of this work. Finally, I want to thank Mr. Oliver Jackson, the editor of this book, for his outstanding guidance over the course of the editorial process.

While elaborating this brief, my mind often went to my academic advisor Prof. W.M. Haddad, who nurtured and guided my passion for mathematics, control theory, and rigorous thinking. His pristine enthusiasm for each and every of his publications will be an everlasting source of inspiration for me. Last, but not least, I dedicate this work to my parents, Franco and Teresa, and my wife Anh. STD.

"O frati," dissi, "che per cento milia
perigli siete giunti a l'occidente,
a questa tanto picciola vigilia

d'i nostri sensi ch'è del rimanente
non vogliate negar l'esperïenza,
di retro al sol, del mondo sanza gente.

Considerate la vostra semenza:
fatti non foste a viver come bruti,
ma per seguir virtute e canoscenza."

'O brothers, who amid a hundred thousand
perils,' I said, 'have come unto the West,
to this so inconsiderable vigil

which is remaining of your senses still
be ye unwilling to deny the knowledge,
following the sun, of the unpeopled world.

Consider ye the seed from which ye sprang;
ye were not made to live like unto brutes,
but for pursuit of virtue and of knowledge.'

Dante, La Divina Commedia,
I, XXVI, vv. 112–120.

Norman, OK, USA
July 2016

Andrea L'Afflitto

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