OPTIMAL ESTIMATION of DYNAMIC SYSTEMS

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John L. Crassidis and John L. Junkins

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Preface

THIS text is designed to introduce the fundamentals of estimation to engineers, scientists, and applied mathematicians. This text is the follow-on to the first estimation book written by the second author in 1978. The current text expands upon the past treatment to provide more comprehensive developments and updates, including new theoretical results in the area. The level of the presentation should be accessible to senior undergraduate and first-year graduate students, and should prove especially well-suited as a self study guide for practicing professionals. The primary motivation of this text is to make a significant contribution toward minimizing the painful process most newcomers must go through in digesting and applying the theory. By stressing the interrelationships between estimation and modelling of dynamic systems, it is hoped that this new and unique perspective will be of perennial interest to other students, scholars, and employees in engineering disciplines.

This work is the outgrowth of the authors' multiple encounters with the subject while motivated by practical problems with spacecraft attitude determination and control, aircraft navigation and tracking, orbit determination, powered rocket trajectories, photogrammetry applications, and identification of vibratory systems. The text has evolved from lecture notes for short courses and seminars given to professionals at various private laboratories and government agencies, and in conjunction with courses taught at the University at Buffalo and Texas A&M University.

To motivate the reader's thinking, the structure of a typical estimation problem often assumes the following form:

- Given a dynamical system, a mathematical model is hypothesized based upon the experience of the investigator, which is consistent with whatever physical laws known to govern the system's behavior, the number and nature of the available measurements, and the degree of accuracy desired. Such mathematical models almost invariably embody a number of poorly known parameters.

- Determine "best" estimates of all poorly known parameters so that the mathematical model provides an "optimal estimate" of the system's actual behavior.

Any systematic method which seeks to solve a problem of the above structure should generally be referred to as an estimation process. Depending upon the nature of the mathematical model of the system and the statistical properties of the measurement errors, the degree of difficulty associated with solution of such problems ranges from near-trivial to impossible.

In writing this text, we have kept in mind three principal objectives:

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1. Document the development of the central concepts and methods of optimal estimation theory in a manner accessible to engineering students, applied mathematicians, and practicing engineers.

2. Illustrate the application of the methods to problems having varying degrees of analytical and numerical difficulty. Where applicable, compare competitive approaches to help the reader develop a feel for the absolute and relative utility of various methods.

3. Present prototype algorithms, giving sufficient detail and discussion to stimulate development of efficient computer programs, as well as intelligent use of programs.

Consistent with the first objective, the major results are developed initially by the route requiring minimum reliance upon the reader's mathematical skills and *a priori* knowledge. This is shown by the first chapter, which introduces least squares methods without the requirement of probability and statistics knowledge. We have decided to include the required prerequisites (such as matrix properties, probability and statistics, and optimization methods) as appendices, so that this information can be made accessible to the readers at their own leisure. Our approach should give the reader an immediate sense of the usefulness of estimation concepts from first principles, while later chapters provide more rigorous developments that use higher-level mathematics and knowledge. In many cases, subsequent developments re-establish the same "end results" by alternative logical/mathematical processes (e.g., the derivation of the continuous-time Kalman filter in Chapter 5). These developments should provide fresh insight and greater appreciation of the underlying theory.

The set of problems selected to accomplish the second objective are typically idealized versions of real-world engineering problems. We believe that bridging the gap between theory and application is important. Several examples are given in each chapter to illustrate the methods of that chapter. The main focus of the text is to stress actual dynamical models. The methods shown are applicable to "block box" representations, but it is hoped that the expanded dynamical models will more clearly illustrate the importance of the theoretical methods in estimation. Chapter 3 provides a review of dynamical systems, which spans the central core of the subject matter and provides a reasonable foundation for immediate application of estimation concepts to a significant class of problems. Chapters 4 and 7 use this subject matter to provide realistic examples, thereby giving the reader a deep understanding of the value of estimation concepts in actual engineering practice. In the applications of Chapters 4 and 7, the methods of the remaining chapters are applied; often with two or more estimation strategies compared and two or more prototype models of the system considered (e.g., the comparison of GPS position determination using nonlinear least squares in §4.1 versus a Kalman filter approach in §7.1).

In adopting the last objective, the authors remain sensitive to the pitfalls of "cookbooks" for a subject as diverse as estimation. The problem solutions and algorithms are not put forth as optimal implementations of the various facets of the theory, nor will the methods succeed in solving every problem to which they formally apply.

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Nonetheless, it is felt that the example algorithms will prove useful, if accepted in the spirit that they are offered; namely as implementations which have proven successful in previous applications. Also, general computer software and coded scripts have deliberately not been included with this text. Instead, a website with computer programs for all the examples shown in the text can be accessed by the reader (see Appendix D). Although computer routines can provide some insights to the subject, we feel that they may hinder rigorous theoretical studies that are required to properly comprehend the material. Therefore, we strongly encourage students to program their own computer routines, using the codes provided from the website for verification purposes only. Most of the general algorithms are summarized in flowchart or table form, which should be adequate for the mechanization of computer routines.

Our philosophy involves rigorous theoretical derivations along with a significant amount of qualitative discussion and judgments. The text is written to enhance student learning by including several practical examples and projects taken from experiences gained by the authors. One of our purposes is to illustrate the importance of both physical and numerical modelling in solving dynamics-based estimation problems found in engineering systems. To encourage student learning we have incorporated both analytical and computer-based problems at the end of each chapter. This promotes working problems from first principles. Furthermore, advanced topics are placed in the chapters for the purpose of engaging the interest of students for further study. These advanced topics also give the practicing engineer a preview of important research issues and current methods. Finally, we have included many qualitative comments where such seems appropriate, and have also provided insights to the practical applications of the methods gained from years of intimate experience with the systems described in the book.

We are indebted to numerous colleagues and students for contributions to various aspects of this work. Many students have provided excellent insights and recommendations to enhance the pedagogical value, as well as developing new problems which are used as exercises. Although there are far too many students to name individually here, our heartfelt thanks and appreciation go out to them. We do wish to acknowledge the significant contributions and discussions on the subject matter to the following individuals: Terry Alfriend, Roberto Alonso, Mark Balas, Itzhack Bar-Itzhack, Russell Carpenter, Yang Cheng, Agamemnon Crassidis, Glenn Creamer, Chris Hall, Jer-Nan Juang, Kok-Lam Lai, E. Glenn Lightsey, F. Landis Markley, Paul Mason, Tom Meyer, D. Joseph Mook, Daniele Mortari, Yaakov Oshman, Tom Pollock, Mark Psiaki, Hanspeter Schaub, Malcolm Shuster, Tarun Singh, Debo Sun, S. Rao Vadali, John Valasek, and Bong Wie. Also, many thanks are due to several people at CRC Press, including: Bob Stern, Jessica Vakili, Nishith Arora, and Helena Redshaw. Finally, our deepest and most sincere appreciation must be expressed to our families for their patience and understanding throughout the years while we prepared this text. This text was produced using LaTeX 2_ε (thanks Yaakov and HP!). Any corrections are welcome via email to *johnc@buffalo.edu* or *junkins@tamu.edu*.

John L. Crassidis
John L. Junkins

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To Pam and Lucas, and in memory of Lucas G.J. Crassidis
and
To Elouise, Stephen and Kathryn

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