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Book Review

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Practical Methods for Optimal Control Using Nonlinear Programming

John T. Betts, SIAM, Philadelphia, PA, 2001, 190 pp., $51.00, ISBN 0-89871-488-5

Over the past decade, there have been major new developments in optimal control theory[1] and numerical methods. It is now possible to solve hitherto complex optimal control problems with relative ease. Much of these advances can only be found in a great variety of papers with varying degrees of technical difficulty, and so it's a pleasure to see a book written by one of the leaders in this field in synthesizing this information.

The outside back cover of this book reads, "This is quite possibly the first book on practical methods that combines nonlinear optimization, mathematical control theory, and numerical solution of ordinary differential or differential-algebraic equations to successfully solve optimal control problems." This is a fair statement taken together with the author's emphasis on "pracitcal methods" spelled throughout the book. With the aid of some relatively straightforward mathematics, the author conveys a wide variety of useful principles. In fact, no theorems are presented. Yet, the reader will find a significant wealth of information on why things work including "what can go wrong." See also Ref. 2 for an excellent survey by the author. By providing a feel for the numerial methods, the author successfully conveys concepts that might be apparently baffling otherwise. For example, one might think that a high-precision variable step size propagator might work well if "pasted" to a good nonlinear programming (NLP) method. That this does not work, as the author explains, is because the function generator introduces noise in the NLP iterations. The author's unique perspecitve that "exposing the function" to the NLP alogrithm provides stability to the iteration process is well taken.

The book is quite short and contains five chapters and an appendix on SOCS: Sparse Optimal Control Software. (The software itself is not provided; it must be purchased from Boeing.) The first two chapters are on methods for nonlinear programming and the third chapter introduces numerical methods for differential equations. Basic optimal control theory and direct collocation methods are introduced in chapter 4, and chapter 5 contains six solved examples using SOCS.

Over the past decade, numerical methods for solving nonlinear programming problems have achieved a very high degree of sophistication. The author has done an excellent job in introducing the fundamentals and summarizing some key developments in sparse nonlinear programming and their application to large scale problems such as those arising in optimal control. While I like the book very much and recommend it, the book falls short in a few significant ways. For starters, although SOCS is used to illustrate the various ideas contained throughout the book, it does not come with the purchase of the book. This is not quite practical. In fairness to the author, SOCS is licensed by Boeing, his employer. I don't believe anybody can and should build their own industry-strength NLP solver by simply reading this book. In this sense, the high dosage of stand-alone NLP topics covered in this book are probably questionable from the perspective of their relationship to optimal control theory. Also, as the author himself emphasizes, an appropriate NLP method is crucial for successfully solving optimal control problems. However, one should not confuse the NLP method with solving optimal control problems. Then there is this issue of some statements made in the book that are either not illustrated or not quite true. For example, in the very first chapter of the book, quadratic convergence is illustrated for Newton's method by way of a numerical solution to a simple problem. A table shows the doubling of the number of significant digits for each successive iteration. The next section contains a discussion on the secant method but no table is provided to compare it with Newton's method. The author writes that "... we can expect convergence will require more iterations ...." Why not just show it? Perhaps a more significant omission I find is that the author does not support his claim (with even a simple numerical example) that the Lagrange multipliers associated with the NLP converge to the continuous costates of the optimal control problem as the density of the mesh increases. This is shown for the Euler method by omitting all boundary conditions. The problem is that it is these annoying boundary conditions that are at the heart of solving optimal control problems! In fact, the Lagrange multipliers hold the key to the convergence of the discretization, and in general can cause havoc to the convergence of the entire problem even when certain Runge–Kutta methods (which are better than Euler) are employed; see for example, Ref. 3. This unfortunate statement is also made in the author's otherwise excellent survey paper.[2]

There are a number of other shortcomings in the book, many of which are ignorable: an extremely short index, a few inconsistencies, and so on. Despite the issues I have raised, this is still an outstanding book. Overall, the author achieves his main goal of conveying a number of useful concepts and ideas without the usual clutter that comes with theorem proving. Mathematicians might not like this book due to its lack of formal mathematics, however, I'm sure most engineers will welcome this style and the insights provided by the author. The numerous aerospace examples discussed in the book, especially in the last chapter, suggest that aerospace engineers will find this book very useful. In fact, I believe the more appropriate audience for this book is the AIAA community, not SIAM. It is an excellent reference book and makes a valuable contribution to the literature.

References

[1]Vinter, R., *Optimal Control*, Birkhauser, Boston, 2000.

[2]Betts, J. T., "Survey of Numerical Methods for Trajectory Optimization," *Journal of Guidance, Control, and Dynamics*, Vol. 21, No. 2, 1998, pp. 193–207.

[3]Hager, W. W., "Runge–Kutta Methods in Optimal Control and the Transformed Adjoint System," *Numerische Mathmatik*, Vol. 87, 2000, pp. 247–282.

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