Guest Editorial
On Applications of Kalman Filtering

THIS represents the sixth in an evolving series of Special Issues of the TRANSACTIONS ON AUTOMATIC CONTROL. The series was launched in December 1971 with the Special Issue on the Linear-Quadratic-Gaussian Problem and has been followed by Special Issues on System Identification and Time Series Analysis, Large-Scale Systems and Decentralized Control, Linear Multivariable Control Systems, and, most recently, the Bellman Special Issue. These issues exhibited a strong theoretical flavor, consonant with the emphases of regular issues of the TRANSACTIONS. This issue is intended to be a distinct departure from its predecessors, as it is concerned entirely with applications. In particular, it deals with the applications of a major result of modern control theory, the Kalman filter.

The idea for a Special Issue, based on applications of the Kalman filter, was suggested by M. Grimble to A. Harvey. At the time, Harvey was Chairman of the Technical Committee on Applications for the CSS. He discussed the possibility with me and a detailed proposal was made to the IDC which was approved in December 1980. The Editorial Board was formed with Associate Editors J. Balchen, P. Belanger, G. Blankenship, B. Friedland, M. Grimble, J. LeMay, J. Mendel, H. Titus, and K. Wall. I want to thank the members of the Editorial Board for their contributions. Without their conscientious and thoughtful efforts, this issue would not exist. Their recommendations were based on the evaluations provided by many reviewers whose objective and constructive comments are greatly appreciated. Finally, we need to express our gratitude to the authors who contributed their ideas and manuscripts to the Special Issue. We regret that every contribution could not be included.

A basic objective defined for the issue was to obtain and present a set of applications that is as wide ranging as possible. By seeking breadth, it was felt that conceptual similarities between disparate problems could be identified and approaches to these problems could be contrasted. We feel that this objective has been achieved. As described below, the applications range from spacecraft orbit determination to the demographics of cattle production. The commonality of concerns that are addressed in these papers is striking. In reading these papers, one is impressed by the cleverness exhibited in achieving successful implementations. But, also, the results may suggest intriguing questions not addressed by the authors. Certainly, other approaches to specific problems may suggest themselves. As many of the systems that are described have been implemented operationally or have been subjected to extensive experimental verification, the "solutions" have the weight of experience and success.

The Kalman filter can be used for a variety of end-purposes. Its basic function is to provide estimates of the current state of the system. But it also serves as the basis for predicting future values of prescribed variables or for improving estimates of variables at earlier times. In many of the papers in this issue, the performance of the Kalman filter is assessed and evaluated, and the estimates serve as the end product for the application. In other papers the filter serves as a component of a system such as a controller or a detector. The performance of the larger system assumes paramount importance and the behavior of the filter is assessed against the broader context.

The papers for the Special Issue have been grouped according to general types of applications (as labeled by the Guest Editor). The breadth of applications is gauged, easily, by reviewing the types. Furthermore, papers have been arranged, in a pseudochronological order. The earliest applications of the Kalman filter dealt with satellite orbit determination. The first paper in this issue, by Campbell *et al.*, describes the use of the filter for orbit determination for the Voyager spacecraft during its Jupiter fly by. The issue concludes with a type of application that is of a more recent vintage and, certainly, very different from orbit determination. Leibundgut *et al.* describe the use of the Kalman filter for predicting cattle populations in France.

The papers, included between those dealing with Voyager orbit determination and cattle demographics, have been categorized as tracking, navigation, ship motion, remote sensing, geophysical exploration, industrial processes, and power systems. Orbit determination, tracking, and navigation problems represent, probably, the first major applications of the Kalman filter and the first seven papers in this issue describe mature and sophisticated examples of these applications. The specific problems are different, but the papers share many common aspects and concerns. For example, dynamic and error models generally have similar bases and origins.

The problems of dynamic modeling and of state variable descriptions tend to be less well-defined in the types of applications other than tracking and navigation. In many instances, a dynamic model for the system can be defined, conceptually, but the resulting description is so complex that it is not very useful. The development of acceptable models upon which the Kalman filter can be based becomes a fundamental concern. This aspect of successful filter implementation is a dominating theme throughout the issue.

The papers on ship motion prediction and position control have many features in common with the tracking and navigation problems. But the modeling of ship/wave interactions requires the development of simple, but effective, models using signal processing or identification techniques. In addition, these papers are concerned with the Kalman filter performance primarily in the context of a control system. For the remote sensing papers, the Kalman filter appears as part of a signal processor that is used for offline analysis. These papers, as well as the geophysical exploration paper, are not concerned with real-time processing. Nonetheless, simple models are used to accomplish the processing, and the performance is based on the achievement of the general goals of the system.

Estimation and control problems abound in industrial processes and power systems. These applications impose the necessity for real-time operation, generally with limited computational capability, using poorly defined models of the process. Simplicity and adaptability are basic concerns in these applications.

It is interesting in reading this issue to identify common problems and to compare the manner in which their solution has been approached and evaluated. As mentioned above, modeling problems are a recurrent topic throughout the issue. Modeling concerns that are addressed include the definition of variables to be included in the state vector, coordinate systems to be used, linearization methods, observability and conditioning of the model, the effects of neglected variables or model errors, etc. Given the basic model, the Kalman filter can be implemented in a variety of ways. In fact, the model and the filter algorithm are interrelated and several papers describe the feedback process that leads to the form of the filter that is implemented.

Requirements of the system impose significant constraints on the design of the filter algorithm. The need for real-time operation can force the development of an implementation that is very different from that which would occur for offline analysis. In many applications, limited computational capability demands simple models and algorithms, and these considerations can exaggerate the divergence control problem. Model errors or uncertainties can dictate the use of adaptive filters or system identification procedures. Since the introduction of the Kalman filter and its initial applications in the early 1960's, many theoretical papers have been stimulated by problems encountered in applying the Kalman filter to practical problems. The insights gained from these analyses manifest themselves throughout the presentations contained in this issue.

There is now, and has been for a long time, a desire among the leaders of the Control Systems Society to provide more emphasis to applications in the activities of the Society. From surveys of the membership, it appears that these attempts have been less than successful. This issue is intended to be a distinct departure from the theoretical character usually assumed by the TRANSACTIONS as a response to long-standing complaints. It constitutes a positive attempt to bridge the so-called "gap between theory and practice" that seems to be referred to frequently. While I question the meaningfulness of a "gap," this issue provides an emphasis to applications that has been lacking.

The officers of the CSS and I will be interested in membership response to the character of this issue. Does this type of publication meet the needs for applications that are raised by many CSS members? If it does, suggestions for other applications-oriented Special Issues will be welcomed by the Chairmen of Technical Committees dealing with applications.

HAROLD W. SORENSON
Guest Editor