Issues in Signal Processing

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Signal processing is an exciting area of research and development. Much recent progress has been driven by applications involving speech and audio processing, image and video processing, radar, sonar, and seismology. The purpose of this technical comment will be to highlight some of the relations between signal processing and control. The two areas share many common methodologies for analysis, design, and system implementation. Recent progress reaffirms that techniques developed to address problems arising in one area often find applications in the other.

In Alan Willsky's insightful book Digital Signal Processing and Control and Estimation Theory: Points of Tangency, Areas of Intersection, and Parallel Directions [1], the Foreword starts with the following sentences:

"The book has grown out of an investigation over the past two years of the relationships between digital signal processing and control and estimation theory. I was motivated to undertake this study by a belief that there are enough similarities and differences in the philosophies, goals, and analytical techniques found in the two fields to indicate that a concentrated effort to understand these better might lead to a number of ideas for interaction and collaboration among researchers."

In the twelve years since the book was published, interactions and collaborations have indeed led to considerable progress, and there are now synergies in both research and development. These days, control system designers and signal processing system designers not only use many of the same analytical models and methods, but they also rely on similar computer-aided design tools, and they assemble hardware systems using the same chips.

With single-board computers and powerful programmable signal processors now...
available as off-the-shelf components, there are common implementation issues to be faced by engineers doing hardware development, whether the application involves a signal processing task or a control task. As a result, the goal of design has become the reduction of performance objectives to a result, the goal of design has become the

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modeling of transducers and actuators, investigating performance/complexity tradeoffs, etc. But the underlying fundamental methods for studying systems and signals comprise the toolbox that is employed in the development of algorithmic solutions.

From this viewpoint, it is not so remarkable that the themes of Willsky's book remain timely. Indeed, the points covered in this article can be categorized with the following list of his chapter topics: Stability; Parameter Identification, State Estimation, and Signal Modeling; Synthesis, Realization, and Implementation; Multidimensional Signal Processing; Nonlinear Systems. My personal experience and interests are reflected in the following presentation, which is not intended to be comprehensive in scope. There is no attempt to give an in-depth discussion of any of the points; in most cases only one or two references are cited as a pointer to published work where more details can be found.

Background

Signal processing plays a role in the implementation of control systems. A plant to be controlled is equipped with sensors and actuators; the control system must take signals from sensors and transform them into command signals suitable for driving the actuators. Thus, the controller must perform the necessary processing of sensory signals in order to derive whatever information is required for achieving satisfactory performance, and it must perform the necessary processing of the control strategy, expressed mathematically, to put it in the form of command signals for the actuators.

A key point is that the signal processing carried out by a control system is viewed mainly (often, only) in terms of effects on closed-loop system performance. For this reason, signal processing topics involving open-loop behavior (e.g., design of finite impulse response (FIR) filters meeting various frequency domain specifications) are often not particularly relevant to control applications. Indeed, concepts of major importance for control applications may be formulated in much different ways than would be the case if the processing is open-loop rather than closed-loop. For instance, (closed-loop) robust control involves essential complications and subtleties going well beyond the formulation used to treat open-loop robust signal processing. For a survey of robust techniques in signal processing, see Kassam and Poor [2].

On the other hand, feedback is an intrinsic part of many signal processing systems, and the tools of control system analysis and design may often be applied to gain understanding and solve problems. Adaptive filtering is one area where considerable progress has been made in this way; see Johnson [3] for a survey of this area. In other cases, new kinds of mathematical tools have been adopted to deal with such signal processing problems, and these tools may sometimes be applied to more general feedback systems of interest to control engineers. Looking to the future, one can envision signal processing applications involving quantum mechanical systems, such as in work on photonic information processing systems, where a feedback-like coupling between observation processes and the underlying system dynamics will need to be considered.

The rest of this article will cover the particular topics listed earlier and offer some remarks about progress in the last few years.

Stability

New tools and perspectives demonstrate that even this most classical of topics offers opportunities for future developments. Khartovk-type results, which demonstrate that the stability of a finite number of "boundary systems" provides a characterization of stability of certain (infinite) parameterized families of linear systems, have attracted considerable attention; see Bar- mish's overview of this topic [4]. Robust stability results of this kind have useful applications in feedback control of plants with parametric uncertainty and in signal processing systems where coefficient quantization may arise.

Nonlinear dynamic behavior in digital filters arising from quantization and feedback has motivated work involving chaos and strange attractors; see Chua and Lin [5]. In some applications, highly irregular signals may have stable statistical properties such as invariant distributions, well-defined spectra, etc. Ergodic theory tools have begun to be applied for characterizing long-term statistical stability of purely deterministic processes. Notable contributions include the work of

Gray on analysis of sigma-delta A/D conversion [6], work of Delchamps on feedback control using quantized observations [8,9], and work by Chase, Serrano, and Ramadge on a class of buffer-control systems [10]. Recent results in ergodic theory for Markov chains have been applied to the study of stochastic adaptive control; see Meyn and Guo [11].

Parameter Identification, State Estimation, and Signal Modeling

A comprehensive treatment of the subject of stochastic linear systems may be found in the recent book by Caines [12]; identification and estimation techniques play important roles in various applications where parameteric signal models are employed; see the book by Ljung and Söderström [13] for a full discussion. Notable progress in adaptive filtering and parametric spectral estimation has been made in recent years; see Johnson [3] and Marple [14] for more details. The control book edited by Desai [15] provides an overview of theoretical developments motivated by applications in modeling of systems and signals. Computational issues and special purpose architectures for real-time implementation have received considerable attention; more will be said about this later. Another set of applications involve the use of state space models for detecting failures or abrupt changes in model parameters; various linear and nonlinear state estimation methods provide solutions to signal processing problems of this type. The book edited by Basseville and Benveniste [16] provides an overview of this area.

Synthesis, Realization, and Implementation

One major advance of the past ten years reflects the pervasive influence of VLSI systems. Distributed and parallel computation provide the means for real-time implementation of many signal processing and control algorithms. The book edited by Tewksbury, Dickinson, and Schwartz [17] provides an overview of the broad range of relevant research areas. For a more detailed treatment of architectural issues, see the book by Kung [18]; for algorithmic issues see Bertsekas and Tsitsiklis [19].

Two other topics of considerable recent interest and important for control and signal processing applications will also be mentioned. The first is reduced-order modeling and system approximation. Hankel approximation methods have received considerable
attention; several contributed chapters in Desai’s book [15] discuss algorithms and applications. Some of the latest theoretical developments are described in papers by Glover, Lam, and Partington [20] and by Chui, Lin, and Ward [21]. Another approach is based on techniques developed for system identification; see Wahlberg [22]. Second, the use of divided-difference discretization for control and estimation problems has been studied; see the book by Middleton and Goodwin [23] and the forthcoming survey paper by Goodwin, Middleton, and Poor [24]. This approach greatly improves the numerical conditioning of discrete-time control and estimation algorithms for continuous-time systems when high sampling rates are used.

Multidimensional Systems

Brief comments cannot do justice to this vast area. For a recent collection of reprinted papers covering several topics where systems and signal processing ideas have been fruitfully combined, see Selected Papers in Multidimensional Digital Signal Processing [25], especially for the papers on image reconstruction, spectral estimation, array processing, and image enhancement. Image sequence processing has gained in importance as a result of telecommunications systems applications (high definition television — HDTV, instant network services — ISDN). The use of Markov random field models in various image processing applications is one particularly nice example. In the context of these models, stochastic relaxation, also known as simulated annealing, and multiresolution techniques have been applied with some success to achieve image segmentation, and to restore degraded images; see Geman and Geman [26] and Bouman and Liu [27] for details.

Nonlinear Systems

Recent developments in nonlinear systems have opened up many new and exciting applications areas within signal processing and control. The use of tools from ergodic theory has already been mentioned. In Gray’s work on quantizers [7], this approach is combined with tools from harmonic analysis to give frequency domain characterizations without resorting to approximate techniques such as describing functions. Nonlinear discrete-time filters have been developed for a range of applications such as transfer function estimation in nonminimum phase communication channels and equalization of nonlinear channels encountered in magnetic recording applications. Nonlinear systems arising in parameter estimation and adaptive control problems have motivated considerable recent work on underlying systems problems. Realization issues associated with parameter estimation problems are studied by Dickinson and Soniag [28]. Stability of slowly time-varying nonlinear systems is an important topic in the context of adaptive control; see the book by Anderson, et al. [29].

Neural networks is an area of tremendous recent activity. The appearance in 1990 of the first volume of the new journal, the IEEE Transactions on Neural Networks, is indicative of the perceived importance of this area; the first issue of the journal contains a number of survey papers that introduce important parts of the field. The IEEE Control Systems Magazine has featured several papers on neural network applications in the past few years. Supervised learning algorithms for training feed-forward networks have produced classification systems for character recognition, speech synthesis and recognition, backgammon playing, and for a variety of other control and signal processing applications. Although it is not widely appreciated, the basic supervised learning algorithm, known in the neural network field (also in the subfield of cognitive studies, which has adopted the name parallel distributed processing — PDP) as back propagation learning, simply amounts to an implementation of gradient descent for multistage optimization; see the recent note by Dreyfus [31] for a discussion.

In other work, Hopfield has popularized a class of continuous-time neural networks governed by gradient dynamics, first in the context of associative, or content-addressable, memories [32], and later in the form where the dynamics are constructed so that the state equilibrium encode (approximate) solutions of certain combinatorial optimization problems; see Hopfield and Tank [33]. The idea of mapping discrete problems onto continuous dynamic systems, thereby employing a form of analog computation, has been studied in a different form by Brockett [34]. A complexity-based analysis of analog computation is formulated in the paper by Vergis, Steiglitz, and Dickinson [35]; there it is argued that computationally intractable (NP hard) combinatorial optimization problems, including those arising in control and signal processing applications, are unlikely to have "practical" analog solutions, at least in a particular worst-case sense.

Conclusions

Prospects for future progress in areas of common interest to control and signal processing are bright. Besides the areas mentioned above, developments involving Intelligent Systems are starting to be seen in robotics, manufacturing, and avionics. Technical considerations involving computational complexity are being used to gain understanding of fundamental system performance limitations. New technologies, such as micromechanical systems and photonics, will find applications in many areas. Advances in computer-aided design and analysis tools will be made. The symbiosis of signal processing and control can be expected to broaden in scope across research, development, and educational activities.

References


