Special Issue on Emerging Technologies

The label of mature technology both exalts and haunts control science and engineering. There is no question that the controls discipline has played critical roles in technological advances over the last few decades. If not for modern control theory, aircraft would not be flying as far or as fast; manufactured goods, from paper to steel to gasoline to Mars Bars, would not be as readily available; Rover would still be just a dog's name; ... the list is endless. We may sometimes complain that our craft is hidden from view in the very products it has enabled, but within the scientific and technical communities, our discipline is certainly recognized as an established one with an enviable record of accomplishments. Controls has been a linchpin of the modern age.

But if our past is glorious, what about our future? Many of the important control problems that challenged us a decade or two ago have now been solved, more or less. In the process industries, for example, multivariable model predictive control (MPC) is widely seen as the solution to process control needs. MPC is not appropriate for every process system, but it provides satisfactory performance for a large fraction. Enthusiasm for, and investment in, new regulatory or supervisory control methods suffer in comparison to technologies that (less equivocally) promise revolutionary operational improvements—for example, communications, sensors, health management, human interfaces. What is true of process control or flight control is not a universal truth. Important new domains for control are appearing. In some of these cases, variations of existing control methods can be gainfully employed, whereas in others, some new thinking is needed.

In any case, this is no crisis call. There are many incremental improvements to be realized, and grist for the research mill aplenty. For confirmation, one need only look at the several control conferences that now take place worldwide. Nearly a thousand papers are presented solely at the IEEE Conference on Decision and Control, the Control System Society's flagship meeting, and most of these report progress in extending conventional methods or filling in holes in the theoretical underpinnings of modern control. The days of breakthrough discoveries may be behind us, the subtext asserts, but there are many problems within our disciplinary boundaries that will keep us busy.

I would assert, and I hope many of you will agree, that we can do better. Conferences tend to be geared toward sustaining the status quo, not disturbing it. Our past successes are a hint of the role we can play in the future shaping of our world.

There is, after all, no end of problems still to be solved, for which society at large is looking at technology as the answer. Virtually all problems of significance involve the analysis, synthesis, or optimization of dynamical systems, and thus are control system problems. Our analytical techniques and pragmatic insights about dynamical systems have many more contributions to make.

It is equally important to remember that control technology is never the whole solution. The mantra of integrating controls expertise with domain knowledge bears frequent repetition (and the synergistic possibilities presented by other technologies must be exploited as well). Even at the initial stage of a research project in controls, when we are excitedly pursuing a technology, we believe is "emerging," its credibility will be suspect until we can intelligently discuss its application to a target problem or domain—and customize the technology based on understanding of the domain.

This special issue contains five feature articles from researchers active in their respective fields. There is an element of risk in this undertaking. The standards of completeness that constitute the yardstick for publications in control science are appropriate for established directions of research. In the interests of originality, some relaxation of these standards is equally appropriate in presenting emerging technologies. It is too early to say whether the technologies and application domains discussed in the following pages will create the impact their exponents are striving for. Yet they are of sufficient interest and promise that broad ex-

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posure through this issue is warranted. Some of the articles have a higher risk factor than others, and they all differ significantly in their degree of mathematical rigor, the degree of maturity of the research they discuss, and the extent to which they stretch the (self-imposed) boundaries of control engineering. But there are also commonalities, in particular the marriage in all cases of the emerging technology itself and discussion of specific applications or problems. Overall, the issue represents a diverse selection of topics that, we believe, have some potential to imbue our discipline with a renewed sense of excitement and vision.

Feedback Control of Buildings

In the first article of this issue, the term emerging control technology takes on a different meaning. We often hear about new control applications in flight control, process control, manufacturing, environmental control, and many other areas. Spencer and Sain discuss the application of feedback control concepts to a novel domain: civil structures, especially buildings. Since at least the Tacoma Narrows bridge collapse in 1940, the relevance of the control engineer's craft to the design of civil engineering structures has been noted; however, these structures have traditionally been passive ones—there is no feedback controller operating within. The situation is now changing, and active control implementations are increasing. This article focuses specifically on buildings and discusses the applicability of both hybrid control, in which active and passive control elements are combined, and semi-active control, a relatively new scheme in which mechanical energy is harvested but not used to control the structure. The authors also discuss computational devices which are huge. The authors show results from an experimental magnetorheological fluid damper capable of delivering a 2-ton force.

Control technology is expected to dramatically improve the performance of civil structures: improving human comfort, better withstanding natural catastrophes, and reducing the impact of malicious human acts. The majority of current applications are in Japan and driven by the need for earthquake protection.

Adaptive Control of Acoustic Noise

Adaptive control has been an emerging control technology for decades; however, although several important research breakthroughs have been made over this period, transitioning this research to practical applications has been only marginally successful. One exception is PID control, where several adaptive autotuning products are available. Here, too, the fraction of PID loops that these products regulate is infinitesimal. Many reasons can be adduced for the limited real-world impact of adaptive control. One that can be singled out is the emphasis on target systems where the cost of failure is unacceptably high.

Adaptive control of acoustic noise, discussed in the article by Jiang, Tsuji, Ohmori, and Sano, is an especially attractive combination of technology and domain in this regard. Given that significant performance improvements can be expected on average, the possibility of occasional worsening of performance, such as may occur through the introduction of excitation signals, is not a show-stopper. Two adaptation algorithms are presented, both of which employ a feedforward controller implemented as an FIR filter. The first algorithm assumes that the dynamics of two acoustic paths are known: (a) from a noise sensor (microphone) to the control actuator (a speaker) and (b) from the speaker to the point where noise cancellation is desired. No additional model is required in this case, and the filter parameters are directly updated. In the second algorithm, this prior knowledge is not needed. Instead, the approach is identification based (with a dither signal introduced to ensure sufficient excitation).

This article does not attempt to prove broad new theorems in adaptive control. Its objective is both more modest and more pragmatic. Insights from the domain are used to develop the algorithms, which are thus tailored for noise control. The authors also eschew simulation-based evaluations—which, for adaptive control, have always been viewed with an element of skepticism—opting instead to demonstrate the effectiveness of their algorithms on an experimental air duct system. Implementation details such as the hardware components required are also described.

Autonomous Underwater Vehicles

If adaptive control has been one of the holy grails of our discipline, autonomous vehicles has been another. We have, of course, recently seen a spectacular success story in this latter area. The Mars rover may have dispelled any doubts as to whether a useful autonomous vehicle could be developed, but cost-effective vehicles for more mundane applications are another story. In the third article, Valavanis, Demetriou, Gracanin, and Matijasevic survey the field of autonomous underwater vehicles (AUVs). Readers may be surprised at the number of prototype vehicles that have been built. The focus of this article is not on specific algorithms for uncrewed operation, but on the equally important issue of control system architecture—sensors, actuators, hardware, software, and the nature of their interconnections. In addition to discussing the architectures of several research vehicles, the authors also describe a new approach they are pursuing. They justify their adoption of an embedded control system design instead of a microcontroller-based approach; the risk and cost associated with the latter is higher, and the embedded controller facilitates the development of application-specific software. The authors are in the process of modifying a commercially available, remotely operated deep-sea vehicle to convert it to an AUV. The article also contains a pointer to a comprehensive Web site maintained by the authors through which interested readers can access further information on AUV developments worldwide.

The AUV is an appealing candidate for the first commercial autonomous vehicles, for some quite pragmatic reasons. The environment is inhospitable for human-operated vehicles, the economic importance of deep-sea operations has increased, and some of the obvious safety issues in deploying terrestrial or airborne autonomous vehicles do not arise. Nevertheless, I look forward to the day when I can trade in my snow shovel for an autonomous snow-blower.

Chaos for Control

If the popular press is to be believed, chaos is more than technology—it is our sociological and ecological condition. Sensitive dependence on initial conditions characterizes not just complex technical systems, but Sino-American linkage via butterfly flittings! The number of natural and biological phenomena that rely on chaotic dynamics for their functioning is an indica-
tion (albeit not proof) that chaos and control, despite the oxymoronic ring, can be bedfellows.

The connections between chaos and control have been an area of research for a few years now. In the majority of these explorations, the focus has been on developing control algorithms to render chaotic plants well behaved— to suppress chaos. The article by Vincent describes an approach which bucks this trend by relying on chaos for improving controllability. The system to be controlled is first put into a chaotic regime, if necessary by open-loop control. The algorithm then goes into a wait mode, simply monitoring the system until it eventually wanders into a neighborhood of a desired fixed point. This neighborhood is such that the system can be driven to the fixed point from within it under state variable feedback control.

Issues of model fidelity, measurement errors, and sensing and actuation delays may appear to doom such notions. In fact, they do not; the specific trajectory followed by the system in its chaotic condition is not critical, provided the chaos is maintained. The algorithms have been implemented and validated in laboratory setups with a bouncing ball system and a two-link pendulum. Other issues, however, remain; in general, this scheme is not intended primarily for applications where conventional measures of control performance—such as settling time or smooth transient behavior—are appropriate. It is emerging technology for a novel class of applications.

Complex Adaptive Systems for the Power Industry

The vision of control has always been considerably broader than its practice and has often been articulated in terms of socio-economic applications. The gap persists partly because the relevance of our existing technology to these applications has been questionable. If the vision is to be realized, new developments are needed that can handle the complexities and uncertainties of, say, strategic decision-making in a competitive business environment. In the last article, Wildberger gives an introduction to complex adaptive systems, an emerging technology being explored for applications in the business realm as well as for physical systems.

Complex adaptive systems refer to object-oriented simulation and optimization models in which the objects, referred to as agents, correspond to entities in the domain of interest. They go beyond object-oriented systems in that the agents are endowed with adaptation capabilities, typically based on genetic algorithms or other evolutionary computing methods. Users can create and connect agents to represent a real or hypothetical system and, through simulation, observe the effects of different initial conditions or different exigencies on the evolution of the system. Further, by enabling the adaptation algorithms in one or more agents, they can determine new systems, differing from the initial one in parameter values or structurally, that optimize some criterion of interest. (There is little hope of attaining the true optimum in most such simulations; the solutions are optimized, not optimal.)

Complex adaptive systems are now being explored for a wide array of applications. This article addresses some applications in the utility industry, including distributed control of the power grid and strategic planning for the power industry as it deals with the challenges, and opportunities, of deregulation and competition.

Conclusions

The emerging control technologies basket contains more than we have had space for in this issue. Some other choice contents are:

- statistical learning theory
- data mining for dynamical systems
- control of microelectromechanical systems
- modeling of economic systems
- biologically inspired control architectures
- the integration of control with system health management
- control via the World Wide Web

We hope to include some of these and other areas in future special issues on this topic.

I encourage readers of this issue to contact the authors of the articles and/or this guest editor with comments, questions, and suggestions for other candidate emerging technologies. Ultimately, emerging control technologies will only become established technologies through a dialogue in which the controls community participates.

This issue would not have been possible without Steve Yurkovich's guiding hand, the assistance of numerous anonymous reviewers (all the articles are refereed), and, of course, the contributing authors. The result of all the hard work appears in the following pages, and I hope you will find it informative, stimulating, and even controversial.

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