Emerging Technologies in Control Engineering

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Despite complaints often heard from researchers that control theory is a mature field whose important problems have been solved, it seems that there are more practical control problems and more opportunities for innovation than ever before. Not only are conventional applications increasingly in need of sophisticated control methods, but exciting new problems are emerging that pose completely new challenges to control system designers.

The purpose of this special issue is to provide an overview of emerging technologies that are expected to become major areas of application for control systems technology. Because of space limitations, this issue can only provide a glimpse of these technologies, and must neglect other areas that might also have been considered as emerging within the broad field of control systems. The technologies that were selected were chosen because of their importance (especially in economic terms) and because of their relevance to the field of control. They are:

- intelligent vehicle highway systems
- semiconductor manufacturing
- mechatronics, and
- microelectromechanical systems.

While these subjects are all applications of control, rather than new methodologies for control, the underlying concept of this special issue is not that new theories are not emerging. As a matter of fact, one of the papers discusses nonlinear control methodologies that were developed just over the last five to ten years. Nevertheless, the emphasis on applications reflects a current situation where control researchers are increasingly required to be involved in state-of-the-art applications to demonstrate the value of their research. Further, the emerging technologies promise to bring new excitement to the engineering side of control, and to help formulate new theoretical problems.

The rest of this paper introduces the papers of this special issue, and the areas that they overview. Discussed are the reasons for the emergence of the new technologies, their importance, and the opportunities that they represent to control engineers.

Intelligent Vehicle Highway Systems

Concepts of intelligent vehicle highway systems (IVHS) were proposed many years ago, but suddenly received a surge of interest, due to congestion problems becoming critical, and due to the practical impossibility of adding new freeways in the congested areas. Research funding received a boost, both from the federal government and from states with congestion problems (California in particular). It is estimated that more than $200 billion will be spent on IVHS in the United States over the next 20 years [2]. Comparable research efforts are also under way in Japan and in Europe.

IVHS systems include route guidance systems, traffic management systems, and automated highways. Route guidance systems can be fairly sophisticated computer-based systems installed in individual cars, exploiting map databases and global positioning systems. Route guidance systems are already available in Japan, and are being developed in the United States as well. At some later time, it is considered that these systems might include optimal routing algorithms and the capability to send as well as receive information about traffic and road conditions.

The real opportunity for control engineering lies in traffic management systems (e.g., the automatic timing of traffic lights...
to optimize flow), and in automated highway systems. Automated highway systems begin with simple onboard systems, providing, for example, automatic braking using proximity sensors. A more advanced concept is that of platooning, i.e., of computer-controlled cars traveling at small distances. This form of longitudinal control would provide higher flow rates. On the other hand, lateral control would be used to reduce lane widths and further increase freeway capacity.

Control problems in this area of technology cover a wide span, ranging from low-level numerical control (longitudinal and lateral vehicle control) to high-level, discrete-event control (scheduling). The third paper in this issue, by J.K. Hedrick, M. Tomizuka, and P. Varaiya, discusses several of these problems and especially those at the lower level. Experimental results obtained as part of the California PATH program are also given. The second paper in this issue, by R.E. Fenton, presents a broader overview and alternative concepts that have been proposed over the years.

Semiconductor Manufacturing

It is no secret that manufacturing is a sector critical to the health of the overall economy, yet one in serious need of help and innovation. The need for control engineers to take a more active part in research in this area has also been recognized. Semiconductor manufacturing in itself is an important subset of manufacturing, and there have been concerns that state-of-the-art equipment was not as easily available to U.S. semiconductor manufacturing as to competitors [3]. Further, feedback control has been identified as one of the most important technologies needing to be incorporated in semiconductor manufacturing. As is often the case in manufacturing, many operations are still being carried out in open-loop.

The National Science Foundation has recognized the study of closed-loop feedback control as an area of critical national importance for intelligent manufacturing of electronic equipment. The Engineering Systems Program and the Solid State and Microstructures Program are jointly funding research projects in the area of reactive ion etching (University of Michigan), rapid thermal processing (New Jersey Institute of Technology), plasma enhanced chemical vapor deposition systems (Carnegie Mellon University), and scheduling policies (University of Illinois). The fourth paper in this special issue, by P.R. Kumar, discusses scheduling policies and the special problems originating in semiconductor manufacturing. The paper summarizes the remarks made by Kumar in his plenary address at the 1993 Conference on Decision and Control.

Mechatronics

Mechatronics is the combination of mechanics, electronics, and control. The emergence of this technology followed progress in power electronics (switching electronics) and computing technology. Opportunities for sophisticated control systems span from the low power range, (e.g., motion control systems used in manufacturing) to the high power range (transportation and aerospace). Overall, mechatronics covers an area of huge economic importance.

1In the manufacturing literature, control sometimes refers to open-loop control, while adaptive control refers to closed-loop control.

The availability of power electronic devices has made it possible to generate variable amplitude/frequency currents of large magnitude. As a result, DC motors have increasingly been replaced by AC motors, leading to higher reliability and lower costs. An example of such use is in locomotives, where DC motors are now being replaced by induction motors. In other applications, AC motors are replacing hydraulic actuators, which are cumbersome and trouble-prone. An example of a future application of this type is in the electric actuation of aircraft and spacecraft control surfaces, evaluated at the NASA Lewis Research Center (Cleveland), and more recently within the Electrically Powered Actuation Design program administered by Wright-Patterson Air Force Base (including flight testing already under way on an F/A-18 [6]).

A new range of control problems has emerged from the use of AC motors (as opposed to DC motors) because of their nonlinear dynamics. Opportunities exist for new methods of nonlinear control in variable-speed applications and in high-speed, high-precision motion control. Opportunities have also emerged for adaptive methods to achieve:

- self-tuning capabilities (e.g., adjustment to user-placed loads in motion control systems)
- adaptation to varying parameters (e.g., to variations of rotor resistance with heating in induction motors)
- diagnostics and failure detection (e.g., failure of the bearings), and
- efficiency maximization.

The topic of efficiency control is itself a major area of current interest. Recently, the Department of Energy announced a collaborative energy efficiency effort, together with the U.S. industry. The effort, called the "motor challenge," was designed to save motor users about $2 billion by the year 2000, and significantly reduce projected U.S. greenhouse gas emissions. A recent book from the American Council for an Energy-Efficient Economy indicates that "adjustable speed drives and other controls are the largest potential source of motor system energy savings." However, despite the large market for high-performance control devices for electric actuators, federal funding for research in the United States is small, and the importance of this area seems to be better recognized in Europe and Japan.

The fifth paper of this issue, by D. Taylor, presents an excellent survey of the work aimed at applying recent nonlinear control theories to electric actuators. Nonlinear motors are ideal candidates for such theories because of the existence of fairly good dynamic models and because of the relative ease to carry out experiments. Conversely, this area of application constitutes an ideal testing ground for the new nonlinear control methods, and could help to direct future research toward areas of practical need.

Microelectromechanical Systems

The field of microelectromechanical systems (MEMS) has grown tremendously over the last few years. MEMS devices have sizes ranging from a few millimeters to a few microns and are fabricated using micromachining techniques or IC fabrication methods. While preliminary concepts for the use of these devices were elaborated as early as in the late 50s [4], recent ideas have been very concrete, and the results have found their way even into consumer products. Applications include process instrumentation, automotive electronics, medical instrumentation, and aerospace. The market for MEMS devices is expected to
reach $8 billion by the year 2000, and research funding is currently provided by the Advanced Research Project Agency and the National Science Foundation at the rate of $8 million and $2 million per year, respectively [8].

MEMS devices under investigation include sensors, passive structures, and microactuators. Most of the current market for MEMS is in the sensor area. Typical sensors are pressure and acceleration sensors, which are now used in automotive applications. Pressure sensors provide measurements of the manifold absolute pressure for the adjustment of air fuel intake ratio. Acceleration sensors are used in air bags. See [1] for an extensive list of current and future applications of these devices.

Microstructures and microactuators are slower in finding their way into commercial products, yet are the real target of opportunity for control engineers. Concrete applications with potentially significant benefits are being studied, including:

- monitoring and control of airflow over aircraft wings to control turbulence
- optimization of performance of combustion and jet engines, through distributed flow control, and
- microsurgery (especially for blood vessels and nervous system repairs).

Various actuators have already been studied, including some based on electrostatic, electromagnetic, piezoelectric, magnetostrictive, and fluidic principles [5]. Of course, applications such as microsurgery would involve far more than microactuators, i.e., microrobots. In general, one problem for control theory that is expected to emerge from this area is that of distributed control with a large number of degrees of freedom (such as for flow control).

The sixth paper of this special issue, by D. Miu and Y.-C. Tai, discusses the research program currently under way at Caltech and UCLA in the area of microstructures and microactuators applied to disk drives. Data storage systems constitute a huge market and are critical to the computer industry. One problem that arises in magnetic disk drives is the realization of extremely narrow track separations, to achieve ultra-high data densities. Track widths in commercial products are currently of the order of 10-20 microns. Tracking is achieved through mechanical means, by moving a rotary arm on which a magnetic head is mounted. It is expected that, within 10 years, the track width will be reduced to sizes of the order of a micron, and achieving such precisions with conventional actuators is certain to pose difficult challenges. One option, discussed by Miu and Tai, will be to use a dual actuator structure, where a microactuator will be mounted at the tip of the arm.

Conclusions

While space constraints limit the number of areas of technology that can be covered, and the extent of this coverage, we hope that this special issue will nevertheless provide a useful introduction to several emerging technologies where one can expect significant and exciting developments in the next decades. There are surely several other areas that could have been considered from the point of view of theory, applications, or both. Suggestions from the readers are welcome, and should be communicated to the editor, as it is possible that the tradition of a special issue on emerging technologies will be continued in years to come. In the meantime, the focus areas of this issue should be recognized as emerging technologies having considerable economic impact. They are also areas of technology where control engineering will have a significant role to play, provided researchers in the field recognize the importance of their involvement in those problems.

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References