Chapter 1

Executive Summary

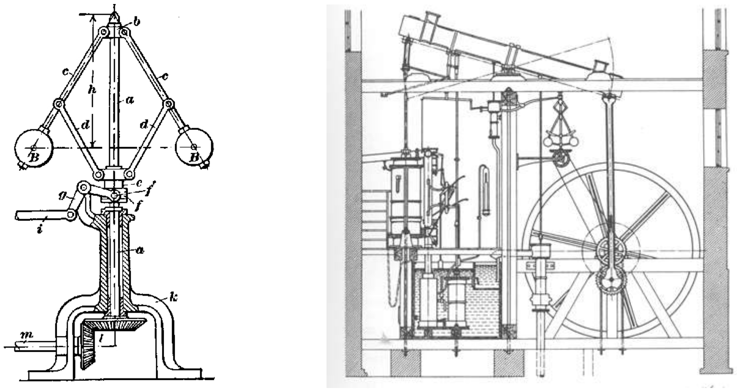
Rapid advances in computing, communications, and sensing technology offer unprecedented opportunities for the field of control to expand its contributions to the economic and defense needs of the nation. This report presents the findings and recommendations of a panel of experts chartered to examine these opportunities. We present an overview of the field, review its successes and impact, and describe the new challenges ahead. We do not attempt to cover the entire field. Rather, we focus on those areas that are undergoing the most rapid change and that require new approaches to meet the challenges and opportunities that face the community.

Overview of Control

Control as defined in this report refers to the use of algorithms and feedback in engineered systems. At its simplest, a control system is a device in which a sensed quantity is used to modify the behavior of a system through computation and actuation. Control systems engineering traces its roots to the industrial revolution, to devices such as the centrifugal governor, shown in Figure 1.1. This device used a flyball mechanism to sense the rotational speed of a steam turbine and adjust the flow of steam into the machine using a series of linkages. By thus regulating the turbine's speed, it provided the safe , reliable , consistent operation that was required to enable the rapid spread of steam-powered factories.

Control played an essential part in the development of technologies such as power, communications, transportation, and manufacturing. Examples include autopilots in military and commercial aircraft (Figure 1.2a), regulation and control of the electrical power grid, and high accuracy positioning of read/write heads in disk drives (Figure 1.2b). Feedback is an enabling technology in a variety of application areas and has been reinvented and patented many times in different contexts.

A modern view of control sees feedback as a tool for uncertainty management. By measuring the operation of a system, comparing it to a reference, and adjusting available control variables, we can cause the system to respond properly even if its dynamic behavior is not exactly known or if external disturbances tend to cause it



(a) (b)

Figure 1.1. *The centrifugal governor (a), developed in the 1780s, was an enabler of the successful Watt steam engine (b), which fueled the industrial revolution. Figures courtesy of Cambridge University.*

to respond incorrectly. This is an essential feature in engineering systems since they must operate reliably and efficiently under a variety of conditions. It is precisely this aspect of control as a means of ensuring robustness to uncertainty that explains why feedback control systems are all around us in the modern technological world. They are in our homes, cars and consumer electronics, in our factories and communications systems, and in our transportation, military and space systems.

The use of control is extremely broad and encompasses a number of different applications. These include control of electromechanical systems, where computer-controlled actuators and sensors regulate the behavior of the system; control of electronic systems, where feedback is used to compensate for component or parameter variations and provide reliable, repeatable performance; and control of information and decision systems, where limited resources are dynamically allocated based on estimates of future needs. Control principles can also be found in areas such as biology, medicine, and economics, where feedback mechanisms are ever present. Increasingly, control is also a mission critical function in engineering systems: the systems will fail if the control system does not work.

Contributions to the field of control come from many disciplines, including pure and applied mathematics; aerospace, chemical, mechanical, and electrical engineering; operations research and economics; and the physical and biological sciences. The interaction with these different fields is an important part of the history and strength of the field.

Successes and Impact

Over the past 40 years, the advent of analog and digital electronics has allowed control technology to spread far beyond its initial applications, and has made it an enabling technology in many applications. Visible successes from past investment

(a) (b)

Figure 1.2. *Applications of control: (a) the Boeing 777 fly-by-wire aircraft and (b) the Seagate Barracuda 36ES2 disk drive. Photographs courtesy of the Boeing Company and Seagate Technology.*

in control include:

- Guidance and control systems for aerospace vehicles, including commercial aircraft, guided missiles, advanced fighter aircraft, launch vehicles, and satellites. These control systems provide stability and tracking in the presence of large environmental and system uncertainties.
- Control systems in the manufacturing industries, from automotive to integrated circuits. Computer controlled machines provide the precise positioning and assembly required for high quality, high yield fabrication of components and products.
- Industrial process control systems, particularly in the hydrocarbon and chemical processing industries. These maintain high product quality by monitoring thousands of sensor signals and making corresponding adjustments to hundreds of valves, heaters, pumps, and other actuators.
- Control of communications systems, including the telephone system, cellular phones, and the Internet. Control systems regulate the signal power levels in transmitters and repeaters, manage packet buffers in network routing equipment, and provide adaptive noise cancellation to respond to varying transmission line characteristics.

These applications have had an enormous impact on the productivity of modern society.

In addition to its impact on engineering applications, control has also made significant intellectual contributions. Control theorists and engineers have made rigorous use of and contributions to mathematics, motivated by the need to develop provably correct techniques for design of feedback systems. They have been consistent advocates of the “systems perspective,” and have developed reliable techniques

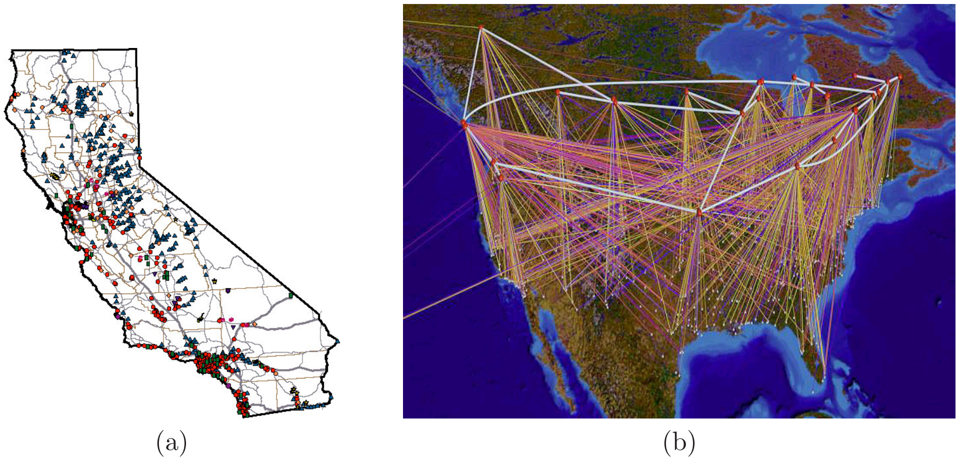

(a) (b)

Figure 1.3. *Modern networked systems: (a) the California power grid and (b) the NSFNET Internet backbone. Figures courtesy of the state of California and the National Center for Supercomputer Applications (NCSA).*

for modeling, analysis, design, and testing that enable design and implementation of the wide variety of very complex engineering systems in use today. Moreover, the control community has been a major source and training ground for people who embrace this systems perspective and who wish to master the substantial set of knowledge and skills it entails.

Future Opportunities and Challenges

As we look forward, the opportunities for new applications that will build on advances in control expand dramatically. The advent of ubiquitous, distributed computation, communication, and sensing systems has begun to create an environment in which we have access to enormous amounts of data and the ability to process and communicate that data in ways that were unimagined 20 years ago. This will have a profound effect on military, commercial and scientific applications, especially as software systems begin to interact with physical systems in more and more integrated ways. Figure 1.3 illustrates two systems where these trends are already evident. Control will be an increasingly essential element of building such interconnected systems, providing high performance, high confidence, and reconfigurable operation in the presence of uncertainties.

In all of these areas, a common feature is that system level requirements far exceed the achievable reliability of individual components. This is precisely where control (in its most general sense) plays a central role, since it allows the system to ensure that it is achieving its goal through correction of its actions based on sensing its current state. The challenge to the field is to go from the traditional view of control systems as a single process with a single controller, to recognizing control systems as a heterogeneous collection of physical and information systems, with intricate interconnections and interactions.

In addition to inexpensive and pervasive computation, communication, and sensing—and the corresponding increased role of information-based systems—an important trend in control is the move from low-level control to higher levels of decision making. This includes such advances as increased autonomy in flight systems (all the way to complete unmanned operation), and integration of local feedback loops into enterprise-wide scheduling and resource allocation systems. Extending the benefits of control to these non-traditional systems offers enormous opportunities in improved efficiency, productivity, safety, and reliability.

Control is a critical technology in defense systems and is increasingly important in the fight against terrorism and asymmetric threats. Control allows the operation of autonomous and semi-autonomous unmanned systems for difficult and dangerous missions, as well as sophisticated command and control systems that enable robust, reconfigurable decision making systems. The use of control in microsystems and senosr webs will improve our ability to detect threats before they cause damage. And new uses of feedback in communications systems will provide reliable, flexible, and secure networks for operation in dynamic, uncertain, and adversarial environments.

In order to realize the potential of control applied to these emerging applications, new methods and approaches must be developed. Among the challenges currently facing the field, a few examples provide insight into the difficulties ahead:

- *Control of systems with both symbolic and continuous dynamics.* Next generation systems will combine logical operations (such as symbolic reasoning and decision making) with continuous quantities (such as voltages, positions, and concentrations). The current theory is not well-tuned for dealing with such systems, especially as we scale to very large systems.

- *Control in distributed, asynchronous, networked environments.* Control distributed across multiple computational units, interconnected through packet-based communications, will require new formalisms for ensuring stability, performance and robustness. This is especially true in applications where one cannot ignore computational and communications constraints in performing control operations.

- *High level coordination and autonomy.* Increasingly, feedback is being designed into enterprise-wide decision systems, including supply chain management and logistics, airspace management and air traffic control, and C4ISR systems. The advances of the last few decades in analysis and design of robust control systems must be extended to these higher level decision making systems if they are to perform reliably in realistic settings.

- *Automatic synthesis of control algorithms, with integrated verification and validation.* Future engineering systems will require the ability to rapidly design, redesign and implement control software. Researchers need to develop much more powerful design tools that automate the entire control design process from model development to hardware-in-the-loop simulation, including system-level software verification and validation.

- *Building very reliable systems from unreliable parts.* Most large engineering systems must continue to operate even when individual components fail. Increasingly, this requires designs that allow the system to automatically reconfigure itself so that its performance degrades gradually rather than abruptly.

Each of these challenges will require many years of effort by the research community to make the results rigorous, practical, and widely available. They will also require investments by funding agencies to ensure that current progress is continued and that forthcoming technologies are realized to their fullest.

Recommendations

To address these challenges and deliver on the promise of the control field, the Panel recommends that the following actions be undertaken:

1. Substantially increase research aimed at the *integration* of control, computer science, communications, and networking. This includes principles, methods and tools for modeling and control of high level, networked, distributed systems, and rigorous techniques for reliable, embedded, real-time software.

2. Substantially increase research in control at higher levels of decision making, moving toward enterprise level systems. This includes work in dynamic resource allocation in the presence of uncertainty, learning and adaptation, and artificial intelligence for dynamic systems.

3. Explore high-risk, long-range applications of control to new domains such as nanotechnology, quantum mechanics, electromagnetics, biology, and environmental science. Dual investigator, interdisciplinary funding might be a particularly useful mechanism in this context.

4. Maintain support for theory and interaction with mathematics, broadly interpreted. The strength of the field relies on its close contact with rigorous mathematics, and this will be increasingly important in the future.

5. Invest in new approaches to education and outreach for the dissemination of control concepts and tools to non-traditional audiences. The community must do a better job of educating a broader range of scientists and engineers on the principles of feedback and the use of control to alter the dynamics of systems and manage uncertainty.

The impact of control is one which will come through many applications, in aerospace and transportation, information and networking, robotics and intelligent machines, materials and processing, and biology and medicine. It will enable us to build more complex systems and to ensure that the systems we build are reliable, efficient, and robust. The Panel's recommendations are founded on the diverse heritage of rigorous work in control and are key actions to realize the opportunities of control in an information rich world.