

Opportunities in Systems and Control: Report of the Panel on Future Directions in Control and Dynamical Systems

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Abstract

The field of *automatic control* provides the principles and methods used to design systems that maintain high performance by automatically adapting to changes in the environment. Aircraft auto-landing systems and sophisticated guided weapons, for example, automatically adjust control surfaces to adapt to changing winds and changes in weight and loads, to accurately and reliably follow prescribed trajectories. Routing protocols in communication networks adapt to changing congestion, queue levels, and network traffic.

Automatic control traces its roots to the beginning of the industrial revolution, where simple governors were used to automatically maintain steam engine speed despite changes in loads, steam supply, and equipment. In the early 20th century the same principles were applied in the emerging field of electronics, yielding feedback amplifiers that automatically maintained constant performance despite large variations in vacuum tube devices. Over the last forty years, the field has seen huge advances, leveraging technology improvements with breakthroughs in the underlying principles and mathematics. Automatic feedback control systems now play critical roles in many fields, including manufacturing, electronics, communications, transportation, computers and networks, and many military systems. The enabling role automatic feedback control technology plays is, however, sometimes unseen: the control methods are hidden in the computer code that carries out the automatic adjustments, or obscured by the difficult mathematics underlying it.

As we stand on the threshold of the 21st century, the opportunities for, and use of, automatic control principles and methods is about to explode. In this new world computing will be ubiquitous, more and more devices will include embedded, cheap, high performance processors and sensors, and wireless networks will greatly enhance information exchange. This will make possible the development of machines with a degree of intelligence and reactivity that will change everyone's life, both in terms of the goods available and the environment in which they live.

Of course new developments will require a significant expansion of the basic tools set of automatic control. The complexity of the control ideas involved in the operation of the internet, autonomous systems, or an enterprise-wide supply chain system are on the boundary of what can be done with available methods, so new developments must be vigorously pursued.

The purpose of this report is to spell out some of the exciting prospects for the field in the current and future technological environment and to explain the critical role we expect it to play over the next decade.

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Contents

1	Executive Summary	1
2	Overview of the Field	5
2.1	What is control?	5
2.2	Examples	5
2.3	Opportunities and challenges now facing us	6
2.4	Overarching themes	6
3	Applications, Opportunities, and Challenges	7
3.1	Aerospace and Transportation	7
3.2	Information and Networks	7
3.3	Biology and Medicine	7
3.4	Materials and Processing	7
3.5	Environment	7
3.6	Robotics and Intelligent Machines	7
4	Recommendations	8
4.1	Increase opportunities for interaction between controls and computer science	8
4.2	Aggressively explore applications of control to large-scale, distributed systems	8
4.3	Support educational, research, and infrastructure initiatives to make systems and control technology more accessible	8
4.4	Maintain support for theory and interaction with mathematics	8

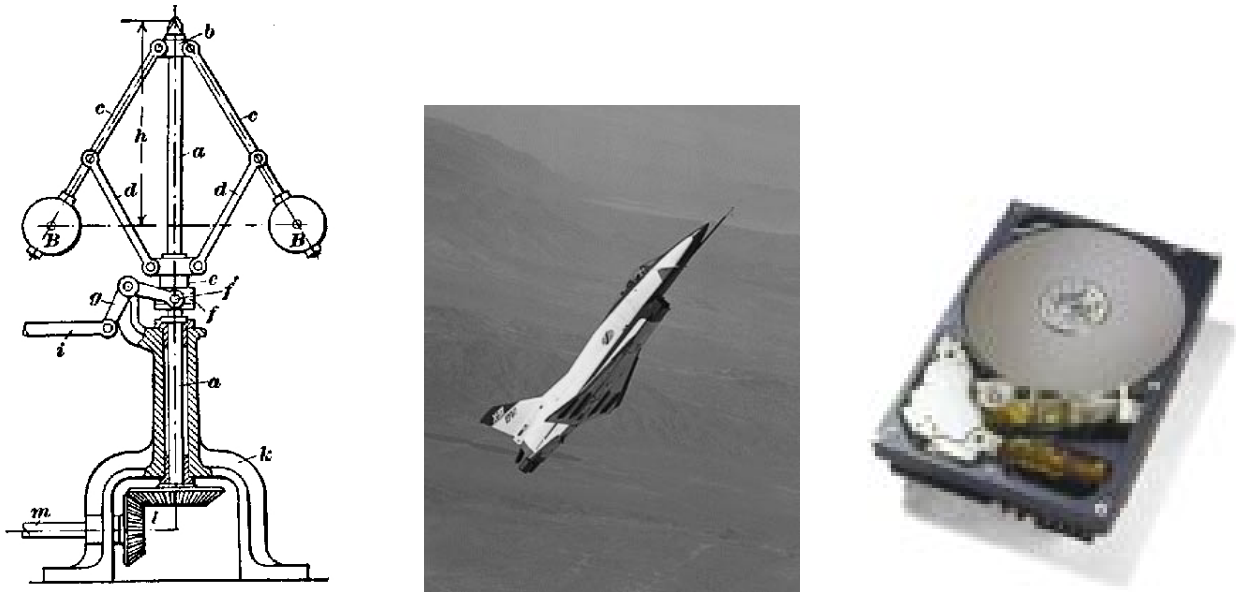


Figure 1: Applications of control: (a) the Watt governor, (b) flight control and (c) disk drives.

1 Executive Summary

Rapid advances in computing, communications, and sensing technology have put the field of Systems and Control in an unprecedented period of opportunity to contribute to the economic and defense needs of the nation. Combined with new challenges in modeling and control of large-scale, complex systems such as materials processing, active control of fluids, and global environmental change; control of distributed, networked systems such as the power grid, the internet, and the financial system; and cooperative control of multi-agent systems that arise in future combat systems, supply chain management, and electronic marketplaces, the field is poised to make great advances in both theory and application, building on its heritage of rigor and impact. This report provides a vision for the field of Systems and Control and describes some of the concrete steps required to take advantage of the tremendous opportunities that lie ahead.

Who we are and what we've done

Control systems engineering traces its roots to the industrial revolution, where the Watt flyball governor (Figure 1) was used to regulate the speed of steam turbines, enabling the safe, reliable, consistent operation that was required for rapid spread of the steam-powered factory.

Over the past 40 years, the advent of analog and digital electronics has allowed control technology to spread far beyond its initial applications, and made it an enabling technology in many applications. Visible successes include the guidance and control of aerospace vehicles in the 1960s (e.g., guided missiles, advanced fighter aircraft, satellites). Other less obvious, but very important, successes include:

- Disk drive head positioning control systems, which are used to rapidly and accurately move the disk drive heads to the correct position on the disk, and then maintain very tight tracking tolerances despite external vibrations, component variation, etc.
- Positioning stages for integrated circuit (IC) steppers, which rapidly position and align the

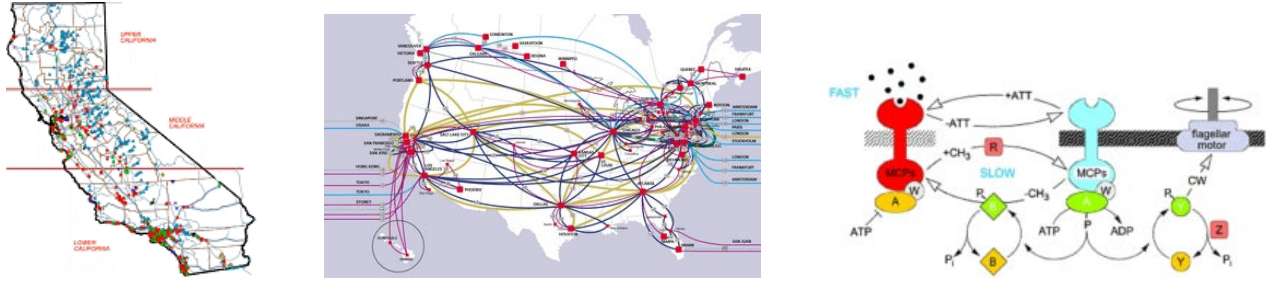


Figure 2: Modern networked systems: (a) the California power network, (b) UUNET's North American backbone and (c) Chemotaxis in *E. Coli*.

wafers used to manufacture ICs during the lithography step, to an extraordinary accuracy.

- A variety of important industrial process control systems maintain high product quality by monitoring hundreds of sensor signals and making adjustments to hundreds of valves, heater, pumps, and other actuators.

The enormous advances over the last 20 years in computing power, data networks, sensors, and actuators have important implications for control systems. Before 1980 or so most applications of advanced control engineering were in expensive, usually military, systems. But now, with the wide availability and low cost of embedded processors and other parts of the electronics infrastructure (such as network interfaces, A/D and D/A converters), many applications have shifted to commercial. One example is automotive engine control; another is positioning and control of the read and write heads on CDROMs, DVDs, and disk drives.

Current control technology is very effective for systems with many actuators and sensors, with dynamics approximately described by differential equations. As an example of a challenging design problem that can be handled by current methods, consider a modern aircraft, perhaps tailless, with blended wing and body, and multiple redundant control surfaces (say, 20), and vectored thrust (i.e., the ability to control the direction as well as the level of thrust from its engines). For sensing, the aircraft might be equipped with a variety of sensors including gyros, accelerometers, and multiple GPS receivers. The dynamics of the aircraft might vary substantially, depending on flight conditions (altitude, cruise speed, angle of attack). Obviously designing a reliable, robust and high performance MIMO feedback controller for such a system is quite challenging. In 1985, it would have been impossible. Today, it is standard practice.

The new environment

As we look forward, the opportunities for new applications of control and new advances in control are many. The advent of ubiquitous, distributed computation, communication, and sensing systems have 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 control, especially as our software systems begin to interact with our physical systems in much more integral ways.

At the same time, control of large-scale, interconnected systems involving physical, chemical, biological, and information science are becoming a reality. New advances in microstructural processing of materials, molecular and biological computing, quantum limits of computation and communications, and control of turbulent flow will rely on the use of feedback and the integration of sensing, actuation, and computation into devices and systems.

In all of these areas, a common feature is that system level requirements far exceed the achievable reliability of the components. This is precisely where feedback (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 an interconnected set of components, to realizing control systems as a heterogeneous collection of physical and information systems, with intricate interconnections and interactions.

Vision for the future

The rich heritage of rigorous work in systems and control theory and the emergence of new technological opportunities with immense impact creates enormous challenges and opportunities for the field. The techniques that have been developed are central to the successful development of new systems of increasing complexity and interconnectivity that achieve exceptional levels of reliability and performance. Cheap, ubiquitous computation, communications, and sensing creates opportunities and the ideas of robustness and performance that lie at the heart of controls will be the dominant challenges of getting these systems to work.

In moving forward, it is essential that controls maintain its connection with mathematics and increase its interaction with computer science. These two fields are central to all applications of controls technology and we must work to both incorporate more of the techniques from these fields into our discipline and to make the results from our fields more accessible to domain experts from these fields and others. At the same time, we should continue to maintain the healthy interaction with the many other fields that has been an essential part of the controls community.

Overview of Recommendations

In order to deliver on this vision, this report outlines a number of recommendations for funding agencies, academic institutions, and researchers:

1. Increase opportunities for interaction between controls and computer science
 - Control-oriented techniques for insuring reliable operation in presence of dynamics and uncertainty are critical for future software-enabled applications
 - Current approaches in software engineering and control synthesis are not sufficient; need to merge ideas from computer science and control theory
2. Aggressively explore applications of control to large-scale, distributed systems
 - Paradigm shift in the role of software interacting with networked systems and control of phenomena that involve complex physical phenomena
 - Essential to explore these opportunities and develop needed insights, framework, theory and tools
3. Support educational, research, and infrastructure initiatives to make systems and control technology more accessible
 - Develop new courses and training modules aimed at non-experts; export systems and control concepts and tools
 - Better training for systems and control experts working in a multi-disciplinary (team) context; support interaction with domain experts

4. Maintain support for theory and interaction with mathematics

- Strength of the field relies on our close contact with rigorous mathematics; increasingly important in the future
- This is in danger of eroding due to the rapid advances of technology and the drive towards rapid implementation.

The basis of these recommendations, and the impact if they are implemented, is detailed in the remainder of the report.

[Note] *The remainder of this report is in outline form. Over the next 3–6 months, we will be soliciting input from the panel and from members of the systems and control community to fill in the various sections. A short description of intent is provided at the top of each chapter to guide the writing and maintain a consistent message throughout the report.*

2 Overview of the Field

[Note] *This section will provide a introduction to modern control, through examples and successes. This is the chapter that you give to your colleagues in other fields (or congressional staffers) when they are trying to understand that control is about, why it is important, and where it is headed. Vignettes may be included as sidebars to provide more information and insight into the main text. The target length for this chapter is 20 pages.*

2.1 What is control?

- A. Control = algorithms plus feedback in engineered systems
 - 1. Last 50 years: careful attention to completeness and correctness
- B. Control technology includes modeling, sensing, actuation, computation (together)
 - 1. Dynamics and stability
 - 2. Careful attention to being correct
- C. Control is about making engineered systems behave in a desirable fashion
 - 1. Feedback as a tool to change dynamics
 - 2. Feedback as a tool to manage uncertainty
 - a. Very powerful: (explain)
 - b. Other major paradigms as well
 - (1) Statistics
 - (2) Digital circuits
 - 3. Explicit framework for description of uncertainty
 - a. Important for all of engineering; we have developed powerful tools for dealing with this
 - b. Feedback has forced us to do this; unmanaged uncertainty can lead to catastrophic failure
 - 4. New techniques for (control-oriented) modeling, ID
 - 5. Integration of software into physical systems
 - a. control configured design
 - b. online reconfiguration
- D. How is this different than physics and computer science?
 - 1. Modeling of interaction is different; input/output approach allows new insights
 - a. Disturbance rejection
 - b. Model reduction (for control)
 - c. Robust interconnection between subsystems
 - 2. Software interacting with the physical environment
 - a. [Hard] Real-time nature of the problem
 - b. Vehicles as peripherals vs computers as implementation medium
 - c. Robust interconnection between subsystems

2.2 Examples

- A. Everyone familiar with thermostats, cruise control, homeostasis, precision guided weapons
- B. In fact: **much** more ubiquitous, **much** more critical disk drives and

CDROMS, IC manufacturing [eg XY stepper], numerically control machine tools, TCP [w/ forward reference to testimonial], wireless power control [eg CDMA], flight controls, power grid (perhaps distinguish between those that require sophisticated tools versus basic ideas; break apart?)

1. Basic ideas of feedback: ...
2. Sophisticated applications: ...
3. Opportunities for doing much more by extending application of control tools
4. Control is sometimes simple, but *finding* it requires the framework and theory

C. Detailed example: flight controls

D. Messages to make sure we capture in above

1. What have we done: industrial revolution, last 40 years
2. Control is central to many things, mostly hidden
3. Robustness is a key element
4. Rigorous approach is essential (?) [need to define what "rigor" is]
5. Not just control theorists doing control

2.3 Opportunities and challenges now facing us

A. New environment

1. Ubiquitous, distributed computation, communications, sensing
2. Large-scale, interconnected systems involving physical, chemical, biological, information sciences, integrated with algorithms and feedback
3. System-level requirements far exceed achievable reliability of components
4. Complexity requires exploration of essential physics
5. Current approach to design of these systems will not solve the problem

B. Vision for the future

C. Approach

D. Maintenance of rigor [challenge]

- a. New respect for heuristics

2.4 Overarching themes

Systems and control technology is a key enabling technology of the industrial world

Systems and control poised to enable advances in many critical new areas

Cheap, ubiquitous computation, communication, sensing creates opportunities and challenges

Interaction with computer science and mathematics is essential

Systems and control must be made more accessible

3 Applications, Opportunities, and Challenges

[Note] *This chapter will give a more detailed view of some of the upcoming challenges, split into different application areas. Each section should be something that an expert in that area would view as credible (which means that we should get experts to help write it). As in the previous chapter, we may want to include vignettes to describe some of the ideas and give a better sense of the role control plays in the various application areas.*

3.1 Aerospace and Transportation

3.2 Information and Networks

3.3 Biology and Medicine

3.4 Materials and Processing

3.5 Environment

3.6 Robotics and Intelligent Machines

4 Recommendations

- 4.1 Increase opportunities for interaction between controls and computer science
- 4.2 Aggressively explore applications of control to large-scale, distributed systems
- 4.3 Support educational, research, and infrastructure initiatives to make systems and control technology more accessible
- 4.4 Maintain support for theory and interaction with mathematics