Feedback Systems

An Introduction for Scientists and Engineers

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http://www.cds.caltech.edu/~murray/FBSwiki

Contents

Preface

This book provides an introduction to the basic principles and tools for the design and analysis of feedback systems. It is intended to serve a diverse audience of scientists and engineers who are interested in understanding and utilizing feedback in physical, biological, information and social systems. We have attempted to keep the mathematical prerequisites to a minimum while being careful not to sacrifice rigor in the process. We have also attempted to make use of examples from a variety of disciplines, illustrating the generality of many of the tools while at the same time showing how they can be applied in specific application domains.

A major goal of this book is to present a concise and insightful view of the current knowledge in feedback and control systems. The field of control started by teaching everything that was known at the time and, as new knowledge was acquired, additional courses were developed to cover new techniques. A consequence of this evolution is that introductory courses have remained the same for many years, and it is often necessary to take many individual courses in order to obtain a good perspective on the field. In developing this book, we have attempted to condense the current knowledge by emphasizing fundamental concepts. We believe that it is important to understand why feedback is useful, to know the language and basic mathematics of control and to grasp the key paradigms that have been developed over the past half century. It is also important to be able to solve simple feedback problems using back-of-the-envelope techniques, to recognize fundamental limitations and difficult control problems and to have a feel for available design methods.

This book was originally developed for use in an experimental course at Caltech involving students from a wide set of backgrounds. The course was offered to undergraduates at the junior and senior levels in traditional engineering disciplines, as well as first- and second-year graduate students in engineering and science. This latter group included graduate students in biology, computer science and physics. Over the course of several years, the text has been classroom tested at Caltech and at Lund University, and the feedback from many students and colleagues has been incorporated to help improve the readability and accessibility of the material.

Because of its intended audience, this book is organized in a slightly unusual fashion compared to many other books on feedback and control. In particular, we introduce a number of concepts in the text that are normally reserved for second-year courses on control and hence often not available to students who are not control systems majors. This has been done at the expense of certain traditional topics, which we felt that the astute student could learn independently and are often explored through the exercises. Examples of topics that we have included are nonlinear dynamics, Lyapunov stability analysis, the matrix exponential, reachability and observability, and fundamental limits of performance and robustness. Topics that we have deemphasized include root locus techniques, lead/lag compensation and detailed rules for generating Bode and Nyquist plots by hand.

Several features of the book are designed to facilitate its dual function as a basic engineering text and as an introduction for researchers in natural, information and social sciences. The bulk of the material is intended to be used regardless of the audience and covers the core principles and tools in the analysis and design of feedback systems. Advanced sections, marked by the "dangerous bend" symbol shown here, contain material that requires a slightly more technical background, of the sort that would be expected of senior undergraduates in engineering. A few sections are marked by two dangerous bend symbols and are intended for readers with more specialized backgrounds, identified at the beginning of the section. To limit the length of the text, several standard results and extensions are given in the exercises, with appropriate hints toward their solutions.

To further augment the printed material contained here, a companion web site has been developed and is available from the publisher's web page:

http://www.cds.caltech.edu/∼murray/amwiki

The web site contains a database of frequently asked questions, supplemental examples and exercises, and lecture material for courses based on this text. The material is organized by chapter and includes a summary of the major points in the text as well as links to external resources. The web site also contains the source code for many examples in the book, as well as utilities to implement the techniques described in the text. Most of the code was originally written using MATLAB M-files but was also tested with LabView MathScript to ensure compatibility with both packages. Many files can also be run using other scripting languages such as Octave, SciLab, SysQuake and Xmath.

The first half of the book focuses almost exclusively on state space control systems. We begin in Chapter 2 with a description of modeling of physical, biological and information systems using ordinary differential equations and difference equations. Chapter 3 presents a number of examples in some detail, primarily as a reference for problems that will be used throughout the text. Following this, Chapter 4 looks at the dynamic behavior of models, including definitions of stability and more complicated nonlinear behavior. We provide advanced sections in this chapter on Lyapunov stability analysis because we find that it is useful in a broad array of applications and is frequently a topic that is not introduced until later in one's studies.

The remaining three chapters of the first half of the book focus on linear systems, beginning with a description of input/output behavior in Chapter 5. In Chapter 6, we formally introduce feedback systems by demonstrating how state space control laws can be designed. This is followed in Chapter 7 by material on output feedback and estimators. Chapters 6 and 7 introduce the key concepts of reachability and observability, which give tremendous insight into the choice of actuators and sensors, whether for engineered or natural systems.

The second half of the book presents material that is often considered to be from the field of “classical control.” This includes the transfer function, introduced in Chapter 8, which is a fundamental tool for understanding feedback systems. Using transfer functions, one can begin to analyze the stability of feedback systems using frequency domain analysis, including the ability to reason about the closed loop behavior of a system from its open loop characteristics. This is the subject of Chapter 9, which revolves around the Nyquist stability criterion.

In Chapters 10 and 11, we again look at the design problem, focusing first on proportional-integral-derivative (PID) controllers and then on the more general process of loop shaping. PID control is by far the most common design technique in control systems and a useful tool for any student. The chapter on frequency domain design introduces many of the ideas of modern control theory, including the sensitivity function. In Chapter 12, we combine the results from the second half of the book to analyze some of the fundamental trade-offs between robustness and performance. This is also a key chapter illustrating the power of the techniques that have been developed and serving as an introduction for more advanced studies.

The book is designed for use in a 10- to 15-week course in feedback systems that provides many of the key concepts needed in a variety of disciplines. For a 10-week course, Chapters 1–2, 4–6 and 8–11 can each be covered in a week’s time, with the omission of some topics from the final chapters. A more leisurely course, spread out over 14–15 weeks, could cover the entire book, with 2 weeks on modeling (Chapters 2 and 3)—particularly for students without much background in ordinary differential equations—and 2 weeks on robust performance (Chapter 12).

The mathematical prerequisites for the book are modest and in keeping with our goal of providing an introduction that serves a broad audience. We assume familiarity with the basic tools of linear algebra, including matrices, vectors and eigenvalues. These are typically covered in a sophomore-level course on the subject, and the textbooks by Apostol [Apo69], Arnold [Arn87] and Strang [Str88] can serve as good references. Similarly, we assume basic knowledge of differential equations, including the concepts of homogeneous and particular solutions for linear ordinary differential equations in one variable. Apostol [Apo69] and Boyce and DiPrima [BD04] cover this material well. Finally, we also make use of complex numbers and functions and, in some of the advanced sections, more detailed concepts in complex variables that are typically covered in a junior-level engineering or physics course in mathematical methods. Apostol [Apo67] or Stewart [Ste02] can be used for the basic material, with Ahlfors [Ahl66], Marsden and Hoffman [MH98] or Saff and Snider [SS02] being good references for the more advanced material. We have chosen not to include appendices summarizing these various topics since there are a number of good books available.

One additional choice that we felt was important was the decision not to rely on a knowledge of Laplace transforms in the book. While their use is by far the most common approach to teaching feedback systems in engineering, many students in the natural and information sciences may lack the necessary mathematical background. Since Laplace transforms are not required in any essential way, we have included them only in an advanced section intended to tie things together for students with that background. Of course, we make tremendous use of *transfer functions*, which we introduce through the notion of response to exponential inputs, an approach we feel is more accessible to a broad array of scientists and engineers. For classes in which students have already had Laplace transforms, it should be quite natural to build on this background in the appropriate sections of the text.

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The authors would like to thank the many people who helped during the preparation of this book. The idea for writing this book came in part from a report on future directions in control [Mur03] to which Stephen Boyd, Roger Brockett, John Doyle and Gunter Stein were major contributors. Kristi Morgansen and Hideo Mabuchi helped teach early versions of the course at Caltech on which much of the text is based, and Steve Waydo served as the head TA for the course taught at Caltech in 2003–2004 and provided numerous comments and corrections. Charlotta Johnsson and Anton Cervin taught from early versions of the manuscript in Lund in 2003–2007 and gave very useful feedback. Other colleagues and students who provided feedback and advice include Leif Andersson, John Carson, K. Mani Chandy, Michel Charpentier, Domitilla Del Vecchio, Kate Galloway, Per Hagander, Toivo Henningsson Perby, Joseph Hellerstein, George Hines, Tore Hägglund, Cole Lepine, Anders Rantzer, Anders Robertsson, Dawn Tilbury and Francisco Zabala. The reviewers for Princeton University Press and Tom Robbins at NI Press also provided valuable comments that significantly improved the organization, layout and focus of the book. Our editor, Vickie Kearn, was a great source of encouragement and help throughout the publishing process. Finally, we would like to thank Caltech, Lund University and the University of California at Santa Barbara for providing many resources, stimulating colleagues and students, and pleasant working environments that greatly aided in the writing of this book.

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Chapter One
Introduction

Feedback is a central feature of life. The process of feedback governs how we grow, respond to stress and challenge, and regulate factors such as body temperature, blood pressure and cholesterol level. The mechanisms operate at every level, from the interaction of proteins in cells to the interaction of organisms in complex ecologies.

M. B. Hoagland and B. Dodson, *The Way Life Works*, 1995 [HD95].

In this chapter we provide an introduction to the basic concept of *feedback* and the related engineering discipline of *control*. We focus on both historical and current examples, with the intention of providing the context for current tools in feedback and control. Much of the material in this chapter is adapted from [Mur03], and the authors gratefully acknowledge the contributions of Roger Brockett and Gunter Stein to portions of this chapter.

1.1 What Is Feedback?

A *dynamical system* is a system whose behavior changes over time, often in response to external stimulation or forcing. The term *feedback* refers to a situation in which two (or more) dynamical systems are connected together such that each system influences the other and their dynamics are thus strongly coupled. Simple causal reasoning about a feedback system is difficult because the first system influences the second and the second system influences the first, leading to a circular argument. This makes reasoning based on cause and effect tricky, and it is necessary to analyze the system as a whole. A consequence of this is that the behavior of feedback systems is often counterintuitive, and it is therefore necessary to resort to formal methods to understand them.

Figure 1.1 illustrates in block diagram form the idea of feedback. We often use the terms *open loop* and *closed loop* when referring to such systems. A system is said to be a closed loop system if the systems are interconnected in a cycle, as shown in Figure 1.1a. If we break the interconnection, we refer to the configuration as an open loop system, as shown in Figure 1.1b.

As the quote at the beginning of this chapter illustrates, a major source of examples of feedback systems is biology. Biological systems make use of feedback in an extraordinary number of ways, on scales ranging from molecules to cells to organisms to ecosystems. One example is the regulation of glucose in the blood-

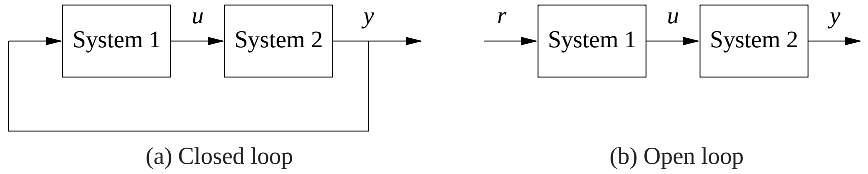


Figure 1.1: Open and closed loop systems. (a) The output of system 1 is used as the input of system 2, and the output of system 2 becomes the input of system 1, creating a closed loop system. (b) The interconnection between system 2 and system 1 is removed, and the system is said to be open loop.

stream through the production of insulin and glucagon by the pancreas. The body attempts to maintain a constant concentration of glucose, which is used by the body's cells to produce energy. When glucose levels rise (after eating a meal, for example), the hormone insulin is released and causes the body to store excess glucose in the liver. When glucose levels are low, the pancreas secretes the hormone glucagon, which has the opposite effect. Referring to Figure 1.1, we can view the liver as system 1 and the pancreas as system 2. The output from the liver is the glucose concentration in the blood, and the output from the pancreas is the amount of insulin or glucagon produced. The interplay between insulin and glucagon secretions throughout the day helps to keep the blood-glucose concentration constant, at about 90 mg per 100 mL of blood.

An early engineering example of a feedback system is a centrifugal governor, in which the shaft of a steam engine is connected to a flyball mechanism that is itself connected to the throttle of the steam engine, as illustrated in Figure 1.2. The system is designed so that as the speed of the engine increases (perhaps because of a lessening of the load on the engine), the flyballs spread apart and a linkage causes the throttle on the steam engine to be closed. This in turn slows down the engine, which causes the flyballs to come back together. We can model this system as a closed loop system by taking system 1 as the steam engine and system 2 as the governor. When properly designed, the flyball governor maintains a constant speed of the engine, roughly independent of the loading conditions. The centrifugal governor was an enabler of the successful Watt steam engine, which fueled the industrial revolution.

Feedback has many interesting properties that can be exploited in designing systems. As in the case of glucose regulation or the flyball governor, feedback can make a system resilient toward external influences. It can also be used to create linear behavior out of nonlinear components, a common approach in electronics. More generally, feedback allows a system to be insensitive both to external disturbances and to variations in its individual elements.

Feedback has potential disadvantages as well. It can create dynamic instabilities in a system, causing oscillations or even runaway behavior. Another drawback,

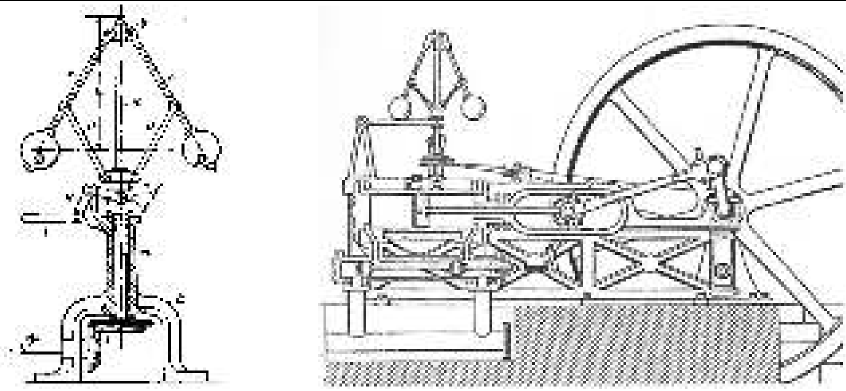


Figure 1.2: The centrifugal governor and the steam engine. The centrifugal governor on the left consists of a set of flyballs that spread apart as the speed of the engine increases. The steam engine on the right uses a centrifugal governor (above and to the left of the flywheel) to regulate its speed. (Credit: Machine a Vapeur Horizontale de Philip Taylor [1828].)

especially in engineering systems, is that feedback can introduce unwanted sensor noise into the system, requiring careful filtering of signals. It is for these reasons that a substantial portion of the study of feedback systems is devoted to developing an understanding of dynamics and a mastery of techniques in dynamical systems.

Feedback systems are ubiquitous in both natural and engineered systems. Control systems maintain the environment, lighting and power in our buildings and factories; they regulate the operation of our cars, consumer electronics and manufacturing processes; they enable our transportation and communications systems; and they are critical elements in our military and space systems. For the most part they are hidden from view, buried within the code of embedded microprocessors, executing their functions accurately and reliably. Feedback has also made it possible to increase dramatically the precision of instruments such as atomic force microscopes (AFMs) and telescopes.

In nature, homeostasis in biological systems maintains thermal, chemical and biological conditions through feedback. At the other end of the size scale, global climate dynamics depend on the feedback interactions between the atmosphere, the oceans, the land and the sun. Ecosystems are filled with examples of feedback due to the complex interactions between animal and plant life. Even the dynamics of economies are based on the feedback between individuals and corporations through markets and the exchange of goods and services.

1.2 What Is Control?

The term *control* has many meanings and often varies between communities. In this book, we define control to be the use of algorithms and feedback in engineered systems. Thus, control includes such examples as feedback loops in electronic amplifiers, setpoint controllers in chemical and materials processing, "fly-by-wire" systems on aircraft and even router protocols that control traffic flow on the Internet. Emerging applications include high-confidence software systems, autonomous vehicles and robots, real-time resource management systems and biologically engineered systems. At its core, control is an *information* science and includes the use of information in both analog and digital representations.

A modern controller senses the operation of a system, compares it against the desired behavior, computes corrective actions based on a model of the system's response to external inputs and actuates the system to effect the desired change. This basic *feedback loop* of sensing, computation and actuation is the central concept in control. The key issues in designing control logic are ensuring that the dynamics of the closed loop system are stable (bounded disturbances give bounded errors) and that they have additional desired behavior (good disturbance attenuation, fast responsiveness to changes in operating point, etc). These properties are established using a variety of modeling and analysis techniques that capture the essential dynamics of the system and permit the exploration of possible behaviors in the presence of uncertainty, noise and component failure.

A typical example of a control system is shown in Figure 1.3. The basic elements of sensing, computation and actuation are clearly seen. In modern control systems, computation is typically implemented on a digital computer, requiring the use of analog-to-digital (A/D) and digital-to-analog (D/A) converters. Uncertainty enters the system through noise in sensing and actuation subsystems, external disturbances that affect the underlying system operation and uncertain dynamics in the system (parameter errors, unmodeled effects, etc). The algorithm that computes the control action as a function of the sensor values is often called a *control law*. The system can be influenced externally by an operator who introduces *command signals* to the system.

Control engineering relies on and shares tools from physics (dynamics and modeling), computer science (information and software) and operations research (optimization, probability theory and game theory), but it is also different from these subjects in both insights and approach.

Perhaps the strongest area of overlap between control and other disciplines is in the modeling of physical systems, which is common across all areas of engineering and science. One of the fundamental differences between control-oriented modeling and modeling in other disciplines is the way in which interactions between subsystems are represented. Control relies on a type of input/output modeling that allows many new insights into the behavior of systems, such as disturbance attenuation and stable interconnection. Model reduction, where a simpler (lower-fidelity) description of the dynamics is derived from a high-fidelity model, is also naturally described in an input/output framework. Perhaps most importantly, modeling in a

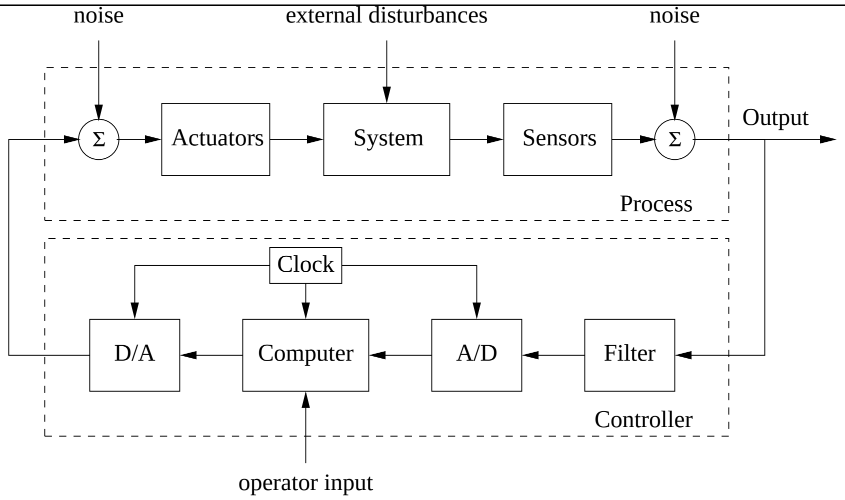


Figure 1.3: Components of a computer-controlled system. The upper dashed box represents the process dynamics, which include the sensors and actuators in addition to the dynamical system being controlled. Noise and external disturbances can perturb the dynamics of the process. The controller is shown in the lower dashed box. It consists of a filter and analog-to-digital (A/D) and digital-to-analog (D/A) converters, as well as a computer that implements the control algorithm. A system clock controls the operation of the controller, synchronizing the A/D, D/A and computing processes. The operator input is also fed to the computer as an external input.

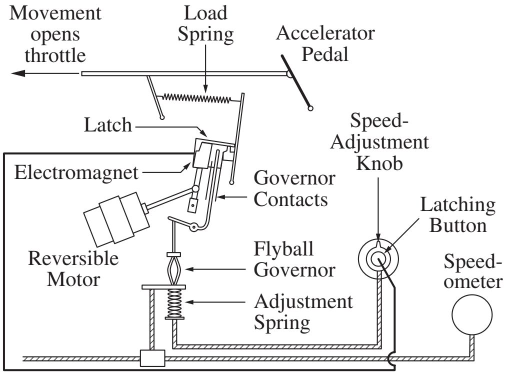
control context allows the design of *robust* interconnections between subsystems, a feature that is crucial in the operation of all large engineered systems.

Control is also closely associated with computer science since virtually all modern control algorithms for engineering systems are implemented in software. However, control algorithms and software can be very different from traditional computer software because of the central role of the dynamics of the system and the real-time nature of the implementation.

1.3 Feedback Examples

Feedback has many interesting and useful properties. It makes it possible to design precise systems from imprecise components and to make relevant quantities in a system change in a prescribed fashion. An unstable system can be stabilized using feedback, and the effects of external disturbances can be reduced. Feedback also offers new degrees of freedom to a designer by exploiting sensing, actuation and computation. In this section we survey some of the important applications and trends for feedback in the world around us.

(a) Honeywell thermostat, 1953



(b) Chrysler cruise control, 1958

Figure 1.4: Early control devices. (a) Honeywell T87 thermostat originally introduced in 1953. The thermostat controls whether a heater is turned on by comparing the current temperature in a room to a desired value that is set using a dial. (b) Chrysler cruise control system introduced in the 1958 Chrysler Imperial [Row58]. A centrifugal governor is used to detect the speed of the vehicle and actuate the throttle. The reference speed is specified through an adjustment spring. (Left figure courtesy of Honeywell International, Inc.)

Early Technological Examples

The proliferation of control in engineered systems occurred primarily in the latter half of the 20th century. There are some important exceptions, such as the centrifugal governor described earlier and the thermostat (Figure 1.4a), designed at the turn of the century to regulate the temperature of buildings.

The thermostat, in particular, is a simple example of feedback control that everyone is familiar with. The device measures the temperature in a building, compares that temperature to a desired setpoint and uses the *feedback error* between the two to operate the heating plant, e.g., to turn heat on when the temperature is too low and to turn it off when the temperature is too high. This explanation captures the essence of feedback, but it is a bit too simple even for a basic device such as the thermostat. Because lags and delays exist in the heating plant and sensor, a good thermostat does a bit of anticipation, turning the heater off before the error actually changes sign. This avoids excessive temperature swings and cycling of the heating plant. This interplay between the dynamics of the process and the operation of the controller is a key element in modern control systems design.

There are many other control system examples that have developed over the years with progressively increasing levels of sophistication. An early system with broad public exposure was the *cruise control* option introduced on automobiles in 1958 (see Figure 1.4b). Cruise control illustrates the dynamic behavior of closed loop feedback systems in action—the slowdown error as the system climbs a grade, the gradual reduction of that error due to integral action in the controller, the small

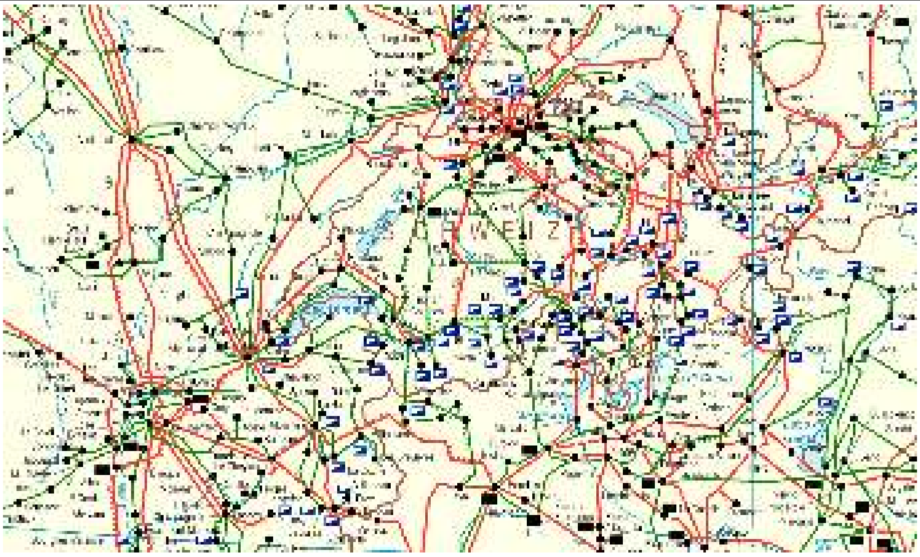


Figure 1.5: A small portion of the European power network. By 2008 European power suppliers will operate a single interconnected network covering a region from the Arctic to the Mediterranean and from the Atlantic to the Urals. In 2004 the installed power was more than 700 GW (7×10^{11} W). (Source: UCTE [www.ucte.org])

overshoot at the top of the climb, etc. Later control systems on automobiles such as emission controls and fuel-metering systems have achieved major reductions of pollutants and increases in fuel economy.

Power Generation and Transmission

Access to electrical power has been one of the major drivers of technological progress in modern society. Much of the early development of control was driven by the generation and distribution of electrical power. Control is mission critical for power systems, and there are many control loops in individual power stations. Control is also important for the operation of the whole power network since it is difficult to store energy and it is thus necessary to match production to consumption. Power management is a straightforward regulation problem for a system with one generator and one power consumer, but it is more difficult in a highly distributed system with many generators and long distances between consumption and generation. Power demand can change rapidly in an unpredictable manner and combining generators and consumers into large networks makes it possible to share loads among many suppliers and to average consumption among many customers. Large transcontinental and transnational power systems have therefore been built, such as the one show in Figure 1.5.

Most electricity is distributed by alternating current (AC) because the transmission voltage can be changed with small power losses using transformers. Alternating current generators can deliver power only if the generators are synchronized to the voltage variations in the network. This means that the rotors of all generators in a network must be synchronized. To achieve this with local decentralized controllers and a small amount of interaction is a challenging problem. Sporadic low-frequency oscillations between distant regions have been observed when regional power grids have been interconnected [KW05].

Safety and reliability are major concerns in power systems. There may be disturbances due to trees falling down on power lines, lightning or equipment failures. There are sophisticated control systems that attempt to keep the system operating even when there are large disturbances. The control actions can be to reduce voltage, to break up the net into subnets or to switch off lines and power users. These safety systems are an essential element of power distribution systems, but in spite of all precautions there are occasionally failures in large power systems. The power system is thus a nice example of a complicated distributed system where control is executed on many levels and in many different ways.

Aerospace and Transportation

In aerospace, control has been a key technological capability tracing back to the beginning of the 20th century. Indeed, the Wright brothers are correctly famous not for demonstrating simply powered flight but *controlled* powered flight. Their early Wright Flyer incorporated moving control surfaces (vertical fins and canards) and warpable wings that allowed the pilot to regulate the aircraft's flight. In fact, the aircraft itself was not stable, so continuous pilot corrections were mandatory. This early example of controlled flight was followed by a fascinating success story of continuous improvements in flight control technology, culminating in the high-performance, highly reliable automatic flight control systems we see in modern commercial and military aircraft today (Figure 1.6).

Similar success stories for control technology have occurred in many other application areas. Early World War II bombsights and fire control servo systems have evolved into today's highly accurate radar-guided guns and precision-guided weapons. Early failure-prone space missions have evolved into routine launch operations, manned landings on the moon, permanently manned space stations, robotic vehicles roving Mars, orbiting vehicles at the outer planets and a host of commercial and military satellites serving various surveillance, communication, navigation and earth observation needs. Cars have advanced from manually tuned mechanical/pneumatic technology to computer-controlled operation of all major functions, including fuel injection, emission control, cruise control, braking and cabin comfort.

Current research in aerospace and transportation systems is investigating the application of feedback to higher levels of decision making, including logical reg-

(a) F/A-18 “Hornet”

(b) X-45 UCAV

Figure 1.6: Military aerospace systems. (a) The F/A-18 aircraft is one of the first production military fighters to use “fly-by-wire” technology. (b) The X-45 (UCAV) unmanned aerial vehicle is capable of autonomous flight, using inertial measurement sensors and the global positioning system (GPS) to monitor its position relative to a desired trajectory. (Photographs courtesy of NASA Dryden Flight Research Center.)

ulation of operating modes, vehicle configurations, payload configurations and health status. These have historically been performed by human operators, but today that boundary is moving and control systems are increasingly taking on these functions. Another dramatic trend on the horizon is the use of large collections of distributed entities with local computation, global communication connections, little regularity imposed by the laws of physics and no possibility of imposing centralized control actions. Examples of this trend include the national airspace management problem, automated highway and traffic management and command and control for future battlefields.

Materials and Processing

The chemical industry is responsible for the remarkable progress in developing new materials that are key to our modern society. In addition to the continuing need to improve product quality, several other factors in the process control industry are drivers for the use of control. Environmental statutes continue to place stricter limitations on the production of pollutants, forcing the use of sophisticated pollution control devices. Environmental safety considerations have led to the design of smaller storage capacities to diminish the risk of major chemical leakage, requiring tighter control on upstream processes and, in some cases, supply chains. And large increases in energy costs have encouraged engineers to design plants that are highly integrated, coupling many processes that used to operate independently. All of these trends increase the complexity of these processes and the performance requirements for the control systems, making control system design increasingly challenging. Some examples of materials-processing technology are shown in Fig-

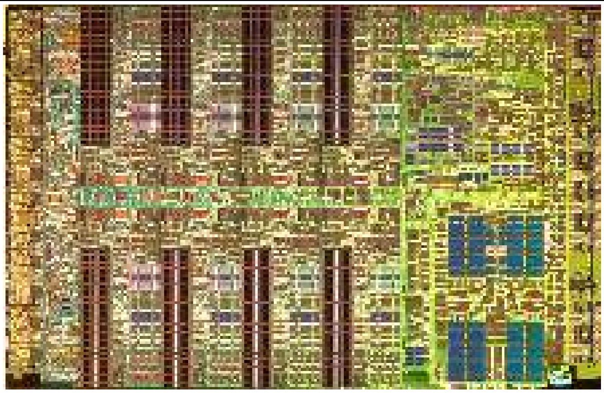


Figure 1.7: Materials processing. Modern materials are processed under carefully controlled conditions, using reactors such as the metal organic chemical vapor deposition (MOCVD) reactor shown on the left, which was for manufacturing superconducting thin films. Using lithography, chemical etching, vapor deposition and other techniques, complex devices can be built, such as the IBM cell processor shown on the right. (MOCVD image courtesy of Bob Kee. IBM cell processor photograph courtesy Tom Way, IBM Corporation; unauthorized use not permitted.)

ure 1.7.

As in many other application areas, new sensor technology is creating new opportunities for control. Online sensors—including laser backscattering, video microscopy and ultraviolet, infrared and Raman spectroscopy—are becoming more robust and less expensive and are appearing in more manufacturing processes. Many of these sensors are already being used by current process control systems, but more sophisticated signal-processing and control techniques are needed to use more effectively the real-time information provided by these sensors. Control engineers also contribute to the design of even better sensors, which are still needed, for example, in the microelectronics industry. As elsewhere, the challenge is making use of the large amounts of data provided by these new sensors in an effective manner. In addition, a control-oriented approach to modeling the essential physics of the underlying processes is required to understand the fundamental limits on observability of the internal state through sensor data.

Instrumentation

The measurement of physical variables is of prime interest in science and engineering. Consider, for example, an accelerometer, where early instruments consisted of a mass suspended on a spring with a deflection sensor. The precision of such an instrument depends critically on accurate calibration of the spring and the sensor. There is also a design compromise because a weak spring gives high sensitivity but low bandwidth.

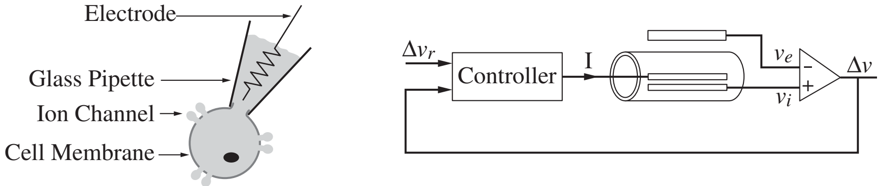


Figure 1.8: The voltage clamp method for measuring ion currents in cells using feedback. A pipet is used to place an electrode in a cell (left and middle) and maintain the potential of the cell at a fixed level. The internal voltage in the cell is v_i, and the voltage of the external fluid is v_e. The feedback system (right) controls the current I into the cell so that the voltage drop across the cell membrane $\Delta v = v_i - v_e$ is equal to its reference value Δv_r. The current I is then equal to the ion current.

A different way of measuring acceleration is to use *force feedback*. The spring is replaced by a voice coil that is controlled so that the mass remains at a constant position. The acceleration is proportional to the current through the voice coil. In such an instrument, the precision depends entirely on the calibration of the voice coil and does not depend on the sensor, which is used only as the feedback signal. The sensitivity/bandwidth compromise is also avoided. This way of using feedback has been applied to many different engineering fields and has resulted in instruments with dramatically improved performance. Force feedback is also used in haptic devices for manual control.

Another important application of feedback is in instrumentation for biological systems. Feedback is widely used to measure ion currents in cells using a device called a *voltage clamp*, which is illustrated in Figure 1.8. Hodgkin and Huxley used the voltage clamp to investigate propagation of action potentials in the giant axon of the squid. In 1963 they shared the Nobel Prize in Medicine with Eccles for “their discoveries concerning the ionic mechanisms involved in excitation and inhibition in the peripheral and central portions of the nerve cell membrane.” A refinement of the voltage clamp called a *patch clamp* made it possible to measure exactly when a single ion channel is opened or closed. This was developed by Neher and Sakmann, who received the 1991 Nobel Prize in Medicine “for their discoveries concerning the function of single ion channels in cells.”

There are many other interesting and useful applications of feedback in scientific instruments. The development of the mass spectrometer is an early example. In a 1935 paper, Nier observed that the deflection of ions depends on both the magnetic and the electric fields [Nie35]. Instead of keeping both fields constant, Nier let the magnetic field fluctuate and the electric field was controlled to keep the ratio between the fields constant. Feedback was implemented using vacuum tube amplifiers. This scheme was crucial for the development of mass spectroscopy.

The Dutch engineer van der Meer invented a clever way to use feedback to maintain a good-quality high-density beam in a particle accelerator [MPTvdM80].

The idea is to sense particle displacement at one point in the accelerator and apply a correcting signal at another point. This scheme, called *stochastic cooling*, was awarded the Nobel Prize in Physics in 1984. The method was essential for the successful experiments at CERN where the existence of the particles W and Z associated with the weak force was first demonstrated.

The 1986 Nobel Prize in Physics—awarded to Binnig and Rohrer for their design of the scanning tunneling microscope—is another example of an innovative use of feedback. The key idea is to move a narrow tip on a cantilever beam across a surface and to register the forces on the tip [BR86]. The deflection of the tip is measured using tunneling. The tunneling current is used by a feedback system to control the position of the cantilever base so that the tunneling current is constant, an example of force feedback. The accuracy is so high that individual atoms can be registered. A map of the atoms is obtained by moving the base of the cantilever horizontally. The performance of the control system is directly reflected in the image quality and scanning speed. This example is described in additional detail in Chapter 3.

Robotics and Intelligent Machines

The goal of cybernetic engineering, already articulated in the 1940s and even before, has been to implement systems capable of exhibiting highly flexible or "intelligent" responses to changing circumstances. In 1948 the MIT mathematician Norbert Wiener gave a widely read account of cybernetics [Wie48]. A more mathematical treatment of the elements of engineering cybernetics was presented by H. S. Tsien in 1954, driven by problems related to the control of missiles [Tsi54]. Together, these works and others of that time form much of the intellectual basis for modern work in robotics and control.

Two accomplishments that demonstrate the successes of the field are the Mars Exploratory Rovers and entertainment robots such as the Sony AIBO, shown in Figure 1.9. The two Mars Exploratory Rovers, launched by the Jet Propulsion Laboratory (JPL), maneuvered on the surface of Mars for more than 4 years starting in January 2004 and sent back pictures and measurements of their environment. The Sony AIBO robot debuted in June 1999 and was the first "entertainment" robot to be mass-marketed by a major international corporation. It was particularly noteworthy because of its use of artificial intelligence (AI) technologies that allowed it to act in response to external stimulation and its own judgment. This higher level of feedback is a key element in robotics, where issues such as obstacle avoidance, goal seeking, learning and autonomy are prevalent.

Despite the enormous progress in robotics over the last half-century, in many ways the field is still in its infancy. Today's robots still exhibit simple behaviors compared with humans, and their ability to locomote, interpret complex sensory inputs, perform higher-level reasoning and cooperate together in teams is limited.

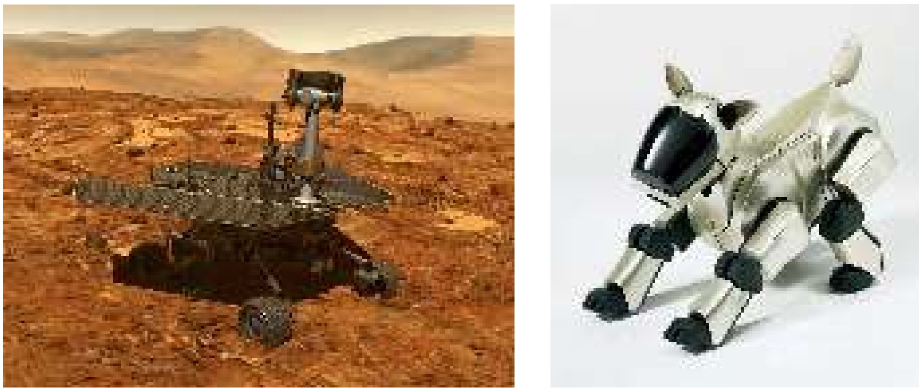


Figure 1.9: Robotic systems. (a) Spirit, one of the two Mars Exploratory Rovers that landed on Mars in January 2004. (b) The Sony AIBO Entertainment Robot, one of the first entertainment robots to be mass-marketed. Both robots make use of feedback between sensors, actuators and computation to function in unknown environments. (Photographs courtesy of Jet Propulsion Laboratory and Sony Electronics, Inc.)

Indeed, much of Wiener's vision for robotics and intelligent machines remains unrealized. While advances are needed in many fields to achieve this vision—including advances in sensing, actuation and energy storage—the opportunity to combine the advances of the AI community in planning, adaptation and learning with the techniques in the control community for modeling, analysis and design of feedback systems presents a renewed path for progress.

Networks and Computing Systems

Control of networks is a large research area spanning many topics, including congestion control, routing, data caching and power management. Several features of these control problems make them very challenging. The dominant feature is the extremely large scale of the system; the Internet is probably the largest feedback control system humans have ever built. Another is the decentralized nature of the control problem: decisions must be made quickly and based only on local information. Stability is complicated by the presence of varying time lags, as information about the network state can be observed or relayed to controllers only after a delay, and the effect of a local control action can be felt throughout the network only after substantial delay. Uncertainty and variation in the network, through network topology, transmission channel characteristics, traffic demand and available resources, may change constantly and unpredictably. Other complicating issues are the diverse traffic characteristics—in terms of arrival statistics at both the packet and flow time scales—and the different requirements for quality of service that the network must support.

Related to the control of networks is control of the servers that sit on these net-