Chapter 1

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.*
>
> Mahlon B. Hoagland and B. Dodson, from *The Way Life Works*, 1995 [3].

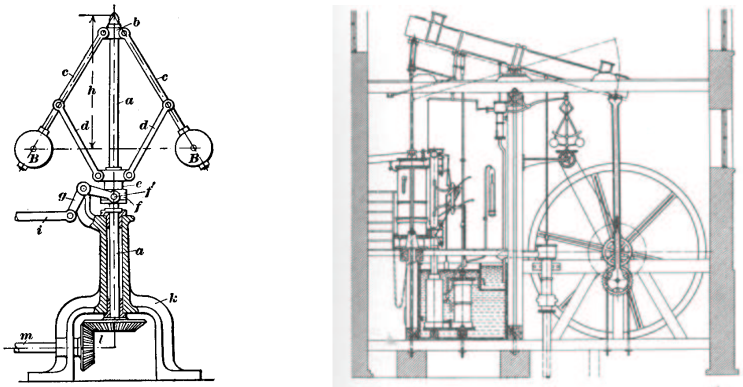
In this chapter we provide an introduction to the basic concept of *feedback* and the related engineering discipline of *control*.

1.1 What is Feedback?

The term *feedback* is used to refer 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 such a 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 a feedback system is often counterintuitive and therefore necessary to resort to formal methods to understand them.

An early example of a feedback system is the centrifugal governor, in which the shaft of a team engine is connected to a flyball mechanism that is itself connected to the throttle of the steam engine, as illustrated in Figure 1.1. [1] The system is designed so that as the speed of the engine increases

[1] The centrifugal governer is often called the "Watt governor", because James Watt



(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 Richard Adamek (copyright 1999) and Cambridge University.

(perhaps due to 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. When properly designed, the flyball governor maintains a constant speed of the engine, roughly independent of the loading conditions.

Feedback has many interesting properties that can be exploited in designing systems. As in the case of the flyball governor, feedback can make a system very resilient towards external influences. It is possible to create linear behavior out of nonlinear components. More generally, feedback allows a system to be very insensitive both to external disturbances and to variations in its individual components. Feedback has one major disadvantage: it may create dynamic instabilities in a system, causing oscillations or even runaway behavior. It is for this reason that a substantial portion of the study of feedback systems is devoted to developing an understanding of dynamics and mastery of techniques in dynamical systems.

Feedback systems are ubiquitous in both natural and engineered systems. Homeostasis in biological systems maintains thermal, chemical, and biological conditions through feedback. Global climate dynamics depend on the feedback interactions between the atmosphere, oceans, land, and the sun.

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popularized its use on steam engines. However, contrary to common belief, James Watt did not invent the flyball governer itself.

Ecologies are filled with examples of feedback, resulting in complex interactions between animal and plant life. 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, set point 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 that 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 dynamics have the desired behavior (good disturbance rejection, fast responsiveness to changes in operating point, etc). These properties are established using a variety of modeling and analysis techniques that capture the essential physics of the system and permit the exploration of possible behaviors in the presence of uncertainty, noise, and component failures.

A typical example of a modern control system is shown in Figure 1.2. The basic elements of 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 physics, and uncertain dynamics in the physical system (parameter errors, unmodeled effects, etc).

Control engineering relies on and shares tools from physics (dynamics and modeling), computer science (information and software) and operations

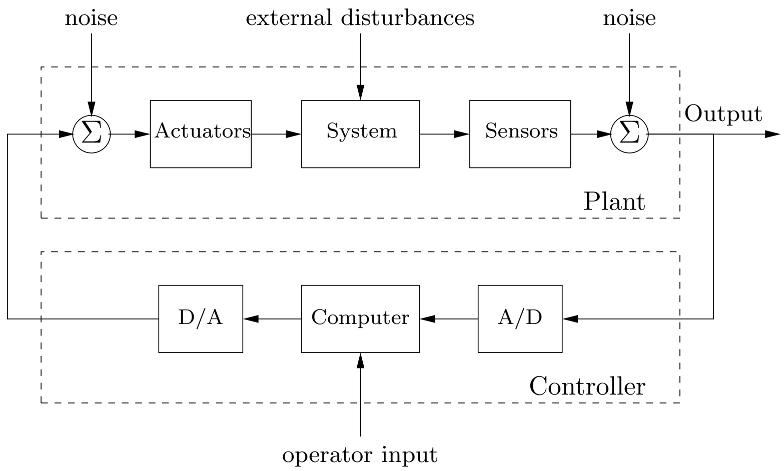


Figure 1.2: Components of a modern control system.

research (optimization and game theory), but it is also different from these subjects, in both insights and approach.

A key difference with many scientific disciplines is that control is fundamentally an engineering science. Unlike natural science, whose goal is to understand nature, the goal of engineering science is to understand and develop new systems that can benefit mankind. Typical examples are systems for transportation, electricity, communication and entertainment that have contributed dramatically to the comfort of life. While engineering originally emerged as traditional disciplines such as mining, civil, mechanical, electrical and computing, control emerged as a *systems* discipline around 1950 and cut across these traditional disciplines. The pinnacle of achievement in engineering science is to find new systems principles that are essential for dealing with complex man-made systems. Feedback is such a principle and it has had a profound impact on engineering systems.

Perhaps the strongest area of overlap between control and other disciplines is in 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 (components) are represented. Control relies on input/output modeling that allows many new insights into the behavior of systems, such as disturbance rejection and stable interconnection. Model reduction, where a simpler (lower-fidelity) description of the dynamics is derived from a high fidelity model, is also very naturally described in an input/output framework. Perhaps most importantly, modeling in a control context allows the design of *robust* interconnections between subsystems, a feature that is crucial in the operation of all large, engineered systems.

Control share many tools with the field of operations research. Optimization and differential games play central roles in each, and both solve problems of asset allocation in the face of uncertainty. The role of dynamics and interconnection (feedback) is much more ingrained within control, as well as the concepts of stability and dynamic performance.

Control is also closely associated with computer science, since virtually all modern control algorithms are implemented in software. However, control algorithms and software are very different from traditional computer software. The physics (dynamics) of the system are paramount in analyzing and designing them and their (hard) real-time nature dominates issues of their implementation. From a software-centric perspective, an F-16 is simply another peripheral, while from a control-centric perspective, the computer is just another implementation medium for the feedback law. Neither of these are adequate abstractions, and this is one of the key areas of current research in the field.

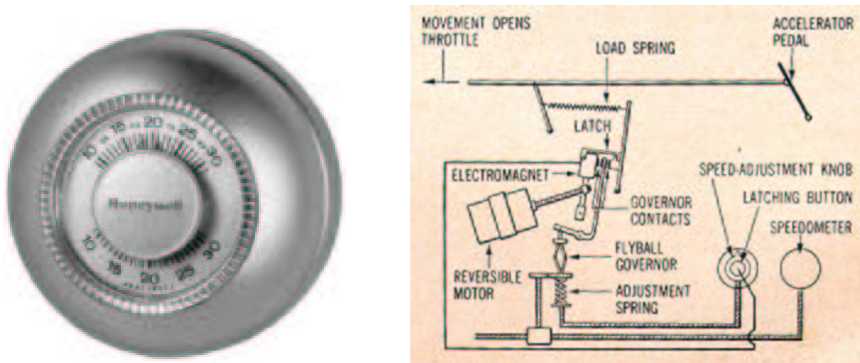
1.3 Control System Examples

Control systems are all around us in the modern technological world. They 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 processors, executing their functions accurately and reliably. Nevertheless, their existence is a major intellectual and engineering accomplishment that is still evolving and growing, promising ever more important consequences to society.

1.3.1 Early Examples

The proliferation of control in engineered systems has occurred primarily in the latter half of the 20th Century. There are some familiar exceptions, such as the Watt governor described earlier and the thermostat (Figure 1.3a), designed at the turn of the century to regulate temperature of buildings.

The thermostat, in particular, is often cited as a simple example of feedback control that everyone can understand. Namely, the device measures



(a) (b)

Figure 1.3: Early control devices: (a) Honeywell T86 thermostat, originally introduced in 1953, (b) Chrysler cruise control system, introduced in the 1958 Chrysler Imperial (note the centrifugal governor) [4].

the temperature in a building, compares that temperature to a desired set point, and uses the "feedback error" between these two to operate the heating plant, e.g., to turn heating on when the temperature is too low and to turn if off when 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. Actually, because lags and delays exist in the heating plant and sensor, a good thermostat does a bit of anticipation, turning the plant off before the error actually changes sign. This avoids excessive temperature swings and cycling of the heating plant.

This modification illustrates that, even in simple cases, good control system design it not entirely trivial. It must take into account the dynamic behavior of the object being controlled in order to do a good job. The more complex the dynamic behavior, the more elaborate the modifications. In fact, the development of a thorough theoretical understanding of the relationship between dynamic behavior and good controllers constitutes the most significant intellectual accomplishment of the control community, and the codification of this understanding into powerful computer aided engineering design tools makes all modern control systems possible.

There are many other control system examples, of course, that have developed over the years with progressively increasing levels of sophistication and impact. An early system with broad public exposure was the "cruise control" option introduced on automobiles in 1958 (see Figure 1.3b). With cruise control, ordinary people experienced the dynamic behavior of closed

Figure 1.4: The F-18 aircraft, one of the first production military fighters to use "fly-by-wire" technology, and the X-45 (UCAV) unmanned aerial vehicle. Photographs courtesy of NASA Dryden Flight Research Center.

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 (but unavoidable) overshoot at the top of the climb, etc. More importantly, by experiencing these systems operating reliably and robustly, the public learned to trust and accept feedback systems, permitting their increasing proliferation all around us. Later control systems on automobiles have had more concrete impact, such as emission controls and fuel metering systems that have achieved major reductions of pollutants and increases in fuel economy.

In the industrial world, control systems have been key enabling technologies for everything from factory automation (starting with numerically controlled machine tools), to process control in oil refineries and chemical plants, to integrated circuit manufacturing, to power generation and distribution. They now also play critical roles in the routing of messages across the Internet (TCP/IP) and in power management for wireless communication systems.

1.3.2 Aerospace and Transportation

Aerospace and transportation encompasses a collection of critically important application areas where control is a key enabling technology. These application areas represent a significant part of the modern world's overall technological capability. They are also a major part of its economic strength, and they contribute greatly to the well being of its people.

In aerospace, specifically, control has been a key technological capability tracing back to the very beginning of the 20th century. Indeed, the Wright brothers are correctly famous not simply for demonstrating powered flight—they actually demonstrated *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 is followed by a fascinating success story of continuous improvements in flight control technology, culminating in the very high performance, highly reliable automatic flight control systems we see on modern commercial and military aircraft today.

Similar success stories for control technology 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.

Despite its many successes, the control needs of some engineered systems today and those of many in the future outstrip the power of current tools and theories. Design problems have grown from so-called "inner loops" in a control hierarchy (e.g. regulating a specified flight parameter) to various "outer loop" functions that provide logical regulation of operating modes, vehicle configurations, payload configurations, health status, etc. [1]. For aircraft, these functions are collectively called "vehicle management." They have historically been performed by pilots or other human operators, but today that boundary is moving, and control systems are increasingly taking on these functions.

Today's engineering methods for designing the upper layers of this hierarchy are far from formal and systematic. In essence, they consist of collecting long lists of logical if-then-else rules from experts, programming these rules, and simulating their execution in operating environments. Because the logical rules provide no inherent smoothness (any state transition is possible) only simulation can be used for evaluation and only exhaustive simulation can guarantee good design properties. Clearly, this is an unacceptable circumstance—one where the strong system-theoretic background and the tradition of rigor held by the control community can make substan-

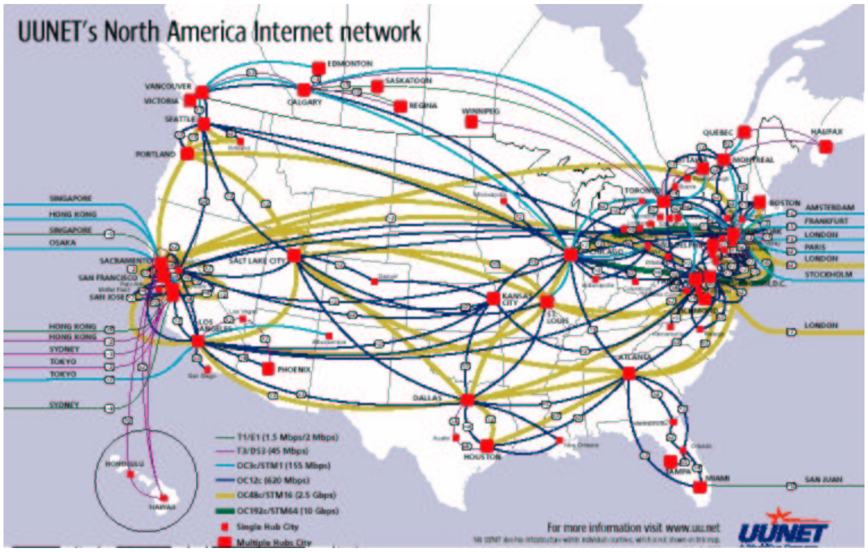


Figure 1.5: UUNET network backbone for North America. Figure courtesy of WorldCom.

tial contributions.

Another dramatic trend on the horizon is a change in dynamics to large collections of distributed entities with local computation, global communication connections, very 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 the command and control for future battlefields.

1.3.3 Information and Networks

The rapid growth of communication networks provides several major opportunities and challenges for control. Although there is overlap, we can divide these roughly into two main areas: control of networks and control over networks.

Control of networks is a large 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 man has ever built. Another is the decentralized nature of the control problem: local 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 only be observed or relayed to controllers after a time delay, and the effect of a local control action can be felt throughout the network after substantial delay. Uncertainty and variation in the network, through network topology, transmission channel characteristics, traffic demand, available resources, and the like, may change constantly and unpredictably. Another complicating issue is the diverse traffic characteristics, in terms of arrival statistics at both the packet and flow time scales, and different requirements for quality of service, in terms of delay, bandwidth, and loss probability, that the network must support.

Resources that must be managed in this environment include computing, storage and transmission capacities at end hosts and routers. Performance of such systems is judged in many ways: throughput, delay, loss rates, fairness, reliability, as well as the speed and quality with which the network adapts to changing traffic patterns, changing resource availability, and changing network congestion.

While the advances in information technology to date have led to a global Internet that allows users to exchange information, it is clear that the next phase will involve much more interaction with the physical environment and the increased use of control over networks. Networks of sensory or actuator nodes with computational capabilities, connected wirelessly or by wires, can form an orchestra that controls our physical environment. Examples include automobiles, smart homes, large manufacturing systems, intelligent highways and networked city services, and enterprise-wide supply and logistics chains. Thus, this next phase of the information technology revolution is the convergence of communications, computing, and control.

As existing networks continue to build out, and network technology becomes cheaper and more reliable than fixed point-to-point connections, even in small localized systems, more and more control systems will operate over networks. We can foresee sensor, actuator, diagnostic, and command and coordination signals all traveling over data networks. The estimation and control functions can be distributed across multiple processors, also linked by data networks. (For example, smart sensors can perform substantial local signal processing before forwarding relevant information over a network.)

Current control systems are almost universally based on synchronous, clocked systems, so they require communication networks that guarantee delivery of sensor, actuator, and other signals with a known, fixed delay. Although current control systems are robust to variations that are included in the design process (such as a variation in some aerodynamic coefficient, motor constant, or moment of inertia), they are not at all tolerant of (unmodeled) communication delays or dropped or lost sensor or actuator packets. Current control system technology is based on a simple communication architecture: all signals travel over synchronous dedicated links, with known (or worst-case bounded) delays and no packet loss. Small dedicated communication networks can be configured to meet these demanding specifications for control systems, but a very interesting question is whether we can develop a theory and practice for control systems that operate in a distributed, asynchronous, packet-based environment.

1.3.4 Robotics and Intelligent Machines

Robotics and intelligent machines refers to a collection of applications involving the development of machines with humanlike behavior. Whereas early robots were primarily used for manufacturing, modern robots include wheeled and legged machines capable of competing in robotic competitions and exploring planets, unmanned aerial vehicles for surveillance and combat, and medical devices that provide new capabilities to doctors. Future applications will involve both increased autonomy and increased interaction with humans and with society. Control is a central element in all of these applications and will be even more important as the next generation of intelligent machines are developed.

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, albeit completely nonmathematical, account of cybernetics [9]. A more mathematical treatment of the elements of engineering cybernetics was presented by H.S. Tsien at Caltech in 1954, driven by problems related to control of missiles [8]. 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 Sojourner robot and the Sony AIBO robot, shown in Fig. 1.6. Sojourner successfully maneuvered on the surface of Mars for 83 days starting in July 1997 and sent back live pictures of its environment. The Sony AIBO robot debuted in June of 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 AI technologies that allowed it to act in response to external stimulation and its own judgment.

It is interesting to note some of the history of the control community in robotics. The IEEE Robotics and Automation Society was jointly founded

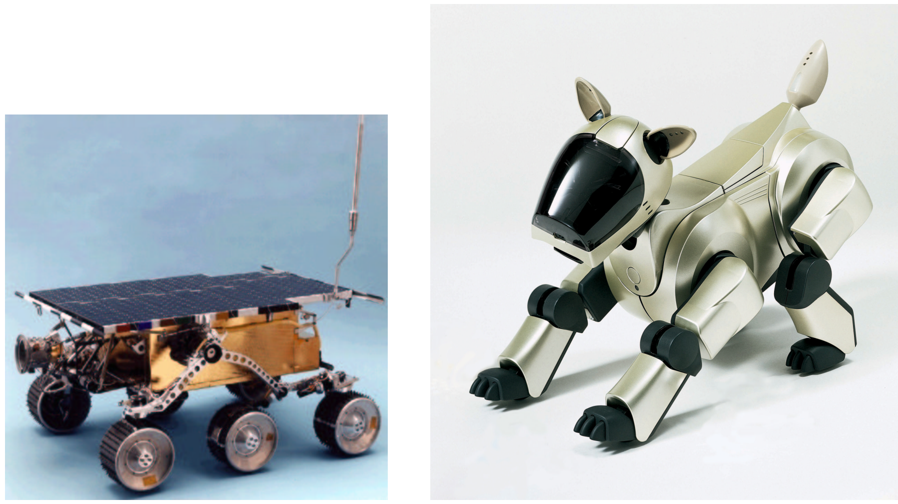


Figure 1.6: The Mars Sojourner and Sony AIBO robots. Photographs courtesy of Jet Propulsion Laboratory and Sony.

in the early 1980s by the Control Systems Society and the Computer Society, indicating the mutual interest in robotics by these two communities. Unfortunately, although many control researchers were active in robotics, the control community did not play a leading role in robotics research throughout much of the 1980s and 90s. This was a missed opportunity, since robotics represents an important collection of applications that combine ideas from computer science, artificial intelligence, and control. New applications in (unmanned) flight control, underwater vehicles, and satellite systems are generating renewed interest in robotics, and many control researchers are becoming active in this area.

Despite the enormous progress in robotics over the last half century, the field is very much in its infancy. Today's robots still exhibit extremely 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. 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.

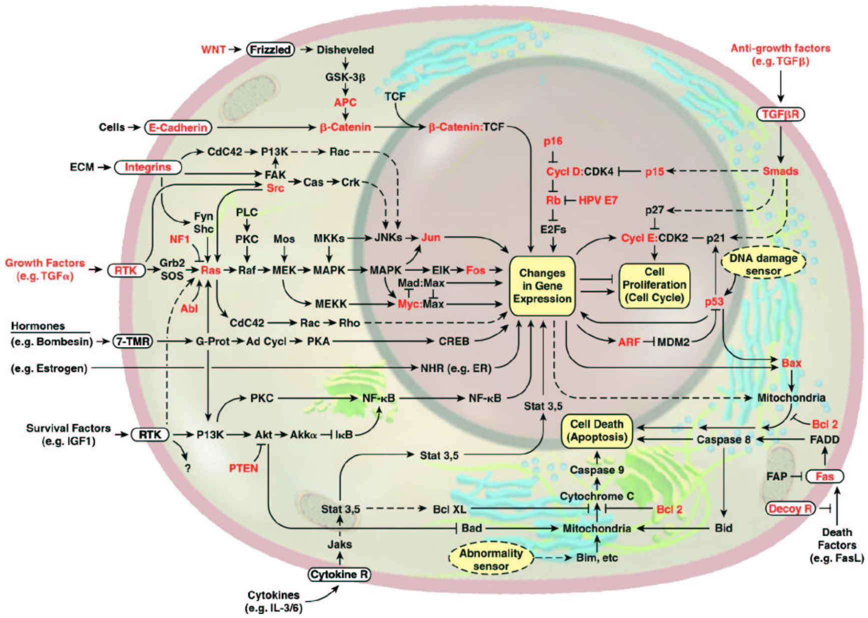


Figure 1.7: The wiring diagram of the growth signaling circuitry of the mammalian cell [2].

1.3.5 Biology and Medicine

At a variety of levels of organization—from molecular to cellular to organismal to populational—biology is becoming more accessible to approaches that are commonly used in engineering: mathematical modeling, systems theory, computation, and abstract approaches to synthesis. Conversely, the accelerating pace of discovery in biological science is suggesting new design principles that may have important practical applications in man-made systems. This synergy at the interface of biology and engineering offers unprecedented opportunities to meet challenges in both areas. The principles of control are central to many of the key questions in biological engineering and will play an enabling role in the future of this field.

A major theme currently underway in the biology community is the science of reverse (and eventually forward) engineering of biological control networks. There are a wide variety of biological phenomena that provide a rich source of examples for control, including gene regulation and signal transduction; hormonal, immunological, and cardiovascular feedback mechanisms; muscular control and locomotion; active sensing, vision, and proprioception; attention and consciousness; and population dynamics and epidemics. Each of these (and many more) provide opportunities to figure out what works, how it works, and what we can do to affect it.

The are also many roles for control in medicine and biomedical research. These included intelligent operating rooms and hospitals; image-guided surgery and therapy; hardware and soft tissue integration; fluid flow control for medicine and biological assays; and the development of physical and neural prostheses. Many of these areas have substantial overlap with robotics.

1.3.6 Materials and Processing

The chemical industry is among the most successful industries in the United States, producing $400 billion of products annually and providing over one million U.S. jobs. Having recorded a trade surplus for 40 consecutive years, it is the country's premier exporting industry: chemical industry exports totaled $72.5 billion in 2000, accounting for more than 10% of all U.S. exports, and generated a record trade surplus in excess of $20 billion in 1997.

Process manufacturing operations will require a continual infusion of advanced information and process control technologies if the chemical industry is to maintain its global ability to deliver products that best serve the customer reliably at the lowest cost. In addition, several new technology areas are being explored that will require new approaches to control to be successful. These range from nanotechnology in areas such as electronics, chemistry, and biomaterials to thin film processing and design of integrated microsystems to supply chain management and enterprise resource allocation. The payoffs for new advances in these areas are substantial, and the use of control is critical to future progress in sectors from semiconductors to pharmaceuticals to bulk materials.

There are several common features within materials and processing that pervade many of the applications. Modeling plays a crucial role, and there is a clear need for better solution methods for multidisciplinary systems combining chemistry, fluid mechanics, thermal sciences, and other disciplines at a variety of temporal and spatial scales. Better numerical methods for traversing these scales and designing, controlling, and optimizing under uncertainty are also needed. And control techniques must make use of increased in situ measurements to control increasingly complex phenomena.

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.

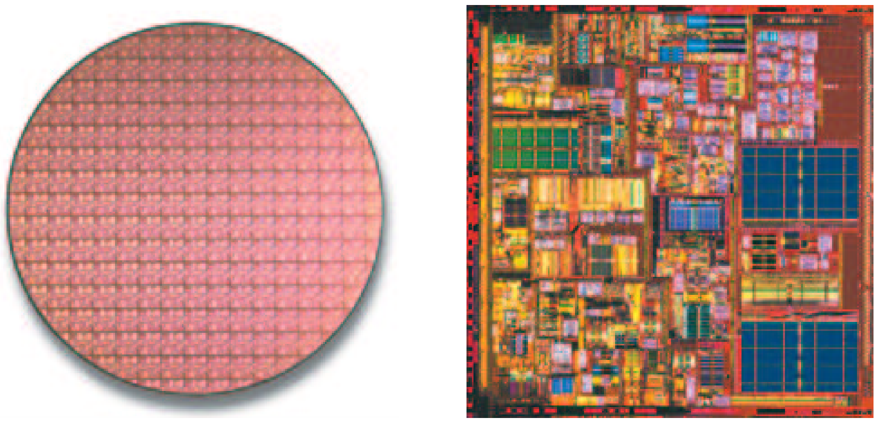


Figure 1.8: Intel Pentium IV wafer and die. Photographs courtesy of Intel.

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 the control system design increasingly challenging.

As in many other application areas, new sensor technology is creating new opportunities for control. Online sensors—including laser backscattering, video microscopy, 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 more effectively use the real-time information provided by these sensors. Control engineers can 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 fundamental limits on observability of the internal state through sensor data.

1.3.7 Other Areas

The previous sections have described some of the major application areas for control. However, there are many more areas where ideas from control are being applied or could be applied. Some of these include:

- Environmental science and engineering, particularly atmospheric systems and microbiological ecosystems
- Economics and finance, including problems such as pricing and hedging options
- Electromagnetics, including active electromagnetic nulling for stealth applications
- Molecular, quantum, and nanoscale systems, including design of nanostructured materials, precision measurement, and quantum information processing
- Energy systems, including load distribution and power management for the electrical grid

1.4 Properties of Feedback

Feedback is a powerful idea, which is used extensively in natural and technical systems. The principle of feedback is very simple: base correcting actions on the difference between desired and actual performance. In engineering feedback has been rediscovered and patented many times in many different contexts. The use of feedback has often resulted in vast improvements in system capability, sometimes they have even be revolutionary as discussed above. Chapter **??**. The reason for this is that feedback has some truly remarkable properties. In this section we will discuss some of the properties of feedback that can be understood intuitively. The benefits of feedback can often be obtained using simple forms of feedback such as on-off control and proportional-derivative-integral (PID) control, which we discuss in subsequent chapters.

Robustness to uncertainty

One of the key uses of feedback is to provide robustness to uncertainty. By measuring the different between the sensed value of a regulated signal and its actual value, we can supply a corrective action. If the system undergoes some change that affects the regulated signal, then we sense this change and try to force the system back to the desired operating point. This is precisely the effect that Watt exploited in his use of the centrifugal governor on steam engines.

Another early example of the use of feedback to provide robustness was the negative feedback amplifier of Black. When telephone communications were developed, amplifiers were used to compensate for signal attenuation in long lines. The vacuum tube was a component that could be used to build amplifiers. Distortion caused by the nonlinear characteristics of the tube amplifier together with amplifier drift were obstacles that prevented development of line amplifiers for a long time. A major breakthrough was Black's invention of the feedback amplifier in 1927. Black used negative feedback which reduces the gain but makes the amplifier very insensitive to variations in tube characteristics. Black's invention made it possible to build stable amplifiers with linear characteristics despite nonlinearities of the vacuum tube amplifier.

Design of dynamics

Another use of feedback is the change the dynamics of a system. Through feedback, we can alter the behavior of a system to meet the needs of an application: systems that are unstable can be stabilized, systems that are sluggish can be made responsive, and systems that have drifting operating points can be held constant. Control theory provides a rich collection of techniques to analyze the stability and dynamic response of complex systems and to place bounds on the behavior of such systems by analyzing the gains of linear and nonlinear operators that describe their components.

An example of the use of control in the design of dynamics comes from the area of flight control. The following quote, from a lecture by Wilbur Wright to the Western Society of Engineers in 1901 [5], illustrates the role of control in the development of the airplane:

> " Men already know how to construct wings or airplanes, which when driven through the air at sufficient speed, will not only sustain the weight of the wings themselves, but also that of the engine, and of the engineer as well. Men also know how to build engines and screws of sufficient lightness and power to drive these planes at sustaining speed ... Inability to balance and steer still confronts students of the flying problem. ... When this one feature has been worked out, the age of flying will have arrived, for all other difficulties are of minor importance."

Figure 1.9: The Curtiss-Sperry E in 1912 (left) and a closeup of the Sperry Autopilot (right).

The Wright brothers thus realized that control was a key issue to enable flight. They resolved the compromise between stability and maneuverability by building an airplane, Kitty Hawk, that was unstable but maneuverable. The pioneering flight was in 1905. Kitty Hawk had a rudder in the front of the airplane, which made the plane very maneuverable. A disadvantage was the necessity for the pilot to keep adjusting the rudder to fly the plane. If the pilot let go of the stick the plane would crash. Other early aviators tried to build stable airplanes. These would have been easier to fly, but because of their poor maneuverability they could not be brought up into the air. By using their insight and skillful experiments the Wright brothers made the first successful flight with Kitty Hawk in 1905.

Since it was quite tiresome to fly an unstable aircraft, there was strong motivation to find a mechanism that would stabilize an aircraft. Such a device, invented by Sperry, was based on the concept of feedback. Sperry used a gyro-stabilized pendulum to provide an indication of the vertical. He then arranged a feedback mechanism that would pull the stick to make the plane go up if it was pointing down and vice versa. The Sperry autopilot is the first use of feedback in aeronautical engineering. Sperry won a prize in a competition for the safest airplane in Paris in 1912. Figure 1.9 is a picture from the event. The autopilot is a good example of how feedback can be used to stabilize an unstable system.

Input/Output Modeling

Control theory also provides new techniques for (control-oriented) system modeling and identification. Since models play an essential role in analysis and design of feedback systems, sophisticated tools have been developed to build such models. These include input/output representations of systems (how disturbances propagate through the system) and data-driven system identification techniques. The use of "forced response" experiments to build models of systems is well developed in the control field and these tools find application in many disciplines, independent of the use of feedback. A strong theory of modeling has also been developed, allowing rigorous definitions of model fidelity and comparisons to experimental data.

Drawbacks of feedback

While feedback has many advantages, it also has some drawbacks. Chief among these is the possibility for instability if the system is not design properly. We are all familiar with the effects of "positive feedback" when the amplification on a microphone is turned up to high in a room. This is an example of a feedback instability, and something that we obviously want to avoid. This is tricky because of the uncertainty that feedback was introduced to compensate for: not only must we design the system to be stable with the nominal system we are designing for, but it must remain stable under all possible perturbations of the dynamics.

Another potential drawback of control is the complexity of embedding a control system into a product. While the cost of sensing, computation, and (to a lesser extent) actuation has decreased dramatically in the past few decades, the fact remains that control systems are often very complicated and hence one must carefully balance the costs and benefits.

1.5 Outline of the Book

Hard to do since this is the only chapter that is written so far...

1.6 References

The material in this section draws heavily from the report of the Panel on Future Directions on Control, Dynamics, and Systems [**?**] and the a recent textbook by one of the authors [**?**]. A fascinating examination of some of the early history of control in the United States has been written by Mindell [6].

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