Chapter 1

Humans and Automation:

System Design and Research Issues

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Chapter 1

INTRODUCTION

This section presents some basic ideas of human factors (as the term is used here; see below) and automation, as separate and distinct entities and emerging disciplines. Because this is meant to be a primer, the intention is not to give a complete and comprehensive treatise on either topic. Many books have been written about each, especially about automation. But I want to start with the separate entities and then illustrate the coming together: the interactions, the cooperations (and lacks thereof), the marriage (however uncomfortable) between humans and automation.

Does it make sense to talk about humans and automation interacting? Is a *human-automation system* an impossibility by definition, an oxymoron? The answer is a loud and clear "NO," and I will employ the term *human-automation system* from time to time without apology. Such a system is more restrictive than *human-machine system* in that it includes only those machines that — by a definition yet to be made — are automated. But they are not fully automated, not 100%. Actually, few systems are 100% automated, with no human interaction whatsoever. Many, many systems are automated to a large extent and *also* have critical human interactions.

In the case of automation per se, some small bit of mathematics is usually deemed essential to say much of anything. However, the purpose of this book is to convey the basic concepts at an intuitive level. Therefore Appendix A presents the mathematical models fundamental to automation, whereas the main body of the book discusses the human-automation relation qualitatively.

Human Factors: What Is It (Are They)?

Definitions

Human factors, also known as *human engineering* or *human factors engineering*, is the application of behavioral and biological sciences to the design of machines and human-machine systems. The most salient behavioral sciences are cognitive psychology and the broader field of experimental psychology (study of sensation, perception, memory, and thinking, as well as motor skill) and to a lesser extent organizational and social

psychology, sociology, and psychometrics, but not clinical psychology. The most salient biological science is human systems physiology (study of organ functions above the cellular level).

Often the term *ergonomics* (derived from the Greek *ergon,* work, and *nomos,* principle or law; literally, "work study") is used as a synonym for *human factors.* However, in some circles ergonomics has come to be associated with the narrower aspect of human factors dealing with anthropometry, biomechanics, and body kinematics as applied to the design of seating and workspaces. The interaction of humans with automation deals less with ergonomics in this traditional sense and more with sensory and cognitive function. The terms *cognitive engineering* and *cognitive ergonomics* have therefore come into vogue.

A Brief History

Throughout history there has been interest in the human body and brain and a practical interest in human performance in the workplace. Leonardo da Vinci made ingenious drawings of human-machine systems. In 1857 a Polish scholar, Wojciech Jastrobowski, published *An Outline of Ergonomics, or The Science of Work.* In the early 1900s Frederick Lewis Taylor, sometimes referred to as the "father of scientific management," tried to put the study of production line efficiency on a scientific basis using time and motion analysis (only to become a symbol of human exploitation several decades later by worker advocates). Edwin Link built early flight simulators at the time of World War I.

Human factors may be said to have begun in earnest as a discipline during World War II, when it was fully appreciated that modern weapons of war required explicit engineering of the interface between human and machine. This meant fitting the user to the machine (aircraft cockpits, radar or sonar workstations, gun sights, etc.) not only in terms of body size and strength but also with respect to limits of vision and hearing, experience, and learning capability. Psychologists, physiologists, and medical doctors in both the United States and Europe (primarily Britain and Germany) were brought into government laboratories to work with engineers and produce explicit system designs and do laboratory experiments to develop guidelines for future systems.

After the war most of these people returned to their domestic jobs (universities, companies, etc.) and brought with them an appreciation of the need to develop human factors as an engineering discipline. Their governments also appreciated the need and continued to support research in various aspects of human factors. In the United States the initial effort was mostly applied research on how to design displays and controls and workstations for defense systems, whereas in Europe the applications were mostly in industrial production, to help rebuild the damaged economies. Tools of human activity analysis from earlier production-line applications were refined and applied to a broad range of human workplaces. Measures of visual and auditory acuity and other aspects of human performance within work settings became commonplace. Several handbooks emerged from this period, notable among them the Van Cott and Kinkade *Human Engineering Guide to Equipment Design* (1972). This early, empirical phase has often been called (disparagingly) "knobs and dials engineering." The design of displays, controls, and workplace layouts, however, has remained as important as it ever was. The problems have just grown more complex, as the reader shall see.

During World War II a number of important theoretical concepts were developed, motivated by the need to build more capabilities into military systems. These included feedback control theory, signal detection theory, and decision theory. Shortly after that war information theory was formally introduced by Bell Laboratories. Initially these ideas were applied to physical systems with little thought to applying them to humans, but human factors engineers were quick to appreciate their broader applicability. The physical inputs and outputs became stimulus to human (what was presented on display devices) and response from human (what was measured from the control devices). The system engineering models became ways of characterizing human experimental data in laboratory experiments and field tests with displays and controls.

Perhaps more important, human factors engineers began to look at information, control, and decision making as a continuous process within a closed loop that also included physical subsystems — more than just sets of independent stimulus-response relations. (An appreciation for this difference may be gained by understanding the discussion of loop equations in Appendix A.) This stage of the development of human factors engineering brought it fully into the realm of systems engineering. Human input-output or transfer equations could be combined with input-output equations of the machinery. In fact, prior to this stage it made little sense to analyze the machine components of systems if the human component, connected in series, could not itself be analyzed in similar terms. So this might be called the "borrowed engineering models" stage of development of the human factors field.

In the early 1970s the computer was becoming more powerful, smaller, and cheaper, first as a minicomputer and a decade later as a microcomputer. This piece of technology changed human-machine systems profoundly. Computers especially changed display technology. Earlier displays were costly mechanical instruments that mostly had to be dedicated to one function. Now they are generated by computers with an

infinite variety of display formats and animated graphics in living color. Computers also changed controls so that the human operator could type commands, use touch screens, or even speak commands and have them understood, in addition to using dedicated buttons, levers, wheels, or pedals. Also, as shall be seen, computers intervened in human-machine systems in many other ways, becoming intelligent agents to search data, give advice, and perform subordinate control functions. The problems for humans interacting with automation have become those of humans interacting with computers, but not only computers on desktops — more likely, computers in a thousand different systems in all walks of life.

Looking back, the progress in human factors or human-machine systems engineering might be summarized by three phases, as represented in Figure 1.1. Phase A (knobs and dials) refers to the traditional biomechanical ergonomics of workstation design. Phase B (borrowed engineering models) refers to the use of quantitative performance models of information processing, signal detection, and control that emerged after World War II. Phase C (human-computer interaction) refers to the variety of human interactions with computers that are occurring today. The development within each component over time is represented by a plot of "progress" (choose your own measure) versus time. Phases A and B have shapes depicting rapid growth at first, which then tapered off but have continued development. Phase C is still developing rapidly and constitutes most of the issues discussed in this book.

During the last half century, government agencies and companies have become more astute about the application of human factors. The U.S. Army, Navy, and Air Force each has a basic research arm with an active human factors program, and applied research is carried out in myriad

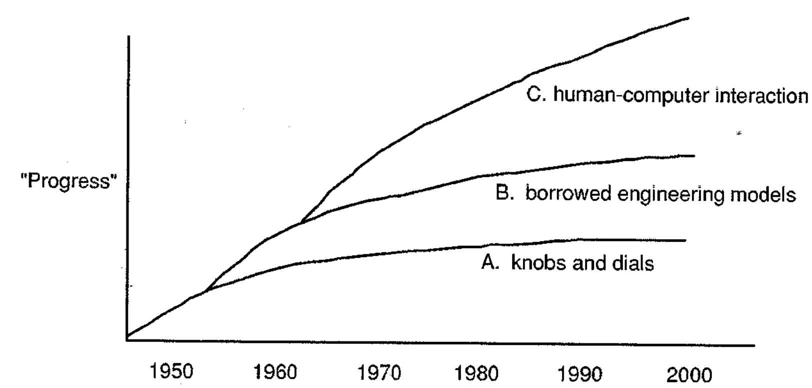

Figure 1.1 The history of intellectual development in human-machine systems engineering.

places, including the National Aeronautics and Space Administration (NASA), Federal Aviation Administration (FAA), Nuclear Regulatory Commission, and Department of Transportation. Professional societies have been founded, including the Human Factors and Ergonomics Society (HFES), which began in 1957 and now has about 5000 members, and the International Ergonomics Association, an umbrella organization that was organized at about the same time, now has more than 25 affiliated human factors/ergonomics societies around the world. The Institute of Electrical and Electronics Engineers (IEEE) Systems, Man, and Cybernetics Society has around 5000 individuals. Academic institutions have set up degree programs in human factors, mostly in psychology and industrial engineering departments; HFES publishes a listing of such programs. In Canada, Europe, and Japan a similar organizing of human factors activities has occurred.

Methods of Human Factors

In systems design, human factors takes the viewpoint of the human user. This is often overlooked by design engineers, who assume that because they themselves are human, the user's viewpoint and constraints will naturally be considered. The fallacy, of course, is that one person doesn't think like another person; a wide range of people must be accommodated. In particular, the designer, who may know the physical problems and physical process very well, does not think like the users (at least, not like 95% of them). So although human factors is often regarded as common sense, it is mostly very uncommon sense!

In contrast to the usual idea that *engineering design* means to design things or physical relations among things (call that *systems design*), *human factors design* means to design the relations between people and things. It requires a different perspective.

Do human factors theories exist? Not a lot, at least not in the same quantitative sense as in physics and engineering. Yes, there is theory in the qualitative sense — lots of that — and it is certainly not my intention to demean qualitative theory. (In fact, much of what will be said in this book can be called qualitative theory!) The quantitative theory that is available is limited to two types. First are those relatively few mathematical models that generalize the transducer properties of the eyes, ears, other sensors, and the musculoskeletal system. Then there are the information, decision, and control models, already referred to, that are borrowed from systems engineering. These are reviewed in Appendix A.

Human factors engineering is mostly an empirical activity, much like medicine, with a growing literature that must be interpreted in a practical context. The human factors practitioner almost always begins with some kind of task analysis to define what variables in what ranges are important (what kind of people to consider, how well trained they are, what motivations they have, etc.). Some part of the literature is always relevant, and, like the physician, the human factors practitioner should know how to access and make use of the experimental literature. Taking recommendations from handbooks and guidebooks may be worth doing for checking one's considerations, but it is definitely not recommended as the sole accession of the literature. Naive application of handbook data can lead to disaster!

It is usually essential to do some kind of ad hoc experiment to understand the problem and get ideas for its solution. Finally, after design solutions become tentative, it is often worth setting up some kind of computer simulation or mockup of the workplace and its displays and controls in order to train some real people who come close to the target population of users and to try out the prototype system with some performance scoring, error observations, and subjective assessments.

Good introductions to human factors engineering are Wickens, Gordon, and Liu (1998); Booher (1990); and Sanders and McCormick (1987).

The Shape of Human Factors Today

In Figure 1.1, Phase C in particular is growing very fast and in many ways, enhanced by artificially intelligent agents, human supervisory control, teleoperation, virtual reality, and many other new developments. Phase C, human-computer interaction, is synonymous with "humans and automation" in the broad sense (and see the definitions of automation in the next section).

Cognitive engineering and *cognitive ergonomics*, terms that were at first offensive to many because "cognitive" smacked of scientific imprecision, have become accepted as the challenge of dealing with human factors in automation. The point is that humans are doing less physical work than previously. Although the problems of humans doing physical work remain important, they are gradually being replaced by the problems of humans interacting mentally with computers and automation. Such interaction still requires seeing, hearing, and button pushing, but the human factors literature is in relatively good shape there. The problems are in attending, perceiving, remembering, deciding, and, in general, thinking — all aspects of that unfortunately still qualitative term, *cognition.*

One form of system representation is cited in this section, one that is both commonly accepted by cognitive engineers and highly relevant to humans and automation. This is Rasmussen's (1976, 1986) idea that human behavior is based on *skills, rules, and knowledge,* elements that are interdependent in the organism, as shown in Figure 1.2.

The interesting thing is that these elements have their counterparts in automation technology. Skill-based behavior corresponds to continuous closed-loop control. Rule-based behavior corresponds to rule-based computer decision making. Knowledge-based behavior, some say, has no counterpart in technology, but others assert that very advanced artificial intelligence comes close. The diagram in Figure 1.2 is an example of a cognitive engineering idea, one that seems to tie together human cognition and computer decision making/control.

Although human interaction with technology is recognized by the public as a salient issue and human factors as a professional discipline is now recognized in some engineering communities (e.g., aerospace and the military), the human factors profession is still struggling for recognition within much of the engineering world. This is particularly true of cognitive engineering or cognitive ergonomics. This is because engineers, having thoroughly utilized and become indoctrinated in Newtonian physics, expect all engineering to be up to that level of analytic codification. Engineers do appreciate that medicine is still an empirical science and that the human body in the health context cannot be expected to meet the standard of garden-variety physics. Somehow the point is missed that in engineering products and systems for people, there is a legitimate cognitive aspect that still must be treated empirically. This can be a frightening idea for engineers.

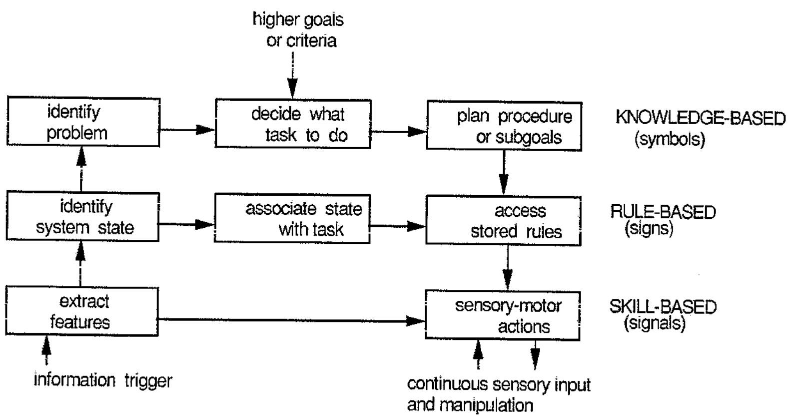

Figure 1.2 The Rasmussen knowledge-rule-skill hierarchy.

What Is Automation?

This section is not meant as a rigorous treatment of automation; rather, it provides an intuitive idea of the essential concepts. Familiarity with elementary notions of functions and differential equations is helpful; further exposition of quantitative ideas is in Appendix A. Readers can also find more rigorous treatments in the library. Those with a background in the theory of decision and control can skip what is already familiar.

Definitions

The term *automation* has several definitions. The *Oxford English Dictionary* (second edition, 1989) defines it as follows:

1. Automatic control of the manufacture of a product through a number of successive stages;
2. the application of automatic control to any branch of industry or science;
3. by extension, the use of electronic or mechanical devices to replace human labor

The term's first use is traceable to a 1952 *Scientific American* article.

With regard to the first meaning, in technical writing today the term has easily grown beyond manufacturing, which was the context of the first use. The second meaning is probably the most widely accepted today, but in this case there is a restriction to what is commonly meant by *automatic control,* which is discussed later. The third meaning, however, is now gaining wide acceptance — namely, any mechanical or electronic replacement of human labor, where labor is taken to mean either physical labor or mental labor. Physical labor was of concern decades ago; mental labor is of primary importance today, at least in the developed nations. Computers that interpret inputs, record data, make decisions, or generate displays are now regarded as automation, including the sensors that go with them, even though in the strict sense none of these functions may be automatic control.

In the fullest contemporary sense of the term, *automation* refers to (a) the mechanization and integration of the sensing of environmental variables (by artificial sensors); (b) data processing and decision making (by computers); and (c) mechanical action (by motors or devices that apply forces on the environment) or "information action" by communication of processed information to people (see Figure 1.3). It can refer to open-loop operation on the environment or closed-loop control.

The term *computerization* formally refers to the instrumentality (the computer) by which a data-processing function is performed. Insofar as the data-processing function is one that replaces (or could replace) a human, one can say that computerization is automation. Computers can perform

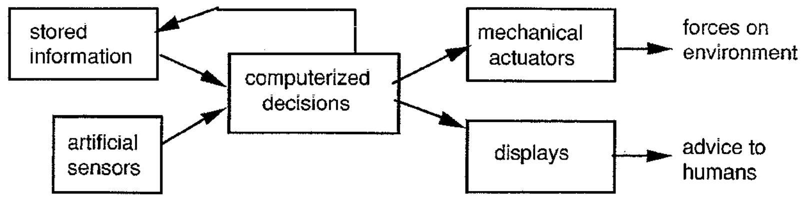

Figure 1.3 The scope of automation.

classical feedback control, which will be considered next, or they can implement crisp or fuzzy rule-based control, which are discussed in Appendix A.

History of Automation

Historically, the first automation was mechanization of manual labor during the Industrial Revolution, although the term was not in use at that time. Steam engines and, later, electric motors were attached to mechanisms that performed routine operations (e.g., sewing, metal stamping) open loop (i.e., without feedback control or self-correction of errors).

Automatic control (feedback control) devices existed early, the most celebrated example being the flyball governor (left panel of Figure 1.4), which was developed to regulate the flow of steam into a steam engine. As the engine shaft (1) rotates faster and faster, centrifugal force acting on the flyballs pushes the balls out (2), moving against a spring, and making the collar slide axially along the shaft (3). This motion is attached to the steam entry valve in such a way that as the balls spin faster, the valve closes more, thereby reducing steam flow to the engine and tending to reduce the

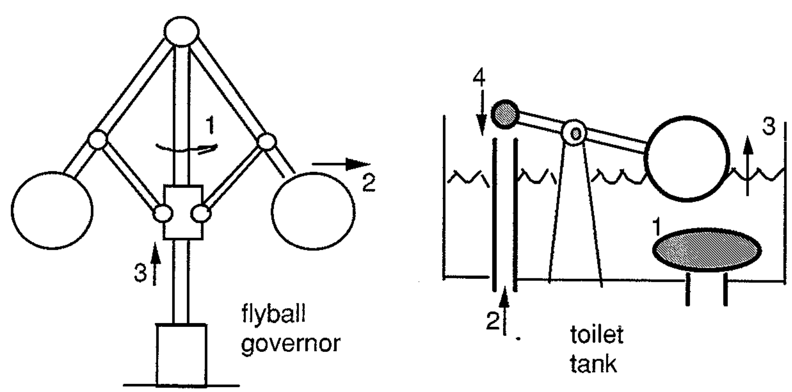

Figure 1.4 Two early automatic controllers.

shaft speed. In this way, with a given setting of the flyball spring, the steam engine comes to an equilibrium speed. Hooking up the flyball device so that faster shaft motion (and flyballs pushing farther out) closes the steam valve is called *negative feedback*. If the attachment were made in the reverse manner, such that faster speed would open the valve, the steam engine would go faster and faster until either it destroyed itself or its speed became limited by its own internal friction.

Another classical example of automatic negative feedback control is the toilet tank (right panel of Figure 1.4). After the toilet is flushed by opening the main valve seat (1) and the water flows into the bowl, the main valve seat (1) then closes by gravity. Then the water supply pressure forces water into the tank (2) and the level rises. As it does so the float ball (3) goes up and eventually forces the supply closure valve (4) down, thereby shutting off further flow into the tank. In this way the water level is regulated to a particular depth in the tank.

Driving a car is another example of negative feedback control, although in this case it is manual rather than automatic. The driver senses whether the car is to the left or to the right of where he or she intends the car to be on the road. If it is to the left, the driver turns a little to the right, and vice versa (this is the negative feedback). In other words, the driver's output — to null any error between desired and actual position on the road — is negative to the visual input. The control gain is the driver's sensitivity to error, the size of the negative steering response relative to the size of the sensed lateral error. The larger the gain, the less the car will deviate owing to any disturbances. (However, if there is a time delay in the system and the gain is too large, control can become oscillatory and even unstable; see Appendix A, section 5.4, to understand why.)

The history of automation includes many engineering developments of sensors, actuators, computers, robots, and all the associated physical systems.

The Status of Automation Today

Automation technology has grown sophisticated, driven by market demands as well as theoretical developments that have occurred at a great pace. Although the diversity of automatic control techniques in the literature is extensive, including so-called optimal control, adaptive control, fuzzy control, and neural nets (the first three are reviewed in Appendix A), the vast majority of practical control applications employ the 50-year-old classical control techniques (see Appendix A). A good general reference to control instrumentation is Shell and Hall (2000).

Computer chips are now part of automobiles, medical devices, home appliances, cameras, watches . . . the list is endless. All of these could be called "automation" in terms of the third Oxford meaning cited earlier. Automation is now a major part of engineering analysis and design, crossing into every traditional branch of engineering.

A Preview of the Critical Issues of Humans and Automation

In this section some hints are given regarding what humans and automation is all about. The point has already been made that automation is here and will remain. In fact, it has been a kind of technological imperative — design engineers automate because they can — and is not always a good idea.

Humans, too, are here to stay — at least as long as the automation, I hope. The automation is supposed to serve the people, not the other way around. So the two must get along. They must live together. They must work together. They must interact.

Automation is still foreign to most people, though. They don't understand it. The more sophisticated it gets, the less they understand it. When they don't understand it, they may not trust it. Or they may overtrust it, attributing to it intelligence that it really does not have. Automation is silent and opaque. It does not reveal its intentions. The people around it cannot always predict what it is doing at the moment or what it is going to do next.

Automation is mostly stupid and single-minded. Unlike people, it is not robust and adaptable. It does what it is programmed to do, which is not always what is desirable or even what the humans using it or affected by it expect it to do.

However, automation can be made to operate in different ways, provide different displays, be controlled in different modes. The problem is that people forget which display or control mode they set it in. Then they may misinterpret what they think the automation is telling them, or what the automation does in response to their command may differ significantly from what they think they asked it to do.

Automation can be reliable, and when it is, people become bored trying to monitor it. People are really not good monitors, anyway. Sometimes the automation fails, though, and when it does, it may be very difficult for the operator to wake up, figure out what has failed, and take corrective action. There simply may be too little time for the human operator to adjust before serious consequences occur.

One form of automation is the decision aid, the advice giver, the expert system, the management information system. It doesn't act, it just tells people how to act. The myth is that decision aids are always safer than

automatic controls because the people can still be depended on. The problem with such systems is that people come to trust them and then to overtrust them. Then the people tend to cease acting independently. At that point the decision aid might as well be connected directly to the machine — the human has no apparent function anymore.

Introducing automation can also be intimidating and alienating. A worker in a manufacturing plant who previously had been a skilled craftsman becomes a button pusher — at least, that's the way he sees himself. He may come to feel that the automation is really in charge, that he has no particular contribution to make, so why should he accept responsibility? The designer of the automation is the only human who is responsible.

It should be evident from these thumbnail expressions that automation poses problems, real and imagined, for the human user or other persons who may be affected. The remainder of the book deals with these issues.