PART I

# Robotic Paradigms

**Contents:**



## Overview

The eight chapters in this part are devoted to describing what is *AI robotics* and the three major paradigms for achieving it. These paradigms characterize the ways in which intelligence is organized in robots. This part of the book also covers architectures that provide exemplars of how to transfer the principles of the paradigm into a coherent, reusable implementation on a single robot or teams of robots.

### What Are Robots?

One of the first questions most people have about robotics is "what is a robot?" followed immediately by "what can they do?"

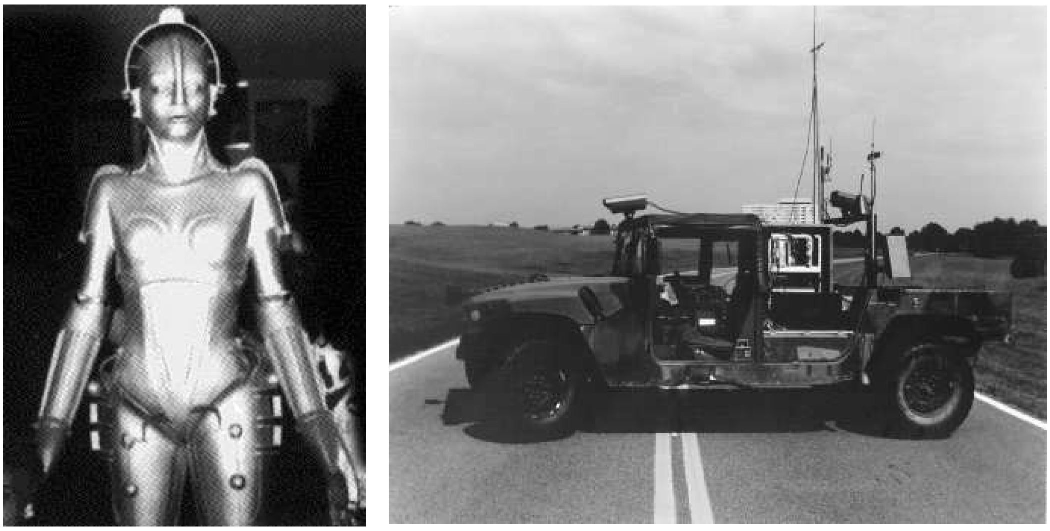
In popular culture, the term "robot" generally connotes some anthropomorphic (human-like) appearance; consider robot "arms" for welding. The tendency to think about robots as having a human-like appearance may stem from the origins of the term "robot." The word "robot" came into the popular consciousness on January 25, 1921, in Prague with the first performance of Karel Capek's play, R.U.R. (Rossum's Universal Robots).[37] In R.U.R., an unseen inventor, Rossum, has created a race of workers made from a vat of biological parts, smart enough to replace a human in any job (hence "universal"). Capek described the workers as robots, a term derived from the Czech word "robota" which is loosely translated as menial laborer. Robot workers implied that the artificial creatures were strictly meant to be servants to free "real" people from any type of labor, but were too lowly to merit respect. This attitude towards robots has disastrous consequences, and the moral of the rather socialist story is that work defines a person.

The shift from robots as human-like servants constructed from biological parts to human-like servants made up of mechanical parts was probably due to science fiction. Three classic films, *Metropolis* (1926), *The Day the Earth Stood Still* (1951), and *Forbidden Planet* (1956), cemented the connotation that robots were mechanical in origin, ignoring the biological origins in Capek's play. Meanwhile, computers were becoming commonplace in industry and accounting, gaining a perception of being literal minded. Industrial automation confirmed this suspicion as robot arms were installed which would go through the motions of assembling parts, even if there were no parts. Eventually, the term robot took on nuances of factory automation: mindlessness and good only for well-defined repetitious types of work. The notion of anthropomorphic, mechanical, and literal-minded robots complemented the viewpoint taken in many of the short stories in Isaac Asimov's perennial favorite collection, *I, Robot*.[15] Many (but not all) of these stories involve either a "robopsychologist," Dr. Susan Calvin, or two erstwhile trouble shooters, Powell and Donovan, diagnosing robots who behaved logically but did the wrong thing.

The shift from human-like mechanical creatures to whatever shape gets the job done is due to reality. While robots are mechanical, they don't have to be anthropomorphic or even animal-like. Consider robot vacuum cleaners; they look like vacuum cleaners, not janitors. And the HelpMate Robotics, Inc., robot which delivers hospital meals to patients to permit nurses more time with patients, looks like a cart, not a nurse.

INTELLIGENT ROBOT

It should be clear from Fig. I.1 that appearance does not form a useful definition of a robot. Therefore, the definition that will be used in this book is *an intelligent robot is a mechanical creature which can function autonomously*. "Intelligent" implies that the robot does not do things in a mindless, repetitive way; it is the opposite of the connotation from factory automation. The "mechanical creature" portion of the definition is an acknowledgment of the fact that our scientific technology uses mechanical building blocks, not biological components (although with recent advances in cloning, this may change). It also emphasizes that a robot is not the same as a computer. A robot may use a computer as a building block, equivalent to a nervous system or brain, but the robot is able to interact with its world: move around, change



a. b.

**Figure I.1** Two views of robots: a) the humanoid robot from the 1926 movie Metropolis (image courtesty Fr. Doug Quinn and the Metropolis Home Page), and b) a HMMWV military vehicle capable of driving on roads and open terrains. (Photograph courtesy of the National Institute for Standards and Technology.)

it, etc. A computer doesn't move around under its own power. "Function autonomously" indicates that the robot can operate, self-contained, under all reasonable conditions without requiring recourse to a human operator. Autonomy means that a robot can adapt to changes in its environment (the lights get turned off) or itself (a part breaks) and continue to reach its goal.

Perhaps the best example of an intelligent mechanical creature which can function autonomously is the Terminator from the 1984 movie of the same name. Even after losing one camera (eye) and having all external coverings (skin, flesh) burned off, it continued to pursue its target (Sarah Connor). Extreme adaptability and autonomy in an extremely scary robot! A more practical (and real) example is *Marvin*, the mail cart robot, for the Baltimore FBI office, described in a Nov. 9, 1996, article in the Denver Post. Marvin is able to accomplish its goal of stopping and delivering mail while adapting to people getting in its way at unpredictable times and locations.

### What are Robotic Paradigms?

PARADIGM

A *paradigm is a philosophy or set of assumptions and/or techniques which characterize an approach to a class of problems*. It is both a way of looking at the world and an implied set of tools for solving problems. No one paradigm is right; rather, some problems seem better suited for different approaches. For example, consider calculus problems. There are problems that could be solved by differentiating in cartesian $(X, Y, Z)$ coordinates, but are much easier to solve if polar coordinates $(r, \theta)$ are used. In the domain of calculus problems, Cartesian and polar coordinates represent two different paradigms for viewing and manipulating a problem. Both produce the correct answer, but one takes less work for certain problems.

Applying the right paradigm makes problem solving easier. Therefore, knowing the paradigms of AI robotics is one key to being able to successfully program a robot for a particular application. It is also interesting from a historical perspective to work through the different paradigms, and to examine the issues that spawned the shift from one paradigm to another.

ROBOTIC PARADIGMS

There are currently three paradigms for organizing intelligence in robots: hierarchical, reactive, and hybrid deliberative/reactive. The paradigms are described in two ways.

ROBOT PARADIGM PRIMITIVES

1. **By the relationship between the three commonly accepted primitives of robotics: SENSE, PLAN, ACT.** The functions of a robot can be divided into three very general categories. If a function is taking in information from the robot's sensors and producing an output useful by other functions, then that function falls in the SENSE category. If the function is taking in information (either from sensors or its own knowledge about how the world works) and producing one or more tasks for the robot to perform (go down the hall, turn left, proceed 3 meters and stop), that function is in the PLAN category. Functions which produce output commands to motor actuators fall into ACT (turn 98°, clockwise, with a turning velocity of 0.2mps). Fig. I.2 attempts to define these three primitives in terms of inputs and outputs; this figure will appear throughout the chapters in Part I.

2. **By the way sensory data is processed and distributed through the system**. How much a person or robot or animal is influenced by what it senses. So it is often difficult to adequately describe a paradigm with just a box labeled SENSE. In some paradigms, sensor information is restricted to being used in a specific, or dedicated, way for each function of a robot;

| ROBOT PRIMITIVES | INPUT | OUTPUT |
|---|---|---|
| SENSE | Sensor data | Sensed information |
| PLAN | Information (sensed and/or cognitive) | Directives |
| ACT | Sensed information or directives | Actuator commands |

**Figure I.2** Robot primitives defined in terms of inputs and outputs.

SENSING ORGANIZATION IN ROBOT PARADIGMS

in that case processing is *local* to each function. Other paradigms expect all sensor information to be first processed into one *global* world model and then subsets of the model distributed to other functions as needed.

## Overview of the Three Paradigms

In order to set the stage for learning details, it may be helpful to begin with a general overview of the robot paradigms. Fig. I.3 shows the differences between the three paradigms in terms of the SENSE, PLAN, ACT primitives.

HIERARCHICAL PARADIGM

The *Hierarchical Paradigm* is the oldest paradigm, and was prevalent from 1967–1990. Under it, the robot operates in a top-down fashion, heavy on planning (see Fig. I.3). This was based on an introspective view of how people think. "I see a door, I decide to head toward it, and I plot a course around the chairs." (Unfortunately, as many cognitive psychologists now know, introspection is not always a good way of getting an accurate assessment of a thought process. We now suspect no one actually plans how they get out of a room; they have default schemas or behaviors.) Under the Hierarchical Paradigm, the robot senses the world, plans the next action, and then acts (SENSE, PLAN, ACT). Then it senses the world, plans, acts. At each step, the robot explicitly plans the next move. The other distinguishing feature of the Hierarchical paradigm is that all the sensing data tends to be gathered into one global world model, a single representation that the planner can use and can be routed to the actions. Constructing generic global world models

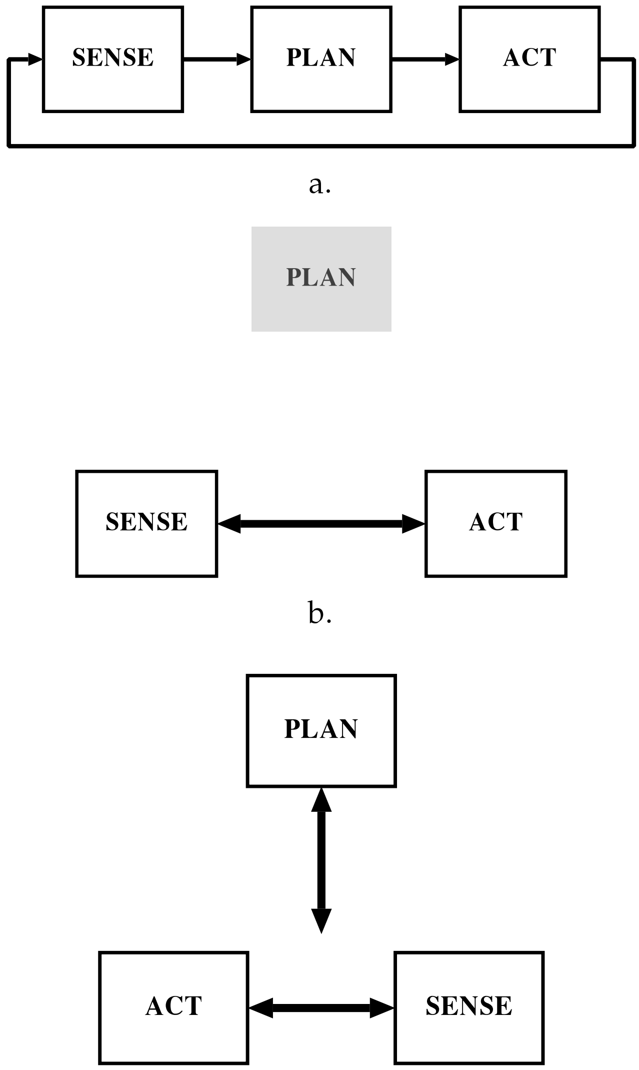



**Figure I.3** Three paradigms: a.) Hierarchical, b.) Reactive, and c.) Hybrid deliberative/reactive.

turns out to be very hard and brittle due to the *frame problem* and the need for a *closed world assumption*.

Fig. I.4 shows how the Hierarchical Paradigm can be thought of as a transitive, or Z-like, flow of events through the primitives given in Fig. I.4. Unfortunately, the flow of events ignored biological evidence that sensed information can be directly coupled to an action, which is why the sensed information input is blacked out.

| ROBOT PRIMITIVES | INPUT | OUTPUT |
|---|---|---|
| SENSE | Sensor data | Sensed information |
| PLAN | Information (sensed and/or cognitive) | Directives |
| ACT | [redacted]directives | Actuator commands |

**Figure I.4** Another view of the Hierarchical Paradigm.

REACTIVE PARADIGM

The *Reactive Paradigm* was a reaction to the Hierarchical Paradigm, and led to exciting advances in robotics. It was heavily used in robotics starting in 1988 and continuing through 1992. It is still used, but since 1992 there has been a tendency toward hybrid architectures. The Reactive Paradigm was made possible by two trends. One was a popular movement among AI researchers to investigate biology and cognitive psychology in order to examine living exemplars of intelligence. Another was the rapidly decreasing cost of computer hardware coupled with the increase in computing power. As a result, researchers could emulate frog and insect behavior with robots costing less than $500 versus the $100,000s Shakey, the first mobile robot, cost.

The Reactive Paradigm threw out planning all together (see Figs. I.3b and I.5). It is a SENSE-ACT (S-A) type of organization. Whereas the Hierarchical Paradigm assumes that the input to a ACT will always be the result of a PLAN, the Reactive Paradigm assumes that the input to an ACT will always be the direct output of a sensor, SENSE.

If the sensor is directly connected to the action, why isn't a robot running under the Reactive Paradigm limited to doing just one thing? The robot has multiple instances of SENSE-ACT couplings, discussed in Ch. 4. These couplings are concurrent processes, called behaviors, which take local sensing data and compute the best action to take independently of what the other processes are doing. One behavior can direct the robot to "move forward 5 meters" (ACT on drive motors) to reach a goal (SENSE the goal), while another behavior can say "turn 90°" (ACT on steer motors) to avoid a collision

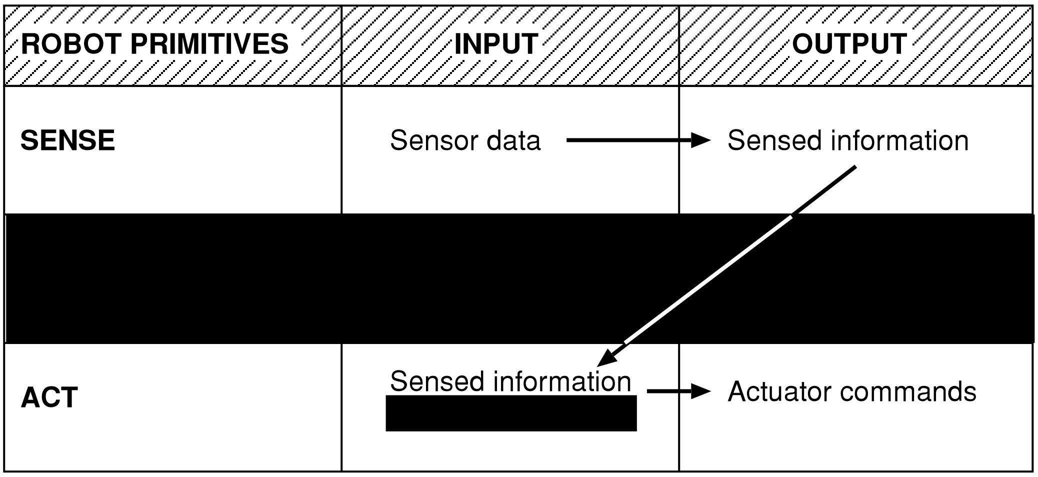



**Figure I.5** The reactive paradigm.

with an object dead ahead (SENSE obstacles). The robot will do a combination of both behaviors, swerving off course temporarily at a 45° angle to avoid the collision. Note that neither behavior directed the robot to ACT with a 45° turn; the final ACT emerged from the combination of the two behaviors.

While the Reactive Paradigm produced exciting results and clever robot insect demonstrations, it quickly became clear that throwing away planning was too extreme for general purpose robots. In some regards, the Reactive Paradigm reflected the work of Harvard psychologist B. F. Skinner in stimulus-response training with animals. It explained how some animals accomplished tasks, but was a dead end in explaining the entire range of human intelligence.

HYBRID DELIBERATIVE/REACTIVE PARADIGM

But the Reactive Paradigm has many desirable properties, especially the fast execution time that came from eliminating any planning. As a result, the Reactive Paradigm serves as the basis for the *Hybrid Deliberative/Reactive Paradigm*, shown in Fig.I.3c. The Hybrid Paradigm emerged in the 1990's and continues to be the current area of research. Under the Hybrid Paradigm, the robot first plans (deliberates) how to best decompose a task into subtasks (also called "mission planning") and then what are the suitable behaviors to accomplish each subtask, etc. Then the behaviors start executing as per the Reactive Paradigm. This type of organization is PLAN, SENSE-ACT (P, S-A), where the comma indicates that planning is done at one step, then sensing and acting are done together. Sensing organization in the Hybrid Paradigm is also a mixture of Hierarchical and Reactive styles. Sensor data gets routed to each behavior that needs that sensor, but is also available to the planner

| ROBOT PRIMITIVES | INPUT | OUTPUT |
|---|---|---|
| **PLAN** | Information (sensed and/or cognitive) | Directives |
| **SENSE-ACT (behaviors)** | Sensor data → | Actuator commands |

**Figure I.6** The hybrid deliberative/reactive paradigm.

for construction of a task-oriented global world model. The planner may also "eavesdrop" on the sensing done by each behavior (i.e., the behavior identifies obstacles that could then be put into a map of the world by the planner). Each function performs computations at its own rate; deliberative planning, which is generally computationally expensive may update every 5 seconds, while the reactive behaviors often execute at 1/60 second. Many robots run at 80 centimeters per second.

## Architectures

Determining that a particular paradigm is well suited for an application is certainly the first step in constructing the AI component of a robot. But that step is quickly followed with the need to use the tools associated with that paradigm. In order to visualize how to apply these paradigms to real-world applications, it is helpful to examine representative architectures. These architectures provide templates for an implementation, as well as examples of what each paradigm really means.

What is an architecture? Arkin offers several definitions in his book, *Behavior-Based Robots.*[10] Two of the definitions he cites from other researchers capture how the term will be used in this book. Following Mataric,[89] an architecture provides a principled way of organizing a control system. However, in addition to providing structure, it imposes constraints on the way the control problem can be solved. Following Dean and Wellman,[43] an architecture describes a set of architectural components and how they interact. This book is interested in the components common in robot architectures; these are the basic building blocks for programming a robot. It also is interested in the principles and rules of thumb for connecting these components together.

ARCHITECTURE

To see the importance of an architecture, consider building a house or a car. There is no "right" design for a house, although most houses share the same components (kitchens, bathrooms, walls, floors, doors, etc.). Likewise with designing robots, there can be multiple ways of organizing the components, even if all the designs follow the same paradigm. This is similar to cars designed by different manufacturers. All internal combustion engine types of cars have the same basic components, but the cars look different (BMWs and Jaguars look quite different than Hondas and Fords). The internal combustion (IC) engine car is a paradigm (as contrasted to the paradigm of an electric car). Within the IC engine car community, the car manufacturers each have their own architecture. The car manufacturers may make slight modifications to the architecture for sedans, convertibles, sport-utility vehicles, etc., to throw out unnecessary options, but each style of car is a particular instance of the architecture. The point is: by studying representative robot architectures and the instances where they were used for a robot application, we can learn the different ways that the components and tools associated with a paradigm can be used to build an artificially intelligent robot.

Since a major objective in robotics is to learn how to build them, an important skill to develop is evaluating whether or not a previously developed architecture (or large chunks of it) will suit the current application. This skill will save both time spent on re-inventing the wheel and avoid subtle problems that other people have encountered and solved. Evaluation requires a set of criteria. The set that will be used in this book is adapted from *Behavior-Based Robotics*:[10]

MODULARITY

1. **Support for modularity:** does it show good software engineering principles?

NICHE TARGETABILITY

2. **Niche targetability:** how well does it work for the intended application?

PORTABILITY

3. **Ease of portability to other domains:** how well would it work for other applications or other robots?

ROBUSTNESS

4. **Robustness:** where is the system vulnerable, and how does it try to reduce that vulnerability?

Note that niche targetability and ease of portability are often at odds with each other. Most of the architectures described in this book were intended to be generic, therefore emphasizing portability. The generic structures, however, often introduce undesirable computational and storage overhead, so in practice the designer must make trade-offs.

## Layout of the Section

This section is divided into eight chapters, one to define robotics and the other seven to intertwine both the theory and practice associated with each paradigm. Ch. 2 describes the Hierarchical Paradigm and two representative architectures. Ch. 3 sets the stage for understanding the Reactive Paradigm by reviewing the key concepts from biology and ethology that served to motivate the shift from Hierarchical to Reactive systems. Ch. 4 describes the Reactive Paradigm and the architectures that originally popularized this approach. It also offers definitions of primitive robot behaviors. Ch. 5 provides guidelines and case studies on designing robot behaviors. It also introduces issues in coordinating and controlling multiple behaviors and the common techniques for resolving these issues. At this point, the reader should be almost able to design and implement a reactive robot system, either in simulation or on a real robot. However, the success of a reactive system depends on the sensing. Ch. 6 discusses simple sonar and computer vision processing techniques that are commonly used in inexpensive robots. Ch. 7 describes the Hybrid Deliberative-Reactive Paradigm, concentrating on architectural trends. Up until this point, the emphasis is towards programming a single robot. Ch. 8 concludes the section by discussing how the principles of the three paradigms have been transferred to teams of robots.

## End Note

*Robot paradigm primitives.*
While the SENSE, PLAN, ACT primitives are generally accepted, some researchers are suggesting that a fourth primitive be added, LEARN. There are no formal architectures at this time which include this, so a true paradigm shift has not yet occurred.

# 1 *From Teleoperation To Autonomy*

**Chapter Objectives:**

- Define *intelligent robot*.
- Be able to describe at least two differences between AI and Engineering approaches to robotics.
- Be able to describe the difference between *telepresence* and *semi-autonomous control*.
- Have some feel for the history and societal impact of robotics.

## 1.1 Overview

This book concentrates on the role of artificial intelligence for robots. At first, that may appear redundant; aren't robots intelligent? The short answer is "no," most robots currently in industry are not intelligent by any definition. This chapter attempts to distinguish an intelligent robot from a non-intelligent robot.

The chapter begins with an overview of artificial intelligence and the social implications of robotics. This is followed with a brief historical perspective on the evolution of robots towards intelligence, as shown in Fig. 1.1. One way of viewing robots is that early on in the 1960's there was a fork in the evolutionary path. Robots for manufacturing took a fork that has focused on engineering robot arms for manufacturing applications. The key to success in industry was precision and repeatability on the assembly line for mass production, in effect, industrial engineers wanted to automate the workplace. Once a robot arm was programmed, it should be able to operate for weeks and months with only minor maintenance. As a result, the emphasis was

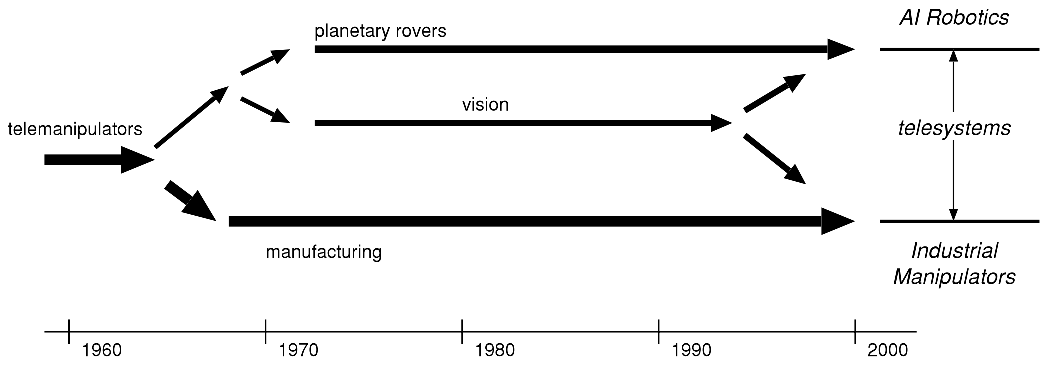



**Figure 1.1** A timeline showing forks in development of robots.

placed on the mechanical aspects of the robot to ensure precision and repeatability and methods to make sure the robot could move precisely and repeatable, quickly enough to make a profit. Because assembly lines were engineered to mass produce a certain product, the robot didn't have to be able to notice any problems. The standards for mass production would make it more economical to devise mechanisms that would ensure parts would be in the correct place. A robot for automation could essentially be blind and senseless.

Robotics for the space program took a different fork, concentrating instead on highly specialized, one-of-a-kind planetary rovers. Unlike a highly automated manufacturing plant, a planetary rover operating on the dark side of the moon (no radio communication) might run into unexpected situations. Consider that on Apollo 17, astronaut and geologist Harrison Schmitt found an orange rock on the moon; an orange rock was totally unexpected. Ideally, a robot would be able to notice something unusual, stop what it was doing (as long as it didn't endanger itself) and investigate. Since it couldn't be preprogrammed to handle all possible contingencies, it had to be able to notice its environment and handle any problems that might occur. At a minimum, a planetary rover had to have some source of sensory inputs, some way of interpreting those inputs, and a way of modifying its actions to respond to a changing world. And the need to sense and adapt to a partially unknown environment is the need for intelligence.

The fork toward AI robots has not reached a termination point of truly autonomous, intelligent robots. In fact, as will be seen in Ch. 2 and 4, it wasn't until the late 1980's that any visible progress toward that end was made. So what happened when someone had an application for a robot which needed real-time adaptability before 1990? In general, the lack of machine intelligence was compensated by the development of mechanisms which allow a human to control all, or parts, of the robot remotely. These mechanisms are generally referred to under the umbrella term: teleoperation. Teleoperation can be viewed as the "stuff" in the middle of the two forks. In practice, intelligent robots such as the Mars Sojourner are controlled with some form of teleoperation. This chapter will cover the flavors of teleoperation, given their importance as a stepping stone towards truly intelligent robots.

The chapter concludes by visiting the issues in AI, and argues that AI is imperative for many robotic applications. Teleoperation is simply not sufficient or desirable as a long term solution. However, it has served as a reasonable patch.

It is interesting to note that the two forks, manufacturing and AI, currently appear to be merging. Manufacturing is now shifting to a "mass customization" phase, where companies which can economically make short runs of special order goods are thriving. The pressure is on for industrial robots, more correctly referred to as industrial manipulators, to be rapidly reprogrammed and more forgiving if a part isn't placed exactly as expected in its workspace. As a result, AI techniques are migrating to industrial manipulators.

## 1.2 How Can a Machine Be Intelligent?

ARTIFICIAL INTELLIGENCE

*The science of making machines act intelligently* is usually referred to as *artificial intelligence*, or AI for short. Artificial Intelligence has no commonly accepted definitions. One of the first textbooks on AI defined it as "the study of ideas that enable computers to be intelligent,"[143] which seemed to beg the question. A later textbook was more specific, "AI is the attempt to get the computer to do things that, for the moment, people are better at."[120] This definition is interesting because it implies that once a task is performed successfully by a computer, then the technique that made it possible is no longer AI, but something mundane. That definition is fairly important to a person researching AI methods for robots, because it explains why certain topics suddenly seem to disappear from the AI literature: it was perceived as being solved! Perhaps the most amusing of all AI definitions was the slogan for the now defunct computer company, Thinking Machines, Inc., "... making machines that will be proud of us."

The term AI is controversial, and has sparked ongoing philosophical debates on whether a machine can ever be intelligent. As Roger Penrose notes in his book, The Emperor's New Mind: "Nevertheless, it would be fair to say that, although many clever things have indeed been done, the simulation of anything that could pass for genuine intelligence is yet a long way off."[115] Engineers often dismiss AI as wild speculation. As a result of such vehement criticisms, many researchers often label their work as "intelligent systems" or "knowledge-based systems" in an attempt to avoid the controversy surrounding the term "AI."

A single, precise definition of AI is not necessary to study AI robotics. AI robotics is the application of AI techniques to robots. More specifically, AI robotics is the consideration of issues traditional covered by AI for application to robotics: learning, planning, reasoning, problem solving, knowledge representation, and computer vision. An article in the May 5, 1997 issue of Newsweek, "Actually, Chess is Easy," discusses why robot applications are more demanding for AI than playing chess. Indeed, the concepts of the reactive paradigm, covered in Chapter 4, influenced major advances in traditional, non-robotic areas of AI, especially planning. So by studying AI robotics, a reader interested in AI is getting exposure to the general issues in AI.

## 1.3 What Can Robots Be Used For?

Now that a working definition of a robot and artificial intelligence has been established, an attempt can be made to answer the question: what can intelligent robots be used for? The short answer is that robots can be used for just about any application that can be thought of. The long answer is that robots are well suited for applications where 1) a human is at significant risk (nuclear, space, military), 2) the economics or menial nature of the application result in inefficient use of human workers (service industry, agriculture), and 3) for humanitarian uses where there is great risk (demining an area of land mines, urban search and rescue). Or as the well-worn joke among roboticists goes, robots are good for *the 3 D's*: jobs that are dirty, dull, or dangerous.

THE 3 D'S

Historically, the military and industry invested in robotics in order to build nuclear weapons and power plants; now, the emphasis is on using robots for environmental remediation and restoration of irradiated and polluted sites. Many of the same technologies developed for the nuclear industry for processing radioactive ore is now being adapted for the pharmaceutical industry; processing immune suppressant drugs may expose workers to highly toxic chemicals.

Another example of a task that poses significant risk to a human is space exploration. People can be protected in space from the hard vacuum, solar radiation, etc., but only at great economic expense. Furthermore, space suits are so bulky that they severely limit an astronaut's ability to perform simple tasks, such as unscrewing and removing an electronics panel on a satellite. Worse yet, having people in space necessitates more people in space. Solar radiation embrittlement of metals suggests that astronauts building a large space station would have to spend as much time repairing previously built portions as adding new components. Even more people would have to be sent into space, requiring a larger structure. the problem escalates. A study by Dr. Jon Erickson's research group at NASA Johnson Space Center argued that a manned mission to Mars was not feasible without robot drones capable of constantly working outside of the vehicle to repair problems introduced by deadly solar radiation.[51] (Interestingly enough, a team of three robots which did just this were featured in the 1971 film, *Silent Running*, as well as by a young R2D2 in *The Phantom Menace*.)

Nuclear physics and space exploration are activities which are often far removed from everyday life, and applications where robots figure more prominently in the future than in current times.

The most obvious use of robots is manufacturing, where repetitious activities in unpleasant surroundings make human workers inefficient or expensive to retain. For example, robot "arms" have been used for welding cars on assembly lines. One reason that welding is now largely robotic is that it is an unpleasant job for a human (hot, sweaty, tedious work) with a low tolerance for inaccuracy. Other applications for robots share similar motivation: to automate menial, unpleasant tasks—usually in the service industry. One such activity is janitorial work, especially maintaining public rest rooms, which has a high turnover in personnel regardless of payscale. The janitorial problem is so severe in some areas of the US, that the Postal Service offered contracts to companies to research and develop robots capable of autonomously cleaning a bathroom (the bathroom could be designed to accommodate a robot).

Agriculture is another area where robots have been explored as an economical alternative to hard to get menial labor. Utah State University has been working with automated harvesters, using GPS (global positioning satellite system) to traverse the field while adapting the speed of harvesting to the rate of food being picked, much like a well-adapted insect. The Department of Mechanical and Material Engineering at the University of Western Australia developed a robot called *Shear Majic* capable of shearing a live sheep. People available for sheep shearing has declined, along with profit margins, increasing the pressure on the sheep industry to develop economic alternatives. Possibly the most creative use of robots for agriculture is a mobile automatic milker developed in the Netherlands and in Italy.[68;32] Rather than have a person attach the milker to a dairy cow, the roboticized milker arm identifies the teats as the cow walks into her stall, targets them, moves about to position itself, and finally reaches up and attaches itself.

Finally, one of the most compelling uses of robots is for humanitarian purposes. Recently, robots have been proposed to help with detecting unexploded ordinance (land mines) and with urban search and rescue (finding survivors after a terrorist bombing of a building or an earthquake). Humanitarian land demining is a challenging task. It is relatively easy to demine an area with bulldozer, but that destroys the fields and improvements made by the civilians and hurts the economy. Various types of robots are being tested in the field, including aerial and ground vehicles.[73]

### 1.3.1 Social implications of robotics

While many applications for artificially intelligent robots will actively reduce risk to a human life, many applications appear to compete with a human's livelihood. Don't robots put people out of work? One of the pervasive themes in society has been the impact of science and technology on the dignity of people. Charlie Chaplin's silent movie, *Modern Times*, presented the world with visual images of how manufacturing-oriented styles of management reduces humans to machines, just "cogs in the wheel."

Robots appear to amplify the tension between productivity and the role of the individual. Indeed, the scientist in *Metropolis* points out to the corporate ruler of the city that now that they have robots, they don't need workers anymore. People who object to robots, or technology in general, are often called *Luddites*, after Ned Ludd, who is often credited with leading a short-lived revolution of workers against mills in Britain. Prior to the industrial revolution in Britain, wool was woven by individuals in their homes or collectives as a cottage industry. Mechanization of the weaving process changed the jobs associated with weaving, the status of being a weaver (it was a skill), and required people to work in a centralized location (like having your telecommuting job terminated). Weavers attempted to organize and destroyed looms and mill owners' properties in reaction. After escalating vi-

LUDDITES

olence in 1812, legislation was passed to end worker violence and protect the mills. The rebelling workers were persecuted. While the Luddite movement may have been motivated by a quality-of-life debate, the term is often applied to anyone who objects to technology, or "progress," for any reason. The connotation is that Luddites have an irrational fear of technological progress.

The impact of robots is unclear, both what is the real story and how people interact with robots. The HelpMate Robotics, Inc. robots and janitorial robots appear to be competing with humans, but are filling a niche where it is hard to get human workers at any price. Cleaning office buildings is menial and boring, plus the hours are bad. One janitorial company has now invested in mobile robots through a Denver-based company, Continental Divide Robotics, citing a 90% yearly turnover in staff, even with profit sharing after two years. The Robotics Industries Association, a trade group, produces annual reports outlining the need for robotics, yet possibly the biggest robot money makers are in the entertainment and toy industries.

The cultural implications of robotics cannot be ignored. While the sheep shearing robots in Australia were successful and were ready to be commercialized for significant economic gains, the sheep industry reportedly rejected the robots. One story goes that the sheep ranchers would not accept a robot shearer unless it had a 0% fatality rate (it's apparently fairly easy to nick an artery on a squirming sheep). But human shearers accidently kill several sheep, while the robots had a demonstrably better rate. The use of machines raises an ethical question: is it acceptable for an animal to die at the hands of a machine rather than a person? What if a robot was performing a piece of intricate surgery on a human?

## 1.4 A Brief History of Robotics

Robotics has its roots in a variety of sources, including the way machines are controlled and the need to perform tasks that put human workers at risk.

In 1942, the United States embarked on a top secret project, called the Manhattan Project, to build a nuclear bomb. The theory for the nuclear bomb had existed for a number of years in academic circles. Many military leaders of both sides of World War II believed the winner would be the side who could build the first nuclear device: the Allied Powers led by USA or the Axis, led by Nazi Germany.

One of the first problems that the scientists and engineers encountered was handling and processing radioactive materials, including uranium and

**Figure 1.2** A Model 8 Telemanipulator. The upper portion of the device is placed in the ceiling, and the portion on the right extends into the hot cell. (Photograph courtesy Central Research Laboratories.)

plutonium, in large quantities. Although the immensity of the dangers of working with nuclear materials was not well understood at the time, all the personnel involved knew there were health risks. One of the first solutions was the *glove box*. Nuclear material was placed in a glass box. A person stood (or sat) behind a leaded glass shield and stuck their hands into thick rubberized gloves. This allowed the worker to see what they were doing and to perform almost any task that they could do without gloves.

But this was not an acceptable solution for highly radioactive materials, and mechanisms to physically remove and completely isolate the nuclear materials from humans had to be developed. One such mechanism was a force reflecting *telemanipulator*, a sophisticated mechanical linkage which translated motions on one end of the mechanism to motions at the other end. A popular telemanipulator is shown in Fig. 1.2.

TELEMANIPULATOR

A nuclear worker would insert their hands into (or around) the telemanipulator, and move it around while watching a display of what the other end of the arm was doing in a containment cell. Telemanipulators are similar in principle to the power gloves now used in computer games, but much harder to use. The mechanical technology of the time did not allow a perfect mapping of hand and arm movements to the robot arm. Often the operator had to make non-intuitive and awkward motions with their arms to get the robot arm to perform a critical manipulation—very much like working in front of a mirror. Likewise, the telemanipulators had challenges in providing force feedback so the operator could feel how hard the gripper was holding an object. The lack of naturalness in controlling the arm (now referred to as a poor Human-Machine Interface) meant that even simple tasks for an unencumbered human could take much longer. Operators might take years of practice to reach the point where they could do a task with a telemanipulator as quickly as they could do it directly.

After World War II, many other countries became interested in producing a nuclear weapon and in exploiting nuclear energy as a replacement for fossil fuels in power plants. The USA and Soviet Union also entered into a nuclear arms race. The need to mass-produce nuclear weapons and to support peaceful uses of nuclear energy kept pressure on engineers to design robot arms which would be easier to control than telemanipulators. Machines that looked more like and acted like robots began to emerge, largely due to advances in control theory. After WWII, pioneering work by Norbert Wiener allowed engineers to accurately control mechanical and electrical devices using cybernetics.

### 1.4.1 Industrial manipulators

Successes with at least partially automating the nuclear industry also meant the technology was available for other applications, especially general manufacturing. Robot arms began being introduced to industries in 1956 by Unimation (although it wouldn't be until 1972 before the company made a profit).[37] The two most common types of robot technology that have evolved for industrial use are robot arms, called industrial manipulators, and mobile carts, called automated guided vehicles (AGVs).

INDUSTRIAL MANIPULATOR

An *industrial manipulator*, to paraphrase the Robot Institute of America's definition, is a reprogrammable and multi-functional mechanism that is designed to move materials, parts, tools, or specialized devices. The emphasis in industrial manipulator design is being able to program them to be able to perform a task repeatedly with a high degree of accuracy and speed. In order to be multi-functional, many manipulators have multiple degrees of freedom, as shown in Fig. 1.4. The MOVEMASTER arm has five degrees of freedom, because it has five joints, each of which is capable of a single rotational degree of freedom. A human arm has three joints (shoulder, el-

**Figure 1.3** An RT3300 industrial manipulator. (Photograph courtesy of Seiko Instruments.)

bow, and wrist), two of which are complex (shoulder and wrist), yielding six degrees of freedom.

Control theory is extremely important in industrial manipulators. Rapidly moving around a large tool like a welding gun introduces interesting problems, like when to start decelerating so the gun will stop in the correct location without overshooting and colliding with the part to be welded. Also, oscillatory motion, in general, is undesirable. Another interesting problem is the joint configuration. If a robot arm has a wrist, elbow and shoulder joints like a human, there are redundant degrees of freedom. Redundant degrees of freedom means there are multiple ways of moving the joints that will accomplish the same motion. Which one is better, more efficient, less stressful on the mechanisms?

BALLISTIC CONTROL
OPEN LOOP CONTROL

It is interesting to note that most manipulator control was assumed to be *ballistic control*, or *open loop control*. In ballistic control, the position trajectory and velocity profile is computed once, then the arm carries it out. There are no "in-flight" corrections, just like a ballistic missile doesn't make any course corrections. In order to accomplish a precise task with ballistic control, everything about the device and how it works has to be modeled and figured into the computation. The opposite of ballistic control is *closed-loop control*, where the error between the goal and current position is noted by a sensor(s),

CLOSED-LOOP CONTROL

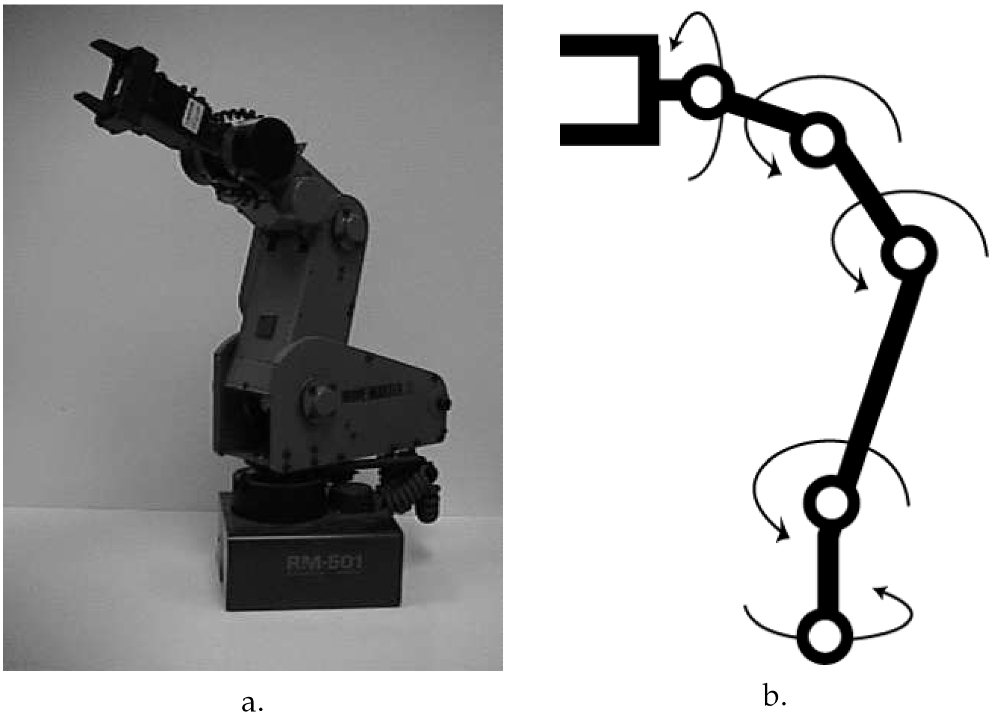


**Figure 1.4** A MOVEMASTER robot: a.) the robot arm and b.) the associated joints.

and a new trajectory and profile is computed and executed, then modified on the next update, and so on. Closed-loop control requires external sensors to provide the error signal, or *feedback*.

FEEDBACK

In general, if the structural properties of the robot and its cargo are known, these questions can be answered and a program can be developed. In practice, the control theory is complex. The dynamics (how the mechanism moves and deforms) and kinematics (how the components of the mechanism are connected) of the system have to be computed for each joint of the robot, then those motions can be propagated to the next joint iteratively. This requires a computationally consuming change of coordinate systems from one joint to the next. To move the gripper in Fig 1.4 requires four changes of coordinates to go from the base of the arm to the gripper. The coordinate transformations often have singularities, causing the equations to perform divide by zeros. It can take a programmer weeks to reprogram a manipulator.

One simplifying solution is to make the robot rigid at the desired velocities, reducing the dynamics. This eliminates having to compute the terms for overshooting and oscillating. However, a robot is made rigid by making it heavier. The end result is that it is not uncommon for a 2 ton robot to be able to handle only a 200 pound payload. Another simplifying solution is to avoid the computations in the dynamics and kinematics and instead have the programmer use a teach pendant. Using a *teach pendant* (which often looks like a joystick or computer game console), the programmer guides the robot through the desired set of motions. The robot remembers these motions and creates a program from them. Teach pendants do not mitigate the danger of working around a 2 ton piece of equipment. Many programmers have to direct the robot to perform delicate tasks, and have to get physically close to the robot in order to see what the robot should do next. This puts the programmer at risk of being hit by the robot should it hit a singularity point in its joint configuration or if the programmer makes a mistake in directing a motion. You don't want to have your head next to a 2 ton robot arm if it suddenly spins around!

TEACH PENDANT

AUTOMATIC GUIDED VEHICLES

*Automatic guided vehicles*, or AGVs, are intended to be the most flexible conveyor system possible: a conveyor which doesn't need a continuous belt or roller table. Ideally an AGV would be able to pick up a bin of parts or manufactured items and deliver them as needed. For example, an AGV might receive a bin containing an assembled engine. It could then deliver it automatically across the shop floor to the car assembly area which needed an engine. As it returned, it might be diverted by the central computer and instructed to pick up a defective part and take it to another area of the shop for reworking.

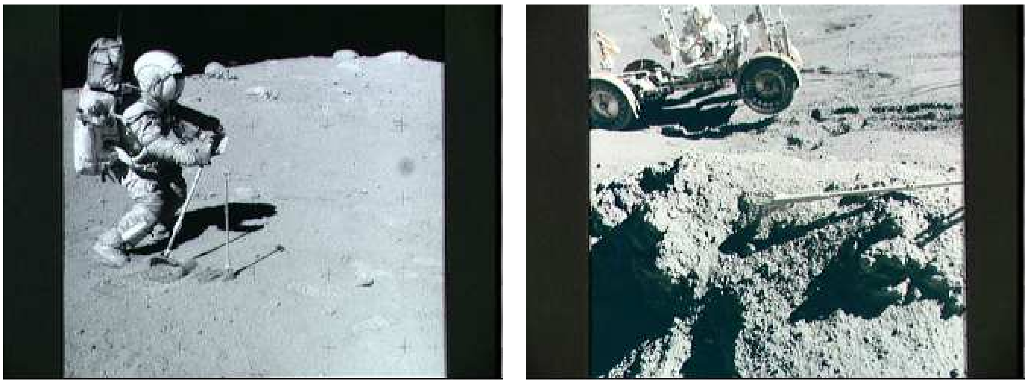
However, navigation (as will be seen in Part II) is complex. The AGV has to know where it is, plan a path from its current location to its goal destination, and to avoid colliding with people, other AGVs, and maintenance workers and tools cluttering the factory floor. This proved too difficult to do, especially for factories with uneven lighting (which interferes with vision) and lots of metal (which interferes with radio controllers and on-board radar and sonar). Various solutions converged on creating a trail for the AGV to follow. One method is to bury a magnetic wire in the floor for the AGV to sense. Unfortunately, changing the path of an AGV required ripping up the concrete floor. This didn't help with the flexibility needs of modern manufacturing. Another method is to put down a strip of photochemical tape for the vehicle to follow. The strip is unfortunately vulnerable, both to wear and to vandalism by unhappy workers. Regardless of the guidance method, in the end the simplest way to thwart an AGV was to something on its path. If the AGV did not have range sensors, then it would be unable to detect an expensive piece of equipment or a person put deliberately in its path. A few costly collisions would usually led to the AGV's removal. If the AGV did have range sensors, it would stop for anything. A well placed lunch box could hold the AGV for hours until a manager happened to notice what was going on. Even better from a disgruntled worker's perspective, many AGVs would make a loud noise to indicate the path was blocked. Imagine having to constantly remove lunch boxes from the path of a dumb machine making unpleasant siren noises.

From the first, robots in the workplace triggered a backlash. Many of the human workers felt threatened by a potential loss of jobs, even though the jobs being mechanized were often menial or dangerous. This was particularly true of manufacturing facilities which were unionized. One engineer reported that on the first day it was used in a hospital, a HelpMate Robotics cart was discovered pushed down the stairs. Future models were modified to have some mechanisms to prevent malicious acts.

BLACK FACTORY

Despite the emerging Luddite effect, industrial engineers in each of the economic powers began working for a *black factory* in the 1980's. A black factory is a factory that has no lights turned on because there are no workers. Computers and robots were expected to allow complete automation of manufacturing processes, and courses in "Computer-Integrated Manufacturing Systems" became popular in engineering schools.

But two unanticipated trends undermined industrial robots in a way that the Luddite movement could not. First, industrial engineers did not have experience designing manufacturing plants with robots. Often industrial manipulators were applied to the wrong application. One of the most embarrassing examples was the IBM Lexington printer plant. The plant was built with a high degree of automation, and the designers wrote numerous articles on the exotic robot technology they had cleverly designed. Unfortunately, IBM had grossly over-estimated the market for printers and the plant sat mostly idle at a loss. While the plant's failure wasn't the fault of robotics, per se, it did cause many manufacturers to have a negative view of automation in general. The second trend was the changing world economy. Customers were demanding "mass customization." Manufacturers who could make short runs of a product tailored to each customer on a large scale were the ones making the money. (Mass customization is also referred to as "agile manufacturing.") However, the lack of adaptability and difficulties in programming industrial robot arms and changing the paths of AGVs interfered with rapid retooling. The lack of adaptability, combined with concerns over worker safety and the Luddite effect, served to discourage companies from investing in robots through most of the 1990's.



a. b.

**Figure 1.5** Motivation for intelligent planetary rovers: a.) Astronaut John Young awkwardly collecting lunar samples on Apollo 16, and b.) Astronaut Jim Irwin stopping the lunar rover as it slides down a hill on Apollo 15. (Photographs courtesy of the National Aeronautics and Space Administration.)

### 1.4.2 Space robotics and the AI approach

While the rise of industrial manipulators and the engineering approach to robotics can in some measure be traced to the nuclear arms race, the rise of the AI approach can be said to start with the space race. On May 25, 1961, spurred by the success of the Soviet Union's Sputnik space programs, President John F. Kennedy announced that United States would put a man on the moon by 1970. Walking on the moon was just one aspect of space exploration. There were concerns about the Soviets setting up military bases on the Moon and Mars and economic exploitation of planetary resources.

Clearly there was going to be a time lag of almost a decade before humans from the USA would go to the Moon. And even then, it would most likely be with experimental spacecraft, posing a risk to the human astronauts. Even without the risk to humans, the bulk of spacesuits would make even trivial tasks difficult for astronauts to perform. Fig. 1.5a shows astronaut John Young on Apollo 16 collecting samples with a lunar rake. The photo shows the awkward way the astronaut had to bend his body and arms to complete the task.

Planetary rovers were a possible solution, either to replace an astronaut or assist him or her. Unfortunately, rover technology in the 1960's was limited. Because of the time delays, a human would be unable to safely control a rover over the notoriously poor radio links of the time, even if the rover went very slow. Therefore, it would be desirable to have a robot that was autonomous. One option would be to have mobile robots land on a planetary conduct preliminary explorations, conduct tests, etc., and radio back the results. These automated planetary rovers would ideally have a high degree of autonomy, much like a trained dog. The robot would receive commands from Earth to explore a particular region. It would navigate around boulders and not fall into canyons, and traverse steep slopes without rolling over. The robot might even be smart enough to regulate its own energy supply, for example, by making sure it was sheltered during the planetary nights and to stop what it was doing and position itself for recharging its solar batteries. A human might even be able to speak to it in a normal way to give it commands.

Getting a mobile robot to the level of a trained dog immediately presented new issues. Just by moving around, a mobile robot could change the world-for instance, by causing a rock slide. Fig. 1.5b shows astronaut Jim Irwin rescuing the lunar rover during an extra-vehicular activity (EVA) on Apollo 15 as it begins to slide downhill. Consider that if an astronaut has difficulty finding a safe parking spot on the moon, how much more challenging it would be for an autonomous rover. Furthermore, an autonomous rover would have no one to rescue it, should it make a mistake.

Consider the impact of uncertain or incomplete information on a rover that didn't have intelligence. If the robot was moving based on a map taken from a telescope or an overhead command module, the map could still contain errors or at the wrong resolution to see certain dangers. In order to navigate successfully, the robot has to compute its path with the new data or risk colliding with a rock or falling into a hole. What if the robot did something broke totally unexpected or all the assumptions about the planet were wrong? In theory, the robot should be able to diagnose the problem and attempt to continue to make progress on its task. What seemed at first like an interim solution to putting humans in space quickly became more complicated.

Clearly, developing a planetary rover and other robots for space was going to require a concentrated, long-term effort. Agencies in the USA such as NASA *Jet Propulsion Laboratory (JPL)* in Pasadena, California, were given the task of developing the robotic technology that would be needed to prepare the way for astronauts in space. They were in a position to take advantage of the outcome of the *Dartmouth Conference*. The Dartmouth Conference was a gathering hosted by the Defense Advanced Research Projects Agency (DARPA) in 1955 of prominent scientists working with computers or on the theory for computers. DARPA was interested in hearing what the potential uses for computers were. One outcome of the conference was the term "artificial intelligence"; the attending scientists believed that computers might become powerful enough to understand human speech and duplicate human reasoning. This in turn suggested that computers might mimic the capabilities of animals and humans sufficiently for a planetary rover to survive for long periods with only simple instructions from Earth.

As an indirect result of the need for robotics converging with the possibility of artificial intelligence, the space program became one of the earliest proponents of developing AI for robotics. NASA also introduced the notion that AI robots would of course be mobile, rather than strapped to a factory floor, and would have to integrate all forms of AI (understanding speech, planning, reasoning, representing the world, learning) into one program—a daunting task which has not yet been reached.

## 1.5 Teleoperation

TELEOPERATION

*Teleoperation* is when a human operator controls a robot from a distance (*tele* means "remote"). The connotation of teleoperation is that the distance is too great for the operator to see what the robot is doing, so radio controlled toy cars are not considered teleoperation systems. The operator and robot have some type of master-slave relationship. In most cases, the human operator sits at a workstation and directs a robot through some sort of interface, as seen in Fig. 1.6.

LOCAL

REMOTE

The control interface could be a joystick, virtual reality gear, or any number of innovative interfaces. The human operator, or teleoperator, is often referred to as the *local* (due to being at the local workstation) and the robot as the *remote* (since it is operating at a remote location from the teleoperator). The local must have some type of display and control mechanisms, while the remote must have sensors, effectors, power, and in the case of mobile robots, mobility.[141] The teleoperator cannot look at what the remote is doing directly, either because the robot is physically remote (e.g., on Mars) or the local has to be shielded (e.g., in a nuclear or pharmaceutical processing plant hot cell).

SENSORS

DISPLAY

COMMUNICATION LINK

Therefore, the *sensors* which acquire information about the remote location, the *display* technology for allowing the operator to see the sensor data, and the *communication link* between the local and remote are critical components of a telesystem.[141]

Teleoperation is a popular solution for controlling remotes because AI technology is nowhere near human levels of competence, especially in terms of

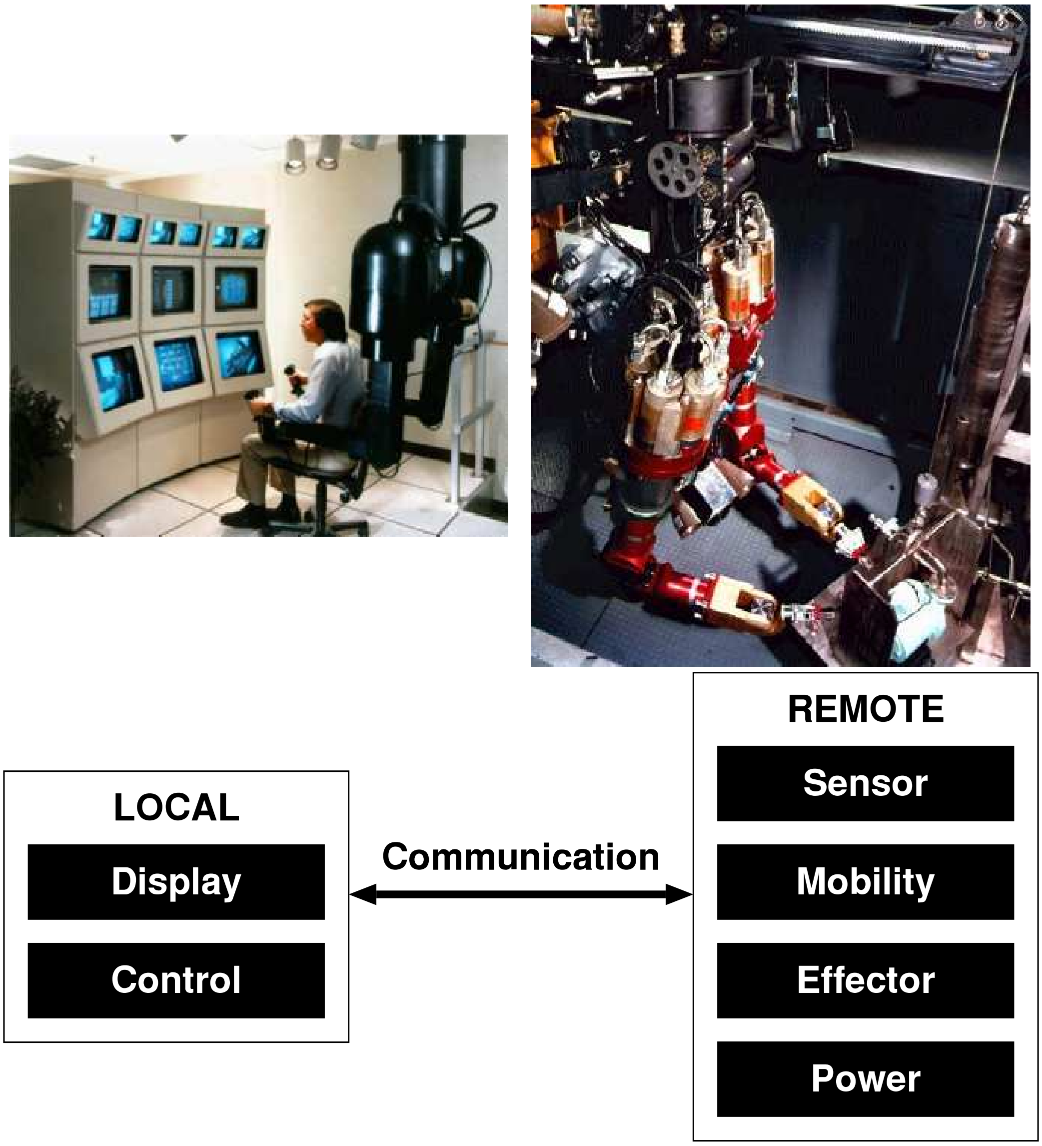



**Figure 1.6** Organization of a telesystem. (Photographs courtesy of Oak Ridge National Laboratory.)

perception and decision making. One example of teleoperation is the exploration of underwater sites such as the Titanic. Having a human control a robot is advantageous because a human can isolate an object of interest, even partially obscured by mud in murky water as described by W. R. Uttal.[141] Humans can also perform dextrous manipulation (e.g., screwing a nut on a bolt), which is very difficult to program a manipulator to do.

**Figure 1.7** Sojourner Mars rover. (Photograph courtesy of the National Aeronautics and Space Administration.)

Another example is the Sojourner robot (shown in Fig. 1.7) which explored Mars from July 5 to September 27, 1997, until it ceased to reply to radio commands. Since there was little data before Sojourner on what Mars is like, it is hard to develop sensors and algorithms which can detect important attributes or even control algorithms to move the robot. It is important that any unusual rocks or rock formations (like the orange rock Dr. Schmitt found on the Moon during Apollo 17) be detected. Humans are particularly adept at perception, especially seeing patterns and anomalies in pictures. Current AI perceptual abilities fall far short of human abilities. Humans are also adept at problem solving. When the Mars Pathfinder craft landed on Mars, the air bags that had cushioned the landing did not deflate properly. When the petals of the lander opened, an airbag was in the way of Sojourner. The solution? The ground controllers sent commands to retract the petals and open them again. That type of problem solving is extremely difficult for the current capabilities of AI.

But teleoperation is not an ideal solution for all situations. Many tasks are repetitive and boring. For example, consider using a joystick to drive a radio-controlled car; after a few hours, it tends to get harder and harder to pay attention. Now imagine trying to control the car while only looking through a small camera mounted in front. The task becomes much harder because of the limited field of view; essentially there is no peripheral vision. Also, the camera may not be transmitting new images very fast because the communication link has a limited bandwidth, so the view is jerky. Most people quickly experience *cognitive fatigue*; their attention wanders and they may even experience headaches and other physical symptoms of stress. Even if the visual display is excellent, the teleoperator may get *simulator sickness* due to the discordance between the visual system saying the operator is moving and the inner ear saying the operator is stationary.[141]

COGNITIVE FATIGUE

SIMULATOR SICKNESS

Another disadvantage of teleoperation is that it can be inefficient to use for applications that have a *large time delay*.[128] A large time delay can result in the teleoperator giving a remote a command, unaware that it will place the remote in jeopardy. Or, an unanticipated event such as a rock fall might occur and destroy the robot before the teleoperator can see the event and command the robot to flee. A rule of thumb, or *heuristic*, is that the time it takes to do a task with traditional teleoperation grows linearly with the transmission delay. A teleoperation task which took 1 minute for a teleoperator to guide a remote to do on the Earth might take 2.5 minutes to do on the Moon, and 140 minutes on Mars.[142] Fortunately, researchers have made some progress with *predictive displays*, which immediately display what the simulation result of the command would be.

TELEOPERATION HEURISTIC

PREDICTIVE DISPLAYS

The impact of time delays is not limited to planetary rovers. A recent example of an application of teleoperation are unmanned aerial vehicles (UAV) used by the United States to verify treaties by flying overhead and taking videos of the ground below. Advanced prototypes of these vehicles can fly autonomously, but take-offs and landings are difficult for on-board computer control. In this case of the Darkstar UAV (shown in Fig. 1.8), human operators were available to assume teleoperation control of the vehicle should it encounter problems during take-off. Unfortunately, the contingency plan did not factor in the 7 second delay introduced by using a satellite as the communications link. Darkstar no. 1 did indeed experience problems on take-off, but the teleoperator could not get commands to it fast enough before it crashed. As a result, it earned the unofficial nickname "Darkspot."

Another practical drawback to teleoperation is that there is at least one person per robot, possibly more. The Predator unmanned aerial vehicle has been used by the United States for verification of the Dayton Accords in Bosnia. One Predator requires at least one teleoperator to fly the vehicle and another teleoperator to command the sensor payload to look at particular areas. Other UAVs have teams composed of up to four teleoperators plus a fifth team member who specializes in takeoffs and landings. These teleop-

**Figure 1.8** Dark Star unmanned aerial vehicle. (Photograph courtesy of DefenseLink, Office of the Assistant Secretary of Defense-Public Affairs.)

erators may have over a year of training before they can fly the vehicle. In the case of UAVs, teleoperation permits a dangerous, important task to be completed, but with a high cost in manpower.

TASK CHARACTERISTICS

According to Wampler,[142] teleoperation is best suited for applications where:

1. The tasks are unstructured and not repetitive.
2. The task workspace cannot be engineered to permit the use of industrial manipulators.
3. Key portions of the task intermittently require dextrous manipulation, especially hand-eye coordination.
4. Key portions of the task require object recognition, situational awareness, or other advanced perception.
5. The needs of the display technology do not exceed the limitations of the communication link (bandwidth, time delays).
6. The availability of trained personnel is not an issue.

### 1.5.1 Telepresence

An early attempt at reducing cognitive fatigue was to add more cameras with faster update rates to widen the field of view and make it more consistent with how a human prefers to look at the world. This may not be practical for many applications because of limited bandwidth. Video telephones, picture phones, or video-conferencing over the Internet with their jerky, asynchronous updates are usually examples of annoying limited bandwidth. In these instances, the physical restrictions on how much and how fast information can be transmitted result in image updates much slower than the rates human brains expect. The result of limited bandwidth is jerky motion and increased cognitive fatigue. So adding more cameras only exacerbates the problem by adding more information that must be transmitted over limited bandwidth.

TELEPRESENCE

VIRTUAL REALITY

One area of current research in teleoperation is the use of *telepresence* to reduce cognitive fatigue and simulator sickness by making the human-robot interface more natural. Telepresence aims for what is popularly called *virtual reality*, where the operator has complete sensor feedback and feels as if she were the robot. If the operator turns to look in a certain direction, the view from the robot is there. If the operator pushes on a joystick for the robot to move forward and the wheels are slipping, the operator would hear and feel the motors straining while seeing that there was no visual change. This provides a more natural interface to the human, but it is very expensive in terms of equipment and requires very high bandwidth rates. It also still requires one person per robot. This is better than traditional teleoperation, but a long way from having one teleoperator control multiple robots.

### 1.5.2 Semi-autonomous control

SEMI-AUTONOMOUS CONTROL

SUPERVISORY CONTROL

Another line of research in teleoperation is *semi-autonomous control*, often called *supervisory control*, where the remote is given an instruction or portion of a task that it can safely do on its own. There are two flavors of semi-autonomous control: continuous assistance, or *shared control*, and *control trading*.

SHARED CONTROL

In continuous assistance systems, the teleoperator and remote share control. The teleoperator can either delegate a task for the robot to do or can do it via direct control. If the teleoperator delegates the task to the robot, the human must still monitor to make sure that nothing goes wrong. This is particularly useful for teleoperating robot arms in space. The operator can relax (relatively) while the robot arm moves into the specified position near a panel, staying on alert in case something goes wrong. Then the operator can take over and perform the actions which require hand-eye coordination. Shared control helps the operator avoid cognitive fatigue by delegating boring, repetitive control actions to the robot. It also exploits the ability of a human to perform delicate operations. However, it still requires a high communication bandwidth.

CONTROL TRADING

An alternative approach is *control trading*, where the human initiates an action for the robot to complete autonomously. The human only interacts with the robot to give it a new command or to interrupt it and change its orders. The overall scheme is very much like a parent giving a 10-year old child a task to do. The parent knows what the child is able to do autonomously (e.g., clean their room). They have a common definition (clean room means go to the bedroom, make the bed, and empty the wastebaskets). The parent doesn't care about the details of how the child cleans the room (e.g., whether the wastebasket is emptied before the bed is made or vice versa). Control trading assumes that the robot is capable of autonomously accomplishing certain tasks without sharing control. The advantage is that, in theory, the local operator can give a robot a task to do, then turn attention to another robot and delegate a task to it, etc. A single operator could control multiple robots because they would not require even casual monitoring while they were performing a task. Supervisory control also reduces the demand on bandwidth and problems with communication delays. Data such as video images need to be transferred only when the local is configuring the remote for a new task, not all the time. Likewise, since the operator is not involved in directly controlling the robot, a 2.5 minute delay in communication is irrelevant; the robot either wrecked itself or it didn't. Unfortunately, control trading assumes that robots have actions that they can perform robustly even in unexpected situations; this may or may not be true. Which brings us back to the need for artificial intelligence.

Sojourner exhibited both flavors of supervisory control. It was primarily programmed for traded control, where the geologists could click on a rock and Sojourner would autonomously navigate close to it, avoiding rocks, etc. However, some JPL employees noted that the geologists tended to prefer to use shared control, watching every movement. A difficulty with most forms of shared control is that it is assumed that the human is smarter than the robot. This may be true, but the remote may have better sensor viewpoints and reaction times.

## 1.6 The Seven Areas of AI

Now that some possible uses and shortcomings of robots have been covered, it is motivating to consider what are the areas of artificial intelligence and how they could be used to overcome these problems. The Handbook of Artificial Intelligence[64] divides up the field into seven main areas: *knowledge representation, understanding natural language, learning, planning and problem solving, inference, search,* and *vision*.

KNOWLEDGE REPRESENTATION

1. **Knowledge representation**. An important, but often overlooked, issue is how does the robot represent its world, its task, and itself. Suppose a robot is scanning a pile of rubble for a human. What kind of data structure and algorithms would it take to represent what a human looks like? One way is to construct a structural model: a person is composed of an oval head, a cylindrical torso, smaller cylindrical arms with bilateral symmetry, etc. Of course, what happens if only a portion of the human is visible?

UNDERSTANDING NATURAL LANGUAGE

2. **Understanding natural language**. Natural language is deceptively challenging, apart from the issue of recognizing words which is now being done by commercial products such as Via Voice and Naturally Speaking. It is not just a matter of looking up words, which is the subject of the following apocryphal story about AI. The story goes that after Sputnik went up, the US government needed to catch up with the Soviet scientists. However, translating Russian scientific articles was time consuming and not many US citizens could read technical reports in Russian. Therefore, the US decided to use these newfangled computers to create translation programs. The day came when the new program was ready for its first test. It was given the proverb: the spirit is willing, but the flesh is weak. The reported output: the vodka is strong, but the meat is rotten.

LEARNING

3. **Learning.** Imagine a robot that could be programmed by just watching a human, or by just trying the task repeatedly itself.

PLANNING, PROBLEM SOLVING

4. **Planning and problem solving.** Intelligence is associated with the ability to plan actions needed to accomplish a goal and solve problems with those plans or when they don't work. One of the earliest childhood fables, the Three Pigs and the Big, Bad Wolf, involves two unintelligent pigs who don't plan ahead and an intelligent pig who is able to solve the problem of why his brothers' houses have failed, as well as plan an unpleasant demise for the wolf.

INFERENCE

5. **Inference**. Inference is generating an answer when there isn't complete information. Consider a planetary rover looking at a dark region on the ground. Its range finder is broken and all it has left is its camera and a fine AI system. Assume that depth information can't be extracted from

the camera. Is the dark region a canyon? Is it a shadow? The rover will need to use inference to either actively or passively disambiguate what the dark region is (e.g., kick a rock at the dark area versus reason that there is nothing nearby that could create that shadow).

SEARCH

6. **Search**. Search doesn't necessarily mean searching a large physical space for an object. In AI terms, search means efficiently examining a knowledge representation of a problem (called a "search space") to find the answer. Deep Blue, the computer that beat the World Chess master Gary Kasparov, won by searching through almost all possible combinations of moves to find the best move to make. The legal moves in chess given the current state of the board formed the search space.

VISION

7. **Vision**. Vision is possibly the most valuable sense humans have. Studies by Harvard psychologist Steven Kosslyn suggest that much of problem solving abilities stem from the ability to visually simulate the effects of actions in our head. As such, AI researchers have pursued creating vision systems both to improve robotic actions and to supplement other work in general machine intelligence.

SOFTWARE AGENTS
WEB-BOT

Finally, there is a temptation to assume that the history of AI Robotics is the story of how advances in AI have improved robotics. But that is not the case. In many regards, robotics has played a pivotal role in advancing AI. Breakthroughs in methods for planning (operations research types of problems) came after the paradigm shift to reactivity in robotics in the late 1980's showed how unpredictable changes in the environment could actually be exploited to simplify programming. Many of the search engines on the world wide web use techniques developed for robotics. These programs are called *software agents*: autonomous programs which can interact with and adapt to their world just like an animal or a smart robot. The term *web-bot* directly reflects on the robotic heritage of these AI systems. Even animation is being changed by advances in AI robotics. According to a keynote address given by Danny Hillis at the 1997 Autonomous Agents conference, animators for Disney's *Hunchback of Notre Dame* programmed each cartoon character in the crowd scenes as if it were a simulation of a robot, and used methods that will be discussed in Ch. 4.

## 1.7 Summary

AI robotics is a distinct field, both historically and in scope, from industrial robotics. Industrial robots has concentrated on control theory issues, particularly solving the dynamics and kinematics of a robot. This is concerned with having the stationary robot perform precise motions, repetitively in a structured factory environment. AI robotics has concentrated on how a mobile robot should handle unpredictable events in an unstructured world. The design of an AI robot should consider how the robot will represent knowledge about the world, whether it needs to understand natural language, can it learn tasks, what kind of planning and problem solving will it have to do, how much inference is expected, how can it rapidly search its database and knowledge for answers, and what mechanisms will it use for perceiving the world.

Teleoperation arose as an intermediate solution to tasks that required automation but for which robots could not be adequately programmed to handle. Teleoperation methods typically are cognitive fatiguing, require high communication bandwidths and short communication delays, and require one or more teleoperators per remote. Telepresence techniques attempt to create a more natural interface for the human to control the robot and interpret what it is doing and seeing, but at a high communication cost. Supervisory control attempts to delegate portions of the task to the remote, either to do autonomously (traded control) or with reduced, but continuous, human interaction (shared control).

## 1.8 Exercises

**Exercise 1.1**

List the four attributes for evaluating an architecture. Based on what you know from your own experience, evaluate MS Windows 95/98/2000 as an architecture for teleoperating a robot.

**Exercise 1.2**

Name the three primitives for expressing the components of a robotics paradigm.

**Exercise 1.3**

Name the three robotic paradigms, and draw the relationship between the primitives.

**Exercise 1.4**

What is an intelligent robot?

**Exercise 1.5**

What is a Luddite?

**Exercise 1.6**

Describe at least two differences between AI and Engineering approaches to robotics.

**Exercise 1.7**

List three problems with teleoperation.

**Exercise 1.8**

Describe the components and the responsibilities of the local and the remote members of a telesystem.

**Exercise 1.9**

Describe the difference between telepresence and semi-autonomous control.

**Exercise 1.10**

List the six characteristics of applications that are well suited for teleoperation. Give at least two examples of potentially good applications for teleoperation not covered in the chapter.

**Exercise 1.11** [*World Wide Web*]

Search the world wide web for sites that permit clients to use a robot remotely (one example is Xavier at Carnegie Mellon University). Decide whether each site is using human supervisory or shared control, and justify your answer.

**Exercise 1.12** [*World Wide Web*]

Search the world wide web for applications and manufacturers of intelligent robots.

**Exercise 1.13** [*World Wide Web*]

Dr. Harrison "Jack" Schmitt is a vocal proponent for space mining of Near Earth Objects (NEOs) such as mineral-rich asteroids. Because of the economics of manned mission, the small size of NEOs, human safety concerns, and the challenges of working in micro-gravity, space mining is expected to require intelligent robots. Search the web for more information on space mining, and give examples of why robots are needed.

**Exercise 1.14** [*Programming*]

(This requires a robot with an on-board video camera and a teleoperation interface.) Teleoperate the robot through a slalom course of obstacles while keeping the robot in view as if controlling a RC car. Now looking only at the output of the video camera, repeat the obstacle course. Repeat the comparison several times, and keep track of the time to complete the course and number of collisions with obstacles. Which viewpoint led to faster completion of the course? Fewer collisions? Why?

**Exercise 1.15** [*Advanced Reading*]

Read "Silicon Babies," Scientific American, December 1991, pp 125-134, on the challenges of AI robotics. List the 7 topics of AI and give examples of robots or researchers addressing each topic.

**Exercise 1.16** [*Science Fiction*]

Read "Stranger in Paradise," Isaac Asimov, The Complete Robot, Doubleday, 1982, and enumerate the problems with telepresence illustrated by this story.

**Exercise 1.17** [*Science Fiction*]

Watch the movie *Star Gate*. The military uses a teleoperated vehicle (in reality, NASA Jet Propulsion Laboratory's Hazbot) to first go through the star gate and test the environmental conditions on the other side. Discuss other ways in which the team could have continued to use the robot to their advantage.

**Exercise 1.18** [*Science Fiction*]

Watch the 1971 movie, *The Andromeda Strain*, by Michael Crichton. The movie has several nerve wracking scenes as the scientists try to telemanipulate an unknown, deadly organism as fast as possible without dropping it. What do you think can be done with today's robots?

## 1.9 End Notes

*Finding robots in the popular press*
There is no one-stop-shopping publication or web site for robot applications. *Robotics World* is a business oriented publication which often has interesting blurbs. *Popular Mechanics* and *Popular Science* often contain short pieces on new robots and applications, although those short bits are often enthusiastically optimistic. A new magazine, *Robot Science and Technology*, appears to be bridging the gap between hobby 'bots and research 'bots. In addition to surfing the web, annual proceedings from the IEEE International Conference on Robotics and Automation (ICRA) and IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS) contain scientific articles on the newest robots emerging from university and government laboratories. *Intelligent Robotic Systems*, ed. by S.G. Tzafestas, Marcel Dekker Inc, NY, 1991. This is a collection of chapters by various researchers and laboratory managers. The work is a bit dated now, but gives some feel for the variety of applications.

*About Joe Engleberger*
Joe Engleberger is often referred to as the "Father of Industrial Robots." His impressive resume includes having formed Unimation. His most recent robotics company made the HelpMate robot for hospitals. Engleberger participates in many robotics

forums, where his sartorial style (he always wears a bow tie) and verbal style (stridently pro-robotics, and that his company should get more money) make him easily recognizable.

*Science fiction and robotics*
For science fiction enthusiasts, take a look at Clute, John, and Nicholls, Peter, "Grolier Science Fiction: The Multimedia Encyclopedia of Science Fiction," Grolier Electronic Publishing, Danbury, CT, 1995. This entertaining CD provides a very detailed, cross-referenced look at robots as a theme in science fiction and a lengthy list (and review) of movies and books with robots in them. One of the most technically accurate movies about robots is *Silent Running*. It was directed by Douglas Trumbull who gained fame for his work in special effects, including *2001: A Space Odyssey, Close Encounters of the Third Kind,* and *Blade Runner*. The bulk of the movie concerns the day to day life of Bruce Dern and three waist-high robots. The robots and how they interact with Dern and their environment are very realistic and consistent with AI robotics. The only downside is a laughably ecologically correct plot (written in part by Steven Bochco and Michael Cimino) complete with songs by Joan Baez. Well worth watching for the 'bots, especially if the audience is curious about the hippie movement.

*Robot name trivia*
Marvin, the mail robot, may be named after the cantankerous robot Marvin in *The Hitchhiker's Guide to the Galaxy*. That Marvin is widely assumed to be named after the cantankerous AI researcher, Dr. Marvin Minksy, at MIT.

*Have Spacesuit, Will Travel.*
John Blitch brought to my attention the difficulty the Apollo astronauts had in accomplishing simple tasks due to the bulky space suits.