1 Autonomy and Control in Animals and Robots

Summary

This chapter introduces the main theme of the book: control of autonomous robots based on biological principles. Numerous mobile robots (with various degrees of autonomy) are presented and discussed to provide a context for the rest of the book. There are overviews of control issues in robotic systems and the overall architecture of mobile robots, including sensors, actuators, and intelligent processors, illustrated by multiple examples.

1.1 What Is Autonomy?

Autonomy refers to systems capable of operating in the real-world environment without any form of external control for extended periods of time. Thus, living systems are the prototypes of autonomous systems: They can survive in a dynamic environment for extended periods, maintain their internal structures and processes, use the environment to locate and obtain materials for sustenance, and exhibit a variety of behaviors (such as feeding, foraging, and mating). They are also, within limits, capable of adapting to environmental change.

The emphasis on behaviors makes it clear that we do not consider a rock an autonomous system. Clearly, it exists in the world without external control, but it is capable neither of operating in the world nor of exhibiting any behaviors.

The emphasis in this book is on autonomous systems created by humans. Frequently, these systems draw inspiration from biology, but not always. For example, many autonomous systems use wheels for locomotion, and no wheels exist in nature. "Capable of operating" implies that these systems perform some function or task. This function may be that intended by their human creator, or it may be an unexpected, emergent behavior. As these systems become more complex, they are likely to exhibit more and more unexpected behaviors.

It should be clear that at the present time, most robots are not fully autonomous, within the scope of the preceding definition. They are not capable of surviving and performing useful tasks in the real world for extended periods, except under highly structured situations. However, if the environment is sufficiently stable and the disturbances to it are not too severe, robots can indeed survive and perform useful tasks for extended periods. Furthermore, the field of robotics is a very active research area at this time, and we can expect robots to exhibit increasing levels of autonomy and intelligence in the near future. In certain structured situations, for example, the international RoboCup competitions, small teams of robots already exhibit full autonomy while playing "robot soccer" (Asada and Kitano 1999a).

1.2 What Is a Robot?

In this book we define a robot as *a machine that senses, thinks, and acts*. Thus, a robot must have sensors, processing ability that emulates some aspects of cognition, and actuators. Sensors are needed to obtain information from the environment. Reactive behaviors (like the stretch reflex in humans) do not require any deep cognitive ability, but on-board intelligence is necessary if the robot is to perform significant tasks autonomously, and actuation is needed to enable the robot to exert forces upon the environment. Generally, these forces will result in motion of the entire robot or one of its elements (such as an arm, a leg, or a wheel).

This definition of a robot is very broad. It includes industrial robot manipulators, such as those used for pick-and-place, painting, or welding operations, provided they incorporate all these three elements. Early industrial manipulators had neither sensing nor reasoning ability; they were preprogrammed to execute specific tasks. Currently most industrial robots are being equipped with computer vision and other sensors and include on-board processors to allow for some autonomy. The definition also encompasses a wide range of mobile robots, from the smallest (currently about 1 cm^3) to robot planes, helicopters or submersibles, humanoids and household robots. Figure 1.1 illustrates some of the robots discussed in this book. It is evident from the pictures in the figure that robots come in a wide variety of shapes and sizes, with varying degrees of autonomy, intelligence, and mobility. We describe each of the robots depicted in figure 1.1 briefly in section 1.8. In later chapters of this book we will encounter them again, with considerably more detail on their anatomy and function.

1.3 Problems of Robot Control

Given the view of autonomy outlined in section 1.1, then what is "robot control"? There appears to be a contradiction between *autonomy*, which implies that a robot is capable of taking care of itself, and *control*, which appears to imply some sort of human intervention. To be sure, some form of "high-level control" is required to ensure that the robots do not harm any humans or equipment or other robots. In effect, this high level of control implies an implementation of Asimov's laws, which can be paraphrased as follows:

1. A robot should never harm a human being.
2. A robot should obey a human being, unless this contradicts the first law.
3. A robot should not harm another robot, unless this contradicts the first or second law.

However, there are other levels of control. At the "lowest" level, we want to be sure that the motors driving robots' wheels or moving their legs are used in stable configurations and do not begin to oscillate when activated. At the next level of control, we need to design robots so that they do not collide with one another or with obstacles, while at the same time maintaining stability at the lowest level. We also expect the robots to be able to perform a number of behaviors, such as "foraging" (gathering prespecified objects from the environment) or "flocking" or "following" (e.g., Matarić 1994), while at the same time avoiding obstacles and maintaining stability. Software architectures allowing for such control processes to proceed in parallel are known as *subsumption* architectures (Brooks 1986) or *behavior-based* architectures (Arkin 1998).

The various levels of control discussed in the foregoing are shown in figure 1.2. The software organization associated with these multiple levels is often termed the *control architecture* of a robot. We examine these various aspects of control in detail in succeeding chapters of this book, but some of the basic issues are discussed in the following paragraphs. Clearly, the higher levels of control provide inputs to the lower levels, but there is also feedback from the lower levels to the upper levels. Sensors provide inputs to the lowest (and sometimes the intermediate level); actions upon the world are exerted from the lowest level.

Note that the upper box in figure 1.2 indicates human input is involved in high-level robot control. Low-level control is clearly autonomous, whereas intermediate-level control is generally autonomous in contemporary mobile robots but may still involve some human input. As indicated previously, this is an extremely active area of research, and we can expect increasing autonomy even at the highest level. "Structure shift," referred to in the figure in the context of high-level control, implies an ability on the part of a robot to reconfigure its physical structure; some robots are already capable of some autonomous reconfiguration (see, e.g., Rus and Chirikjian 2001; Shen, Salemi, and Will 2002).

Low-level control systems encountered in other, more common venues are frequently taken for granted, without recognition that they were in fact designed using

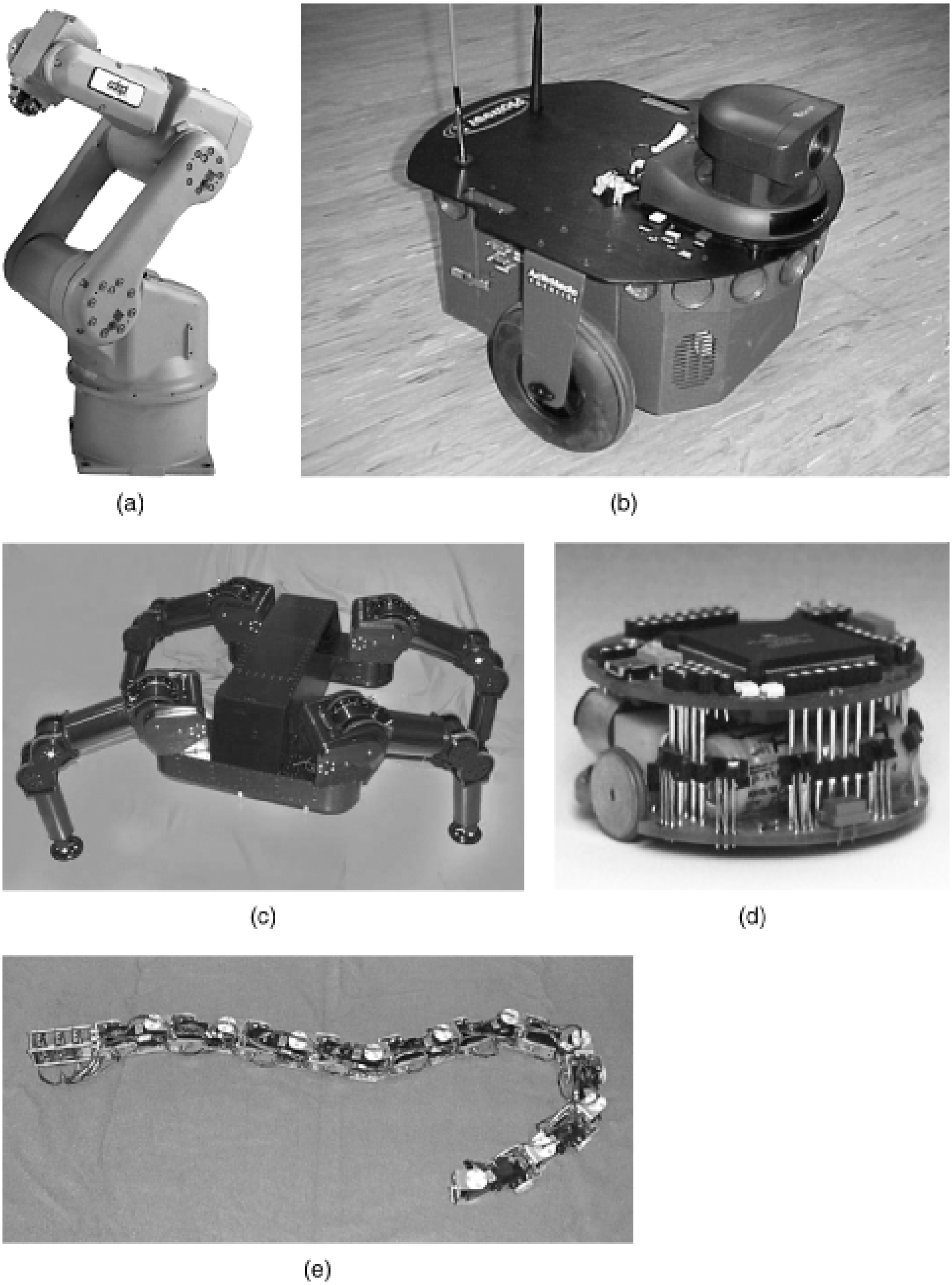
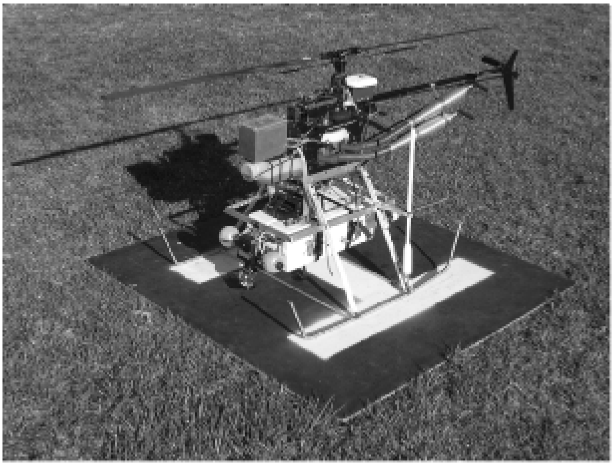


Figure 1.1
(a) a typical industrial manipulator (photograph courtesy of Adept Technology, Inc.); (b) a Pioneer mobile robot, commonly used in research laboratories (photograph courtesy of ActivMedia Robotics); (c) a large quadruped robot (TITAN IX) developed by the Hirose-Yoneda Laboratory at the Tokyo Institute of Technology (photograph courtesy of Shigeo Hirose); (d) a small Khepera robot, about 7 cm in diameter, originally developed at the Swiss Federal Institute of Technology and available commercially from



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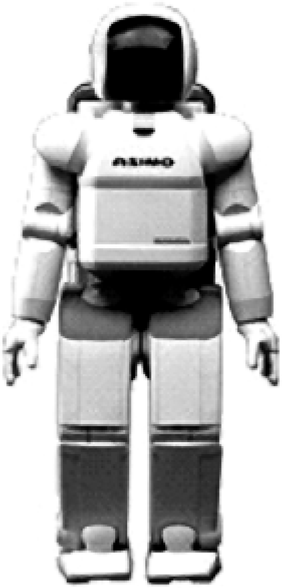

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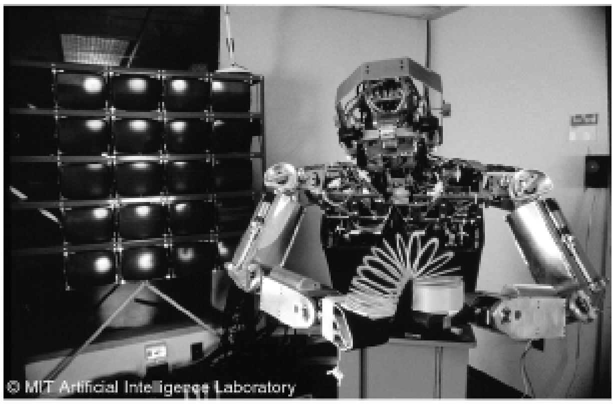


(j)

Figure 1.1 (continued)
K-Team S.A. in Lausanne, Switzerland (photograph courtesy of K-Team); (e) articulated snakelike robot constructed by Kevin Dowling at Carnegie Mellon University (courtesy of Kevin Dowling); (f) the AVATAR robot helicopter developed at the University of Southern California courtesy of Gavrav Sukhatine; (g) Roomba, a household vacuum-cleaning robot from iRobot Corporation (photograph courtesy of iRobot Corporation); (h) AIBO, a pet robot from Sony Corporation (photograph courtesy of Sony); (i) ASIMO, a biped walking robot from Honda Motor Company Ltd. (photograph courtesy of Honda); (j) Cog, a humanoid torso with significant cognitive abilities as well as arm and head movements, developed at the Artificial Intelligence Laboratory at the Massachusetts Institute of Technology (photograph courtesy of Rodney Brooks and Annika Pfluger)

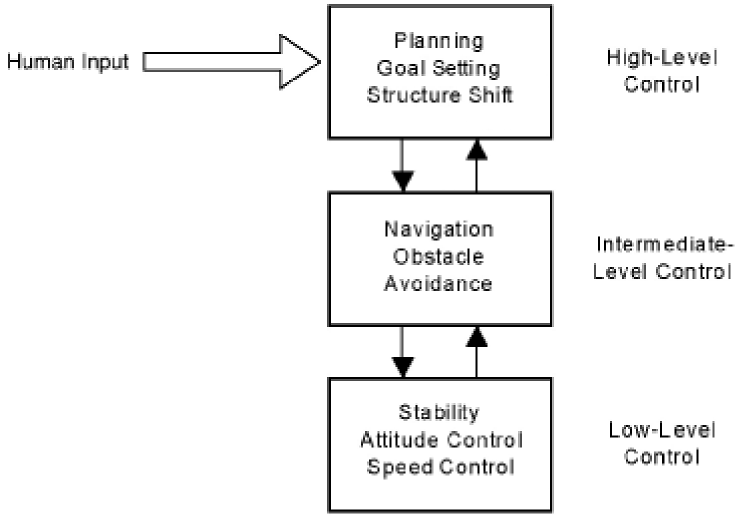


Figure 1.2
Levels of control in autonomous robots

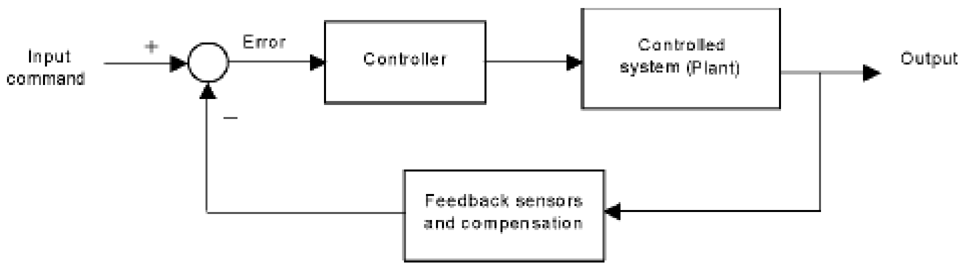


Figure 1.3
Basic control system

the techniques of control theory. For example, such automobile systems as power steering or power brakes are in fact feedback control systems, with the general structure shown in figure 1.3.

The *input command* in the figure may represent, for example, in the case of power steering, the desired orientation of the front wheels (as commanded by the steering wheel). The error is the difference between the commanded direction and the actual direction. This error signal is the input into a controller (frequently a microprocessor) that generates an input signal to the actual motor that moves the wheels. The resulting wheel direction is now measured using sensors and compared with the input command. Systems of this type are known as negative feedback control systems, since the feedback signal has the opposite sign from the input command. It is important to note that the system illustrated in this figure is a dynamic system, not a static one. This means that it is described by differential equations to represent the variables and their rates of change (derivatives with respect to time); static systems are described by algebraic equations, since they do not depend on time.

Note, however, that nothing is as simple as it seems in a feedback control system. If the driver applies a clockwise motion to the steering wheel, followed a fraction of a second later by a counterclockwise motion (as may happen when avoiding an object in the roadway), and these motions are repeated, it is important that there be no delay in comparing the feedback signal with the input. Assume that the driver produces the second (counterclockwise) command 0.5 seconds after the first command. Assume that the controller, controlled system, and feedback boxes do not alter the shape of the signal they receive, but simply delay it in time by 0.5 seconds. Then the input command, actual output position, and error signals will have the form shown in figure 1.4.

If the feedback signal is delayed by 0.5 seconds, it is evident that when it arrives at the comparator and is subtracted from the input signal, it will in fact add to the input, thus producing an error signal that grows in time, as shown in the lower waveform of figure 1.4. Improperly designed control systems may display such increasing oscillations even when the input signal is returned to zero. This phenomenon is known as *instability*. Many robots move so slowly that such unstable behaviors are highly unlikely. However, future generations of autonomous robots are expected to exhibit much higher response speeds, and hence their low-level controllers will have to be designed carefully to avoid instabilities.

Although the foregoing example concerned the steering control system in an automobile, similar systems provide the speed or orientation control of a wheeled robot, for example, or the leg position control of walking robots. Of course, in order to control these or any other variables, we need to be able to measure their values and then exert correcting forces. Hence, the issues of control system design are intimately related to selection and design of sensors and actuators. We consider these various aspects of robot control systems in later chapters. Various approaches to the design of engineering control systems are discussed in chapter 4.

1.4 Biologically Inspired Robot Control

In a general sense, engineering and biological control systems have similar structures, as illustrated in figure 1.5. Panel (a) shows a prototypical biological control system, in which the command signal is provided by the central nervous system, the computations required by the controller are performed either locally or by the brain, and the "plant" refers to the dynamics of the controlled system. Panel (b) shows the

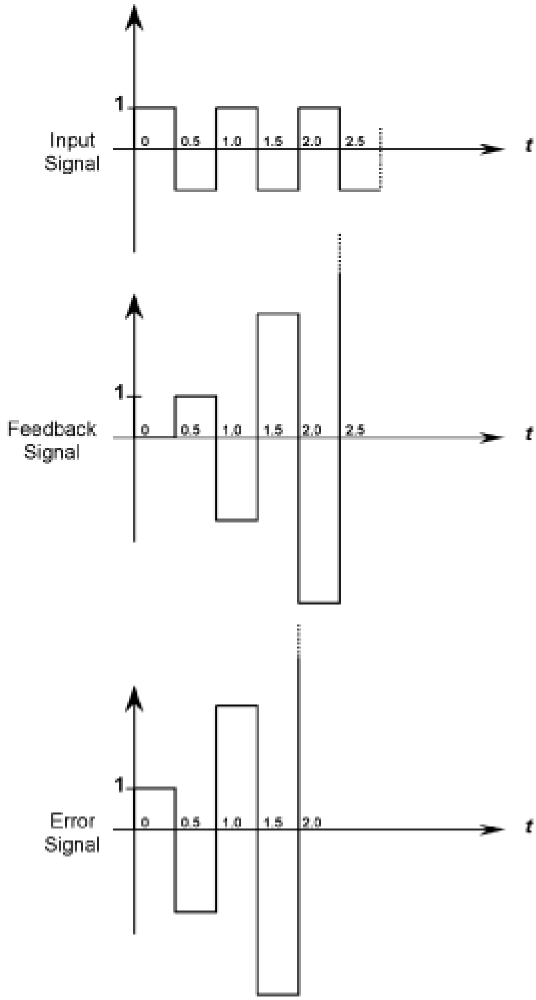


Figure 1.4
Emergence of oscillations in a feedback system

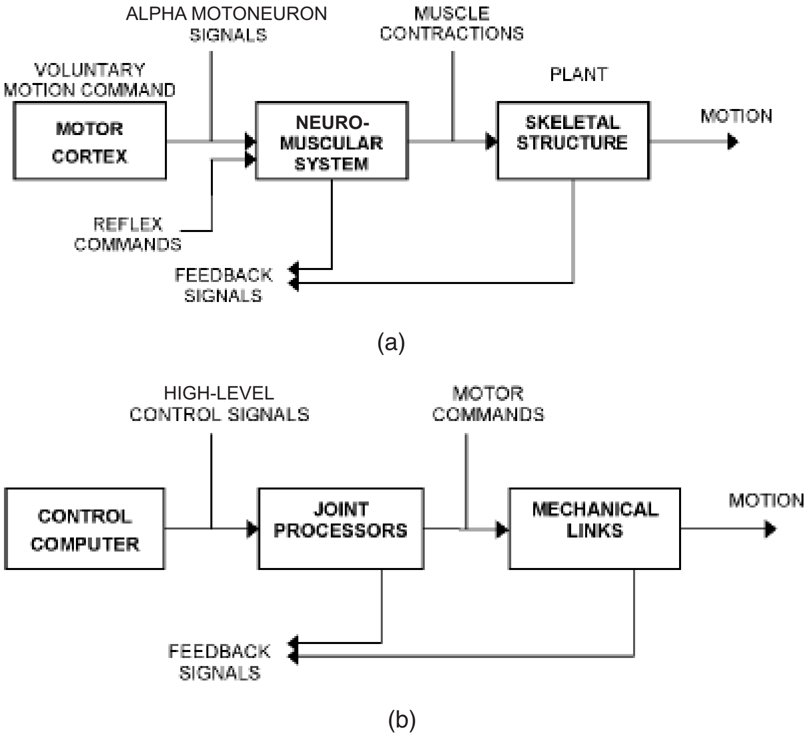


Figure 1.5
Control systems: (a) biological and (b) analogous engineering (robot)

engineering counterpart to the biological system in panel (a). It is equivalent to the control system shown in figure 1.3 but shows some of the details associated with controlling the legs of a walking robot.

It is important to note that one should not take analogies of the type shown in figure 1.5 too seriously, since biological systems are more complex than and may behave in ways quite distinct from human-designed systems. Consider, for example, the control of body temperature. It is well known that the body core temperature in humans is maintained at approximately 37°C. However, the system that maintains this constant temperature (and a number of other homeostatic systems) does not behave like the engineering systems in figure 1.2, since there is no reference temperature input. In other words, whereas an engineering system may have a "reference" value (e.g., the voltage from a battery), the body's temperature control system has no such standard value. Furthermore, the diagram depicted in figure 1.2 is used primarily (but not exclusively) to describe linear control systems, that is, systems in which both the plant and the controller can be described by linear differential equations.

Table 1.1
Some characteristics of biological control systems

Adapt to changes in internal and external environment
Usually nonlinear
Hierarchical organization
Include redundancy
May involve multiple control loops
Control is frequently distributed
Control may be based on multiple performance criteria
May display limit cycle oscillations

In general, biological systems are nonlinear. A number of biological variables appear to oscillate with small amplitudes in a manner characteristic of certain nonlinear systems. These oscillations are known as *limit cycles* (see chapter 4). Biological systems adapt to their environment and change their control systems accordingly, whereas engineering systems tend to be fixed and nonadaptive. Table 1.1 lists some of the more important characteristics of biological control systems. We discuss most of these issues in more detail in chapter 2.

Recent research has increasingly emphasized the use of behavior-based strategies for control of autonomous robots (Brooks 1986; Maes and Brooks 1990; Arkin 1998; Beer 1990). One of the major motivating factors behind this approach to autonomy arises from the difficulties associated with traditional methods, which require accurate knowledge of the robot's dynamics and kinematics, as well as carefully constructed maps of the environment in which they operate. Such approaches are not well suited to time-varying and unpredictable, unstructured situations. As a solution to this problem, Brooks and others have proposed reactive strategies: The robot senses the environment and reacts with appropriate behaviors as required. As we show in chapter 5, current behavior-based architectures augment reactive behaviors with planning and reasoning; the latter are sometimes referred to as *deliberative* components of the robot's control architecture.

1.5 Sensors

Robots need sensors both to receive information from the outside world and to monitor their internal environment. Many (but not all) robot sensors are devices that attempt to imitate some of the properties of animal senses. In this section we provide a brief introduction to the major sensory systems in animals, indicate how some of the features of these sensors are incorporated into sensing devices used with mobile robots, and list the major limitations of these devices. Sensors are discussed in greater detail in chapter 3.

Exteroceptive sensors are used to obtain information from the external environment. We frequently speak of the ''five senses'' (vision, hearing, olfaction, touch, and taste), but each of these major categories in living systems encompasses an exquisite and complex array of sensory dimensions. Furthermore, perception of the outside world by animals is based on an interaction of the sensory apparatus proper with corresponding processing centers in the brain. Hence, design of an artificial ''eye'' for a robot requires not only a light-sensitive receptor, but some aspects of the visual cortex. Robot vision systems usually include a camera (with resolution comparable to or better than standard television cameras) and software designed for such tasks as detecting edges, enhancing contrast, or recognizing objects. Clearly, some of these features are based on living prototypes. The compound eyes of certain insects have other properties, not yet imitated by robot sensors.

The human visual system includes neural circuits tuned to the perception of lines in particular directions. The frog visual system is highly tuned to the detection of moving insects (Lettvin et al. 1959). The design of robot sensory systems may include some aspects of both of these features. This would be highly desirable if one wished, for example, to design a robot helicopter to recognize particular landmarks on the ground or a robot frog to catch and digest flies. The situation is similar with the other senses. In general, then, robot sensors are very limited compared to their living equivalents. For example, some animal sensory systems, such as the olfactory system of certain insects (capable of detecting a few molecules of pheromones) or the visual system of raptors, such as eagles or hawks, are incredibly sensitive to particular signals. Engineering approximations to some of these animal sensory systems are used on robots. Most robots are equipped with obstacle detectors that operate using ultrasound or lasers. These detectors emit a signal and pick up the echo from an object, in a manner analogous to the navigation system of bats. On the other hand, it is possible to design robot sensors capable of detecting physical phenomena not detectable by sensory systems of living animals. For example, a robot equipped with a Geiger counter can detect ionizing radiation, which vertebrates cannot do. Similarly, robot sensors can be designed to detect ultraviolet or microwave radiation. Other exteroceptive sensors in robots include those able to detect sound, object texture (touch), certain odors, temperature, and slippage. These and other sensors are discussed in chapter 3.

Proprioceptive sensors monitor the organism's or robot's internal environment. In view of the differences between engineering systems and living systems, proprioceptive robot sensors may not have living models. For example, a robot may need to monitor its wheel rotations and its battery voltage level, which have no human or animal counterparts. Monitoring the joint angles and leg motor currents in a legged robot corresponds to human systems' obtaining of information from Golgi tendon organs and muscle spindles, but the analogy is gross at best. In robots employing artificial muscles (which contract when stimulated), it may be possible to design sensors with properties that mimic those in living muscle, but it is not clear that such a design would be desirable in view of their large number and complexity. The goal of proprioceptive sensors in robots is to provide signals indicative of the robot's internal states, in order to improve control, to identify and correct faults, or to provide feedback to humans.

1.6 Actuators

A robot must be able to interact physically with the environment in which it is operating. In fact, the key difference between a robot and a "softbot" or software agent lies primarily in a robot's having actuators that permit it to affect the environment, say, by exerting forces upon it or moving through it, which a softbot lacks. Various actuators are discussed in detail in chapter 3. Some of the most common actuators are

- artificial muscles of various types, none of which are very good approximations of living muscles;
- electric motors, the most common actuators in mobile robots, used both to provide locomotion by powering wheels or legs, and for manipulation by actuating robot arms (special-purpose motors, such as stepper motors, are used for precision movement);
- pneumatic and hydraulic actuators, used in industry for large manipulation tasks, but seldom for mobile robots.

1.7 Intelligence

As noted in section 1.2, a robot is a machine that senses, thinks, and acts. Computers are the brains of robots and are essential elements of these systems. The continuing decreases in size and weight of microprocessors, coupled with increases in speed and memory, have had major effects on the development of mobile robots. Since at present a single chip can have the processing power of a mainframe computer only twenty years ago, small mobile robots are now being equipped with extremely powerful on-board computers. Hence, the limited cognitive abilities of these robots (and thus their ability to perform increasingly complex tasks) are due to software rather than hardware. "Intelligence" appears in these systems in a number of ways:

1. *Sensor processing* Raw outputs from sensors are not very useful for controlling behavior. Thus, robot vision systems frequently include special-purpose software for locating areas in the environment that differ in some way from the surround ("blob

detection''), for edge detection, for contrast enhancement, and so on. Biological sensors also include such preprocessing (e.g., ''What the frog's eye tells the frog's brain'' [Lettvin et al. 1959]). Placing some of this processing in the sensors reduces the load on the robot's central processor.

2. *Reflex behaviors* In living systems there are rapid reaction paths from sensing to actuation (reflexes) that do not involve higher centers in the nervous system. Withdrawing the hand upon touching a hot stove or the knee-jerk reflex are examples. In the latter, when the physician taps the tendon below the patella with her hammer, specialized sense organs within the muscle fibers (*muscle spindles*) sense the resulting lengthening of the fiber and send a signal to the spinal cord, resulting in contraction of the muscle. When the leg of an insect contacts an obstacle, such as a rock, while walking, the leg is withdrawn and moved higher in an attempt to clear the obstacle. When included in the behavior of a walking machine, such behavior appears ''intelligent'' (Brooks 1989; Sukhatme 1997).

3. *Special-purpose programs* Such applications as navigation, localization, and obstacle avoidance may be included in robot software.

4. *Cognitive functions* Artificial-intelligence research is providing robot computers with continual improvements in a number of cognitive functions, including reasoning, learning, and planning.

The organization of the above components of robot control software is known as the robot's *software architecture*. It is generally hierarchical in structure, with the reactive components appearing at the lowest level and those components involving planning and learning at the highest level, as illustrated in the ''three-level architecture'' of figure 1.6. Human control inputs are applied at the highest level. Robot architectures are discussed in detail in chapter 5.

All of these aspects of robot design are discussed in later chapters of the book. Suffice it to say at this point that the field is moving very rapidly, so that we can expect fairly dramatic improvements in robot intelligence in the coming decades. But will the robots then be so intelligent that they may refuse to obey us (see chapter 15)?

1.8 A Brief Survey of Current Robots and Associated Control Issues

We now consider the robots illustrated in figure 1.1. Robotics developed along two distinct paths, one concerned primarily with manipulation of objects, and a second with mobility. Although both types of robots are discussed in later chapters, the book's emphasis is on mobile robots. Here we introduce only some of the major aspects of the robots in this figure and indicate some of the control problems that appear with each major design.

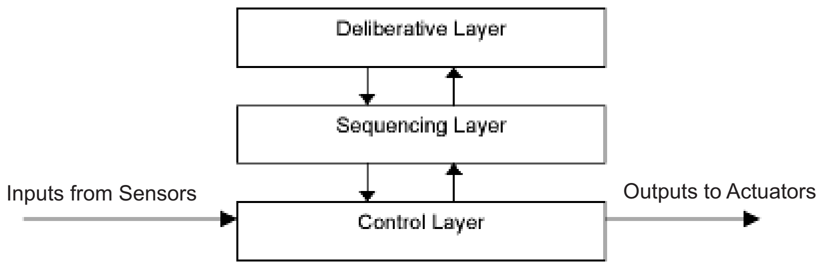


Figure 1.6
Typical three-level architecture for mobile robots

1.8.1 Industrial Manipulators

The development of manipulators began with devices to facilitate remote handling of radioactive materials, during and shortly after World War II. Human operators could move remote arms and grippers by means of joysticks, instrumented gloves, and so on. Such systems were known as "tele-manipulators," since they involved manipulation at a distance. These systems led to manipulators for industry to facilitate such tasks as material handling, welding, and spray painting, all of which present some hazards to human operators. Typical industrial manipulators are illustrated in figure 1.7 (see Engelberger 1980; Niku 2001). Manipulation is discussed in chapter 10.

Note that the robots in this figure display a superficial resemblance to a human arm. The "shoulder" joint allows for motion of the entire structure, as well as rotation about a vertical axis. The "elbow" joint allows for motion in a single plane. The wrist, which is not clearly shown in either illustration in this figure, may allow for 3 degrees of freedom (dof) of rotation (pitch, roll, and yaw). In addition, the end effector or gripper may allow for an additional degree of freedom, resulting in a total of 7 dof for the robot. Practical robots may have fewer dof.

It should also be noted that early manipulators had no sensors. They were entirely preprogrammed to follow desired trajectories. A master painter could move the end effector (holding a spray gun) of a painting robot to follow the desired spray path; this motion was memorized by the system and then repeated exactly, time after time. Contemporary industrial manipulators, in contrast, are equipped with vision, touch, and other sensors as well as on- or off-board computers, thus endowing these systems with the possibility of some autonomous and adaptive behavior.

The control issues in manipulator design center on problems of coordinate transformation. Control of the end effector ("hand") position of the robot is obtained through motors, some of which may be located at the shoulder or elbow of the device. Hence, it is necessary to transform desired end effector positions and orienta-

(a) (b)

Figure 1.7
Typical industrial robots: (a) IRB 6400 spot welding robot (photograph courtesy of ABB Ltd.) and (b) KR15 loading and palletizing robot (photograph courtesy of KUKA Roboter GmbH)

tions into appropriate motor rotations at these other joints. Typically, the transformation requires the inversion of coordinate transformation matrices (see chapter 10).

1.8.2 A Pioneer Mobile Robot

As noted previously, the second path of robot development was concerned with mobile robots, devices capable of moving in their environment by means of legs or wheels. (More recent mobile robots are also capable of mobility in the air and under water.) Figure 1.8 shows a commonly used research robot, the Pioneer 3-AT, made by ActivMedia Robotics, in Amherst, New Hampshire. Note that this robot has four wheels, a number of sonar proximity sensors along the front surface, and a complex of communication equipment on its top surface. Some Pioneers are equipped with laser range sensors, global positioning satellite (GPS) receivers, and other sensing devices.

Control of the position, orientation and, velocity of the Pioneer (and other wheeled robots) is obtained through electric motors driving the wheels. Generally, the control systems for the driving motors make use of feedback; careful design is needed to avoid the possibility of instability (see chapter 4). Differential control of a pair of wheels may allow the robot to turn in place, or the robot may have a minimum turning radius (like an automobile). Further control problems will arise when

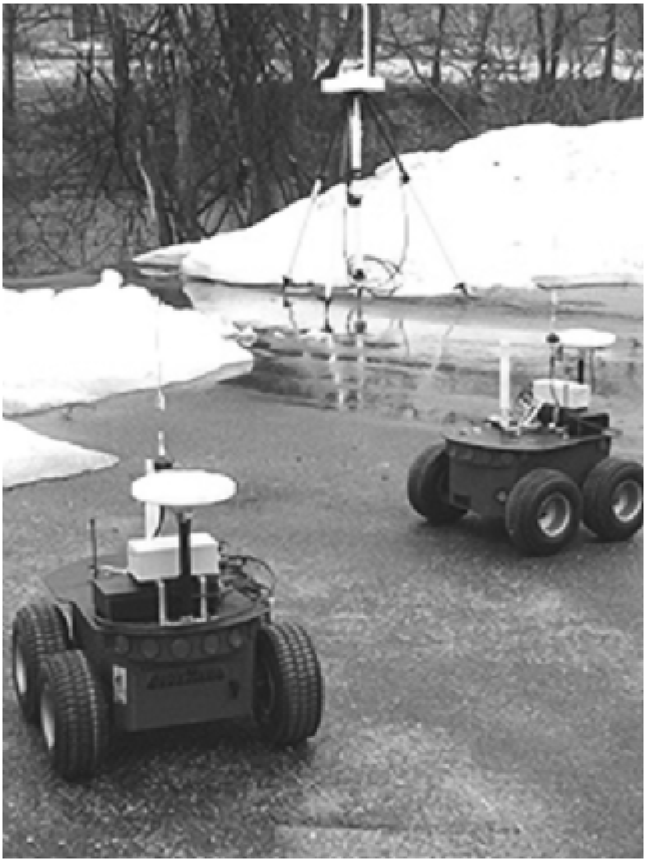


Figure 1.8
Pioneer 3-AT robots (photograph courtesy of ActivMedia Robotics)

the robot is attempting to navigate from a starting to a goal position. The simplest way to control a trajectory is by counting wheel revolutions. Unfortunately, this method, known as *odometry*, can lead to very large trajectory errors, since the robot wheels may slip. Hence, more complex methods of trajectory control are needed (possibly involving Kalman filters or other statistical methods), or additional sensors (such as vision) may be used to identify landmarks for navigation. Wheeled robots are discussed in more detail in chapter 7.

1.8.3 TITAN Quadrupeds

By contrast with the wheeled Pioneer robot, a number of laboratories have designed and built legged robots with two, four, six and even eight legs. Clearly, the broad

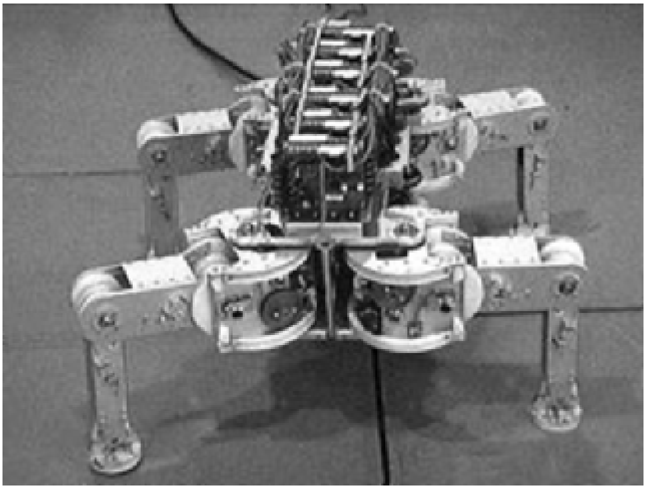


Figure 1.9
TITAN VIII quadruped robot (photograph courtesy of Shigeo Hirose)

architecture of these machines is based on biological prototypes, but the robots generally have fewer degrees of freedom and hence are much less complex than the animals on which they are based. The four-legged machine shown in figure 1.9 (known as TITAN VIII, with TITAN standing for Tokyo Institute of Technology Aruku Norimono [walking vehicle]), was constructed in the Hirose-Yoneda Laboratory of the Tokyo Institute of Technology. Shigeo Hirose is one of the best robot designers in the world at the present time. He developed the theory of stability for legged locomotion machines and has built a series of increasingly sophisticated quadruped robots. The major features of TITAN VIII include

- 12 degrees of freedom (each leg has 3 dof);
- a weight of 19 kg, not including battery and computer, and ability to carry a payload of 5 to 7 kg;
- a potentiometer in each joint for position feedback for control;
- unique control systems known as Titech, designed in Hirose's laboratory, as motor drivers;
- ability to walk at a maximum speed of 0.9 m/sec, which is remarkably fast for a machine of this weight.

TITAN VIII is commercially available for a price (at the time of this writing) of 1.5 million yen.

The latest in the TITAN series is TITAN IX, shown in figure 1.1(c). This robot is equipped with adaptive feet, enabling it to walk on uneven terrain; it also has the ability to recover from falls and can climb stairs autonomously. One of the most interesting features of this robot is that it can stand on three legs and use the fourth leg, equipped with an adjustable gripper, as a manipulator. Four-legged robots are discussed in more detail in chapter 9.

Two types of control problems appear in connection with quadruped robots, involving static and dynamic stability. Static stability refers to the ability of the robot to maintain an upright posture while standing (or while moving very slowly, so that dynamic effects are negligible). With quadrupeds (also known as tetrapods), this means that when one leg is off the ground, the projection of the system's center of gravity must lie within the triangle formed by the three legs on the ground. It is evident that if the center of gravity is outside of this triangle, it will exert torque and cause the animal or robot to fall. Animals adjust their center-of-gravity position as they walk to ensure static stability. In robots this may require an active control system. The situation is more complex when the animal moves rapidly, for example, a horse in gallop. In this case all four legs may be off the ground for brief periods, and dynamic stability requires the consideration of inertial forces due to the motion as well as gravity.

1.8.4 Khepera Mobile Robot

The robot illustrated in figure 1.1(d), the Khepera mobile robot, is designed for "tabletop robotics" experiments. It was designed by Jean-Daniel Nicoud at École Polytechnique Fédérale de Lausanne (EPFL), usually referred to in English as the Swiss Federal Institute of Technology, and is now manufactured by K-Team S.A. in Lausanne. Its cylindrical body is approximately 7 cm in diameter. It has two active wheels and a third support point. The basic robot includes the drive motors and on-board processor, but many additional modules, compatible with the size and shape of the platform, namely, with the same form factor, can be added. These include vision and other sensors as well as a gripper.

A wide variety of software is available for the Kheperas, ranging from that for navigation and obstacle avoidance to that for simulators. Kheperas are being used extensively for research in such areas as robot learning and group interaction. Good control system design ensures that the wheels of Kheperas do not break into oscillations even with rapid changes of velocity.

1.8.5 Snake Robots

The robots discussed in the foregoing consist of a body and either wheels or legs to provide mobility. Several investigators have also constructed articulated, segmented robots whose motion approximates that of snakes. Figure 1.10 shows a snake robot developed at the Fraunhofer Institute for Autonomous Intelligent Systems in Germany. See also figure 1.1(e) that shows a snake robot designed and constructed by Kevin Dowling at Carnegie Mellon University.

The undulating movement of a snake (or, equivalently, an eel, such as the lamprey) requires coordination and sequencing of muscle contractions along the spinal cord, enabling the successive segments of the animal to move in turn (Grillner and Dubuc 1988). Thus, building a robot snake requires the construction of a multisegmented body with the appropriate control sequence to allow smooth, undulating movements, as in Ostrowski and Burdick 1996 and Dowling 1997. The movements of a snake are assumed to be controlled by central pattern generators in the spinal cord (Grillner and Dubuc 1988). The Dowling snake in figure 1.1e consists of ten segments; each link has a 2-dof servo, thus allowing movement in three dimensions. The front segment holds a television camera, thus providing for the robot a "snake's eye" view of the world. Snake robots are discussed further in chapter 7.

1.8.6 A Robot Helicopter

The wheeled and legged robots we have discussed in the previous sections were designed to work on land, but there are also robots that fly through the air (e.g., Montgomery, Fagg, and Bekey 1995) or swim under water (e.g., Yuh, Ura, and Bekey 1997). Figure 1.11 shows an autonomous robot helicopter, AVATAR (Autonomous Vehicle Aerial Tracking and Reconnaissance), developed at the University of Southern California (USC) by the author's colleagues and their students.

Clearly, the problems inherent in the control of a robotic air vehicle are quite different from those involved in the control of land vehicles. First, to remain airborne, the vehicle must generate sufficient lift to overcome both drag and gravitational forces. This implies a need for sufficient forward speed for an aircraft and sufficient rotational velocity for the rotor (effectively, a rotary wing) on a helicopter. Speed, in turn, means that dynamic effects cannot be neglected, as they often can be and are with relatively slow land vehicles.[1]

The dynamics of helicopters are quite complex, since they include aerodynamics, blade bending (and possible oscillations), and the interaction among various control modes. Much of the control in helicopters is obtained by adjustment of the pitch of the rotor blades, once every revolution (hence referred to as "cyclic"). This cyclic adjustment increases lift on one blade while decreasing it on the other, affecting both the vehicle's pitch and its roll. A control mode called the "collective" changes the pitch of the rotor blades by the same amount (collectively); this change affects the

1. In my opinion, some control of dynamic effects will need to be included in most mobile robot models in the near future, as these vehicles become faster and are used in increasingly unstructured domains. Dynamic models are scarce partly because a great deal of robotics work is done by computer scientists, and many computer science curricula do not include differential equations.

Figure 1.10
Snake robot developed at the Fraunhofer Institute for Autonomous Intelligent Systems in Germany (photograph courtesy of the Fraunhofer Institute)

Figure 1.11
The AVATAR robot helicopter (in flight) developed at the University of Southern California (photograph courtesy of Stefan Hrabar and Gaurav Sukhatme)

thrust, thus increasing or decreasing the helicopter's lift. Tail rotor pitch affects the vehicle's yaw. There is a great deal of cross-coupling between control modes. For example, changes in the thrust level (from the throttle or the collective) produce torques about the yaw axis, which need to be counteracted by the tail rotor to ensure that the helicopter's heading does not change. Hence, the resulting differential equations governing helicopter dynamics are highly nonlinear. For this reason many investigators in the area of robot helicopters (e.g., Montgomery [1999]) have not attempted to solve the complete set of equations governing the dynamics, relying rather on heuristics, simulation, and trial-and-error methods to find proper values for control system gains.

The control of robot helicopters is greatly facilitated by using a hierarchical, behavior-based architecture of the type employed in AVATAR. The architecture of this robot helicopter is discussed in chapter 5 as a case study.

Interest in robot air vehicles of various types is likely to increase in the future, for both military and civilian applications. These may include airplanes, helicopters, and even flying vehicles with flapping wings, modeled on birds and insects.

1.8.7 Roomba, a Household Robot

The use of robots as household helpers has been in the public imagination for generations. The popular 1960s television program *The Jetsons* featured a household robot, dressed like a maid with an apron, who pushed a vacuum cleaner. In 2002, the U.S. robotics company iRobot began selling a completely autonomous vacuum-cleaning robot, Roomba (figure 1.1g), at a base price of $199. This remarkable little robot is turned on, a room size (small, medium, or large) is selected, and the machine is fully autonomous thereafter. It moves about the room in an increasing spiral motion until it reaches a wall, where it shifts to a wall-following mode using sonar sensing. The exterior of the round machine is equipped with touch sensors, so that when it comes in contact with an object (say, a chair leg), it shifts direction. With a battery life of about one and a half hours, it is capable of cleaning even a large room, although not as well as a handheld vacuum cleaner.

Roomba has a number of interesting features. For example, it senses the edge of a surface on which it is traveling and stops if there is a sudden drop (e.g., at the top of a stairwell). As a result of its performance and modest cost, it is reported that some 1 million of these robots had been sold as of late 2004. A European vacuuming robot, manufactured by Electrolux, is named Trilobite. The Roomba and the Trilobite are among the first household robots; many more are expected in the coming decade.

1.8.8 AIBO, an Entertainment Robot

Sony introduced AIBO (Artificial Intelligence Robot), the first robot pet, in the late 1990s. The machine has since been modified and improved several times, as well as drastically reduced in cost. The third-generation AIBO ERS-7, released in 2004, is shown in figure 1.1(h).

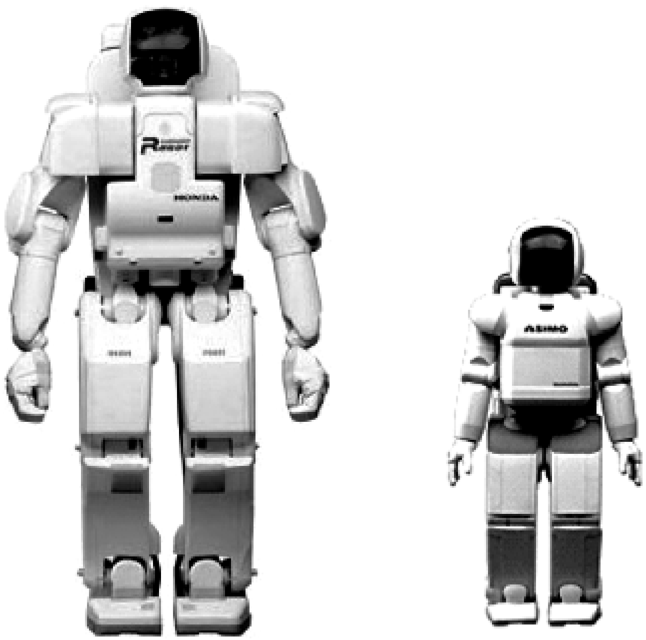
AIBO is a remarkable robot in a number of ways:

1. It is capable a number of autonomous behaviors, such as chasing and playing with a ball, by virtue of its excellent vision system and the coupling of vision with leg movements (both for chasing and for "kicking" the ball).
2. If it falls down, it is capable of getting up.
3. It can receive input commands from human users by touch or by voice, which enables it perform other behaviors such as lying down, sitting, or waving.
4. The on-board computer is sufficiently sophisticated so that robot laboratories (if given access to the code by Sony) can program new behaviors.
5. AIBOs can interact with one another, so that they are now being used by a number of institutions in "robot soccer" competitions (RoboCup) (Asada and Kitano 1999a).

These behaviors make the robot surprisingly lifelike, so that it can be a playmate for children as well as a laboratory tool or a soccer player. The next decade is likely to bring many more semiautonomous toys. The potential market in entertainment robotics is very, very large, compared to, say, that in industrial robotics.

1.8.9 ASIMO, a Biped Walker

In the early 1990s Japan announced a national research effort to create humanoid robots, that is, machines with a physical resemblance to a human body structure and having an ability to walk on two legs. In response to this challenge, Honda Motor Company Ltd. designed and built a series of walking machines known as the P-1, P-2, and P-3 (figure 1.12). As we discuss in later chapters, biped walkers had previously been built, but none was capable of the degree of stable walking (and stair climbing!) that characterized Honda's machines. All the P-series humanoids were teleoperated from a complex remote control station, but once turned on to, say, forward walking, or climbing a set of stairs, the robot was capable of performing the



(a) (b)

Figure 1.12
Humanoid robots from Honda: (a) P-3, (b) ASIMO (photographs courtesy of Honda Motor Company Ltd.)

repeated movements on its own. These machines were quite large (some two meters tall) and heavy, due in part to the on-board batteries the robots carried in a backpack. In 2001 Honda introduced ASIMO (Advanced Step in Innovative Mobility), a robot the size of child, also illustrated in figure 1.16. Biped robots are discussed in more detail in chapter 8.

Walking robots have always fascinated people. Although the P-series robots and ASIMO were neither very autonomous nor very "intelligent," their ability to walk stably on two legs made them a sensation wherever they were displayed. (Recent versions of ASIMO display a number of features associated with intelligence, such as speech recognition and synthesis.) When a machine of approximately human size is capable of walking, it immediately assumes a humanlike character, and people tend to assume that it may also have other humanlike characteristics. Clearly, our homes and places of business are built for access to erect bipeds. The popular imagination leads directly to humanlike robots capable of assisting us in our homes. Although this type of autonomy is not likely to be achieved in the near future, these walking robots have spurred an international interest in humanoid robots, leading to international conferences and a number of research programs in this field (see chapter 13 and section 1.8.10).

1.8.10 Cog

The final example in this overview of autonomous robots is Cog (figure 1.1(j)), a humanoid torso developed in the Artificial Intelligence Laboratory at the Massachusetts Institute of Technology (MIT). As the figure shows, in contrast to the mobile robots described above, Cog is a humanoid torso in a fixed location, with movable arms, head, and eyes. The arms are sophisticated subsystems, as is the head. However, the power of Cog lies in its intelligence, that is, its ability to interact with humans and to learn.

In fact, the fundamental thesis of the Cog project is that "humanoid intelligence requires humanoid interactions with the world." This means that interaction with humans forms the basis of the robot's design. Cog's designers have found that even a few simple humanlike behaviors on the part of the robot (such as following a human's position with its camera eyes, or gesticulating while speaking) are sufficient to make humans treat the robot as if it were another human.

Cog can be considered to be a "brain" coupled with a set of sensors and actuators that try to approximate the sensory and motor dynamics of a human torso, except for a flexible spine. The major degrees of motor freedom in the trunk, head, and arms of a human are all there in the robot. It has vision (from cameras), hearing was being developed as this book was being written, and some proprioception was possible via joint position sensors. As noted, the uniqueness of this robot arises from its intelligence, so that it can also be viewed as a hardware platform for artificial-intelligence research. Cog was retired from active research in late 2004. Humanoid robots are discussed in detail in chapter 13.

1.9 Concluding Remarks and Organization of the Book

This chapter has provided an overview of the entire field of mobile robots. We have introduced some of the fundamental concepts (including biological models), discussed sensors and actuators for robots and the basic control architectures used in robot software, and touched on robot intelligence. Since one of the themes of the book concerns control of robots, we have dealt with both low-level and high-level control concepts. Finally, the breadth of the field has been illustrated with a large number of examples from current research in and applications of mobile robots.

The rest of the book is organized as follows: Chapters 2–6 deal with background material, including robot hardware, control from both a biological and an engineering perspective, software architectures, and robot intelligence. Specifically:

- Chapter 2 introduces biological control systems, to provide a basis for evaluating robot control systems.
- Chapter 3 surveys the major hardware components of robots, including structure, sensors, and actuators, as well as cognitive architectures and control methods.
- Chapter 4 is an engineering counterpart to chapter 2, with an overview of low-level robot control.
- Chapter 5 deals with software architectures for mobile autonomous robots.
- Chapter 6 is devoted to issues surrounding intelligence and learning.

Chapters 7–13 discuss various implementations and applications of robots. Specifically:

- Chapter 7 provides an overview of robot locomotion, including a discussion of wheeled, legged, flying, swimming, and crawling robots.
- Chapters 8 and 9 are devoted to legged locomotion. Chapter 8 deals with biped locomotion, and Chapter 9 considers locomotion with four, six, and eight legs.
- Chapters 10 and 11 survey robot manipulation, including both arms and hands. Although the focus of the book is on robot mobility, many mobile robots have (or will have) arms. To grasp objects, these arms must terminate in hands. Hence, chapters 10 and 11 provide a brief overview of these topics.
- Chapter 12 considers the control and coordination issues in multiple-robot systems.
- Chapter 13 concerns humanoid robots, thus building on the material on biped locomotion in chapter 8 as well as that on arm movements and grasping in chapters 10 and 11.

Chapters 14–15 cover current and future research and are followed by an appendix. Specifically:

- Chapter 14 focuses on issues of localization ("Where am I?"), navigation, and mapping, all currently subjects of intensive research efforts.
- Chapter 15 presents the author's view of the future of robotics, including both the potential increased usefulness of robots to humanity and the possible dangers that may arise from large numbers of increasingly intelligent and autonomous robots.
- For readers unfamiliar with the basic concepts of linear feedback control and the use of Laplace transforms, an intuitive introduction to these concepts is provided in the book's appendix.