are useful for controlling high performance robots. We also discuss the control of so-called **nonholonomic systems** such as mobile robots.

Force Control

In the example robot task above, once the manipulator has reached location A, it must follow the contour S maintaining a constant force normal to the surface. Conceivably, knowing the location of the object and the shape of the contour, one could carry out this task using position control alone. This would be quite difficult to accomplish in practice, however. Since the manipulator itself possesses high rigidity, any errors in position due to uncertainty in the exact location of the surface or tool would give rise to extremely large forces at the end effector that could damage the tool, the surface, or the robot. A better approach is to measure the forces of interaction directly and use a **force control** scheme to accomplish the task. In Chapter 9 we discuss force control and compliance, along with common approaches to force control, namely **hybrid control** and **impedance control**.

Computer Vision

Cameras have become reliable and relatively inexpensive sensors in many robotic applications. Unlike joint sensors, which give information about the internal configuration of the robot, cameras can be used not only to measure the position of the robot but also to locate objects in the robot's workspace. In Chapter 11 we discuss the use of computer vision to determine position and orientation of objects.

Vision-Based Control

In some cases, we may wish to control the motion of the manipulator relative to some target as the end effector moves through free space. Here, force control cannot be used. Instead, we can use computer vision to close the control loop around the vision sensor. This is the topic of Chapter 12. There are several approaches to vision-based control, but we will focus on the method of Image-Based Visual Servo (IBVS). With IBVS, an error measured in image coordinates is directly mapped to a control input that governs the motion of the camera. This method has become very popular in recent years, and it relies on mathematical development analogous to that given in Chapter 4.

PROBLEMS

1-1 What are the key features that distinguish robots from other forms of automation such as CNC milling machines?

1-2 Briefly define each of the following terms: forward kinematics, inverse kinematics, trajectory planning, workspace, accuracy, repeatability, resolution, joint variable, spherical wrist, end effector.

1-3 What are the main ways to classify robots?

1-4 Make a list of 10 robot applications. For each application discuss which type of manipulator would be best suited; which least suited. Justify your choices in each case.

1-5 List several applications for nonservo robots; for point-to-point robots; for continuous path robots.

1-6 List five applications that a continuous path robot could do that a point-to-point robot could not do.

1-7 List five applications for which computer vision would be useful in robotics.

1-8 List five applications for which either tactile sensing or force feedback control would be useful in robotics.

1-9 Find out how many industrial robots are currently in operation in Japan. How many are in operation in the United States? What country ranks third in the number of industrial robots in use?

1-10 Suppose we could close every factory today and reopen them tomorrow fully automated with robots. What would be some of the economic and social consequences of such a development?

1-11 Suppose a law were passed banning all future use of industrial robots. What would be some of the economic and social consequences of such an act?

1-12 Discuss applications for which redundant manipulators would be useful.

1-13 Referring to Figure 1.25, suppose that the tip of a single link travels a distance d between two points. A linear axis would travel the distance d while a rotational link would travel through an arc length $\ell\theta$ as shown. Using the law of cosines, show that the distance d is given by

$$d = \ell\sqrt{2(1-\cos\theta)}$$

which is of course less than $\ell\theta$. With 10-bit accuracy, $\ell = 1$ meter, and $\theta = 90°$, what is the resolution of the linear link? of the rotational link?

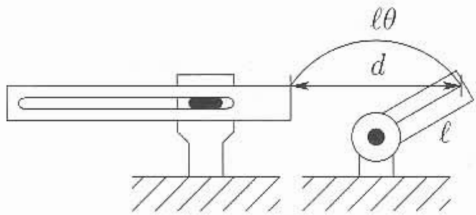

Figure 1.25: Diagram for Problem 1-15.

1-14 For the single-link revolute arm shown in Figure 1.25, if the length of the link is 50 cm and the arm travels 180 degrees, what is the control resolution obtained with an 8-bit encoder?

1-15 Repeat Problem 1.14 assuming that the 8-bit encoder is located on the motor shaft that is connected to the link through a 50:1 gear reduction. Assume perfect gears.

1-16 Why is accuracy generally less than repeatability?

1-17 How could manipulator accuracy be improved using endpoint sensing? What difficulties might endpoint sensing introduce into the control problem?

1-18 Derive Equation (1.8).

1-19 For the two-link manipulator of Figure 1.20 suppose $a_1 = a_2 = 1$.

1. Find the coordinates of the tool when $\theta_1 = \frac{\pi}{6}$ and $\theta_2 = \frac{\pi}{2}$.
2. If the joint velocities are constant at $\dot{\theta}_1 = 1$, $\dot{\theta}_2 = 2$, what is the velocity of the tool? What is the instantaneous tool velocity when $\theta_1 = \theta_2 = \frac{\pi}{4}$?
3. Write a computer program to plot the joint angles as a function of time given the tool locations and velocities as a function of time in Cartesian coordinates.
4. Suppose we desire that the tool follow a straight line between the points (0,2) and (2,0) at constant speed s. Plot the time history of joint angles.

1-20. For the two-link planar manipulator of Figure 1.20 is it possible for there to be an infinite number of solutions to the inverse kinematic equations? If so, explain how this can occur.

1-21 Explain why it might be desirable to reduce the mass of distal links in a manipulator design. List some ways this can be done. Discuss any possible disadvantages of such designs.

NOTES AND REFERENCES

We give below some of the important milestones in the history of modern robotics.

1947 — The first servoed electric powered teleoperator is developed.

1948 — A teleoperator is developed incorporating force feedback.

1949 — Research on numerically controlled milling machine is initiated.

1954 — George Devol designs the first programmable robot

1956 — Joseph Engelberger, a Columbia University physics student, buys the rights to Devol's robot and founds the Unimation Company.

1961 — The first Unimate robot is installed in a Trenton, New Jersey plant of General Motors to tend a die casting machine.

1961 — The first robot incorporating force feedback is developed.

1963 — The first robot vision system is developed.

1971 — The Stanford Arm is developed at Stanford University.

1973 — The first robot programming language (WAVE) is developed at Stanford.

1974 — Cincinnati Milacron introduced the T^3 robot with computer control.

1975 — Unimation Inc. registers its first financial profit.

1976 — The Remote Center Compliance (RCC) device for part insertion in assembly is developed at Draper Labs in Boston.

1976 — Robot arms are used on the Viking I and II space probes and land on Mars.

1978 — Unimation introduces the PUMA robot, based on designs from a General Motors study.

1979 — The SCARA robot design is introduced in Japan.

1981 — The first direct-drive robot is developed at Carnegie-Mellon University.