12

SENSORS

Chapters 11, 12, and 13 of this book are concerned with sensors and their use. In Chapter 11, we discussed force control and determined that precise control of force required a good quality force-torque sensor, either mounted on the wrist of the robot or under the workpiece. In Chapter 13, we will address computer vision, the principal noncontact sense in robotics.

In this chapter, we will describe several other sensors that may be used in robot systems. These sensors all exhibit "local" properties, in that they sense the properties of a surface which is touching or nearly touching the robot's hand. Use of such sensors allows the robot to interact with its environment in an adaptive, "intelligent" way.

This chapter differs from most of the remainder of this book because as yet there exists neither paradigms for the design of such sensors nor well-structured techniques for choosing the appropriate sensor for particular applications. In the absence of paradigms, we will simply describe several sensors and discuss typical properties and potential applications.

12.1 TOUCH SENSORS*

The need for touch sensors occurs in many robotics applications, from picking oranges to loading machines (see Harmon, 1980 for a good

*The author is grateful to Jack Rebman of the Lord Corporation for his assistance in the preparation of this chapter.

summary and review). Probably the most important application currently is the general problem of locating, identifying, and organizing parts that need to be assembled. This application frequently employs computer vision systems such as those described in Chapter 13. However, many cases require positional information that cannot be provided by computer vision because of two major deficiencies inherent in computer vision systems.

The first deficiency is accuracy. In a typical parts handling operation (Page, Snyder, and Rajala, 1983), the vision system could position the robot to within $\frac{1}{4}$ inch while maintaining a field of view of 5 feet horizontally. Such positioning accuracy is quite good for a vision system, but it may not be adequate for the precise positioning needed to insert a part into a machine tool.

The second major deficiency of computer vision arises from the fairly obvious fact that a computer vision system cannot see behind the part. If gripping relies on somehow reaching around the part, blind gripping may lead to damage of the parts to the rear.

For both these reasons, a "smart" gripper is often needed, even in systems with vision. Such sensory capabilities may take on a variety of forms, as will be demonstrated in this section. Another survey of hand-mounted sensors may be found in Bejczy (1977).

The more sophisticated electronic sensors emulate the human sense of touch. The physiological sense of touch has two distinct aspects: the *cutaneous sense*, which refers to the ability to perceive textural patterns encountered by the skin surface; and the *kinesthetic sense*, which refers to the ability to determine forces and moments.

A touch sensor system thus includes the capability to detect such things as (Rebman and Trull, 1978)

1. Presence
2. Part shape, location, orientation
3. Contact area pressure and pressure distribution
4. Force magnitude, location, and direction
5. Moment magnitude, plane, and direction

The major components of a tactile sensor system are

1. A touch surface
2. A transduction medium, which converts local forces or moments into electrical signals.
3. Structure
4. Control/interface

Hill and Sevard (1973) describe a gripper in which each finger is equipped with seven sensitive panels to be used in collision detection.

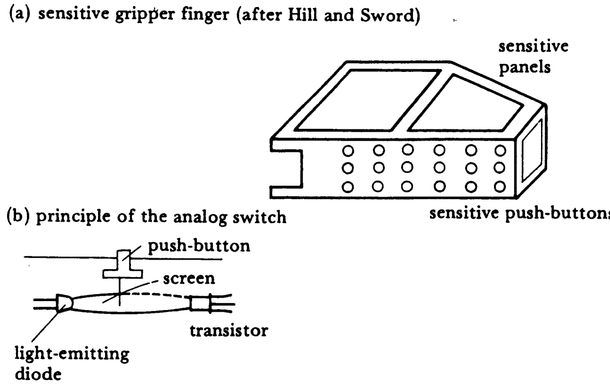

Figure 12.1(a) (Coiffet) Sensitive finger.

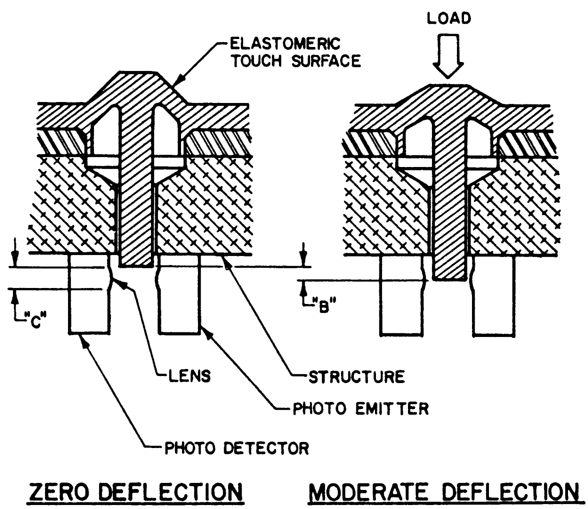

Figure 12.1(b) (Rebman & Trull) Sensitive site detail. (*Courtesy ASME*)

In addition, the inside of each finger is covered with an array of 18 pushbottons. As each button is pressed, it partially interrupts a beam of light (Figure 12.1). The more pressure on the button, the more the beam is blocked. This signal is detected and provides a rough outline of the object being grasped. A refined and robust sensor (Figure 12.1(b)) using this concept has been developed for industrial applications by Lord Corporation (Rebman, 1983).

The concept of sensitive panels has been extensively used by (Kinoshita and Mori, 1972), who describes a multifingered, articulated, hand with sensitive panels on the inside of each link of each finger. As might be expected, the transformations to relate sensor output to three-dimensional surface contour are very complex.

Sensors described by Peruchon (1979) and Page, Puch, and Heginbotham (1976) use arrays of small metal rods and detect the deflection of each rod. The Peruchon sensor uses the rod as a variable core in an inductor and detects the change in inductance as the rod is brought into contact with the surface. The Page sensor detects not the height, but the variation in height of each rod. The sensor is brought down slowly on the part while the stand is vibrated (Figure 12.2). When all the rods move together, the part is in full contact with the gripper.

Several researchers (Bejczy, 1980; St. Clair and Snyder, 1978) have reported on experiments with conductive elastomers or *artificial skins*. While they vary in details, these systems are conceptually similar, and we describe only the system by St. Clair and Snyder (1978).

A conductive elastomer is a rubberlike material whose electrical conductivity changes (locally) when compressed. In this system, the elastomer was laid over a printed circuit board etched with 16 pairs of concentric rings. Each pair of rings formed a sensing element (Figure

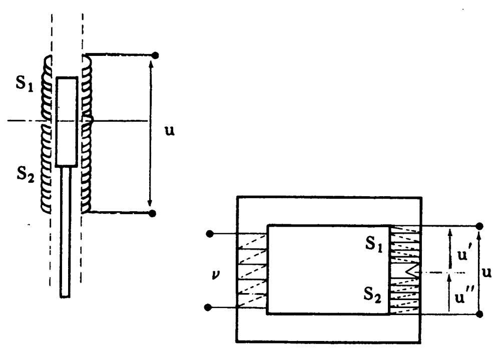

Figure 12.2(a) (Coiffet) Principle of the Peruchon sensor.

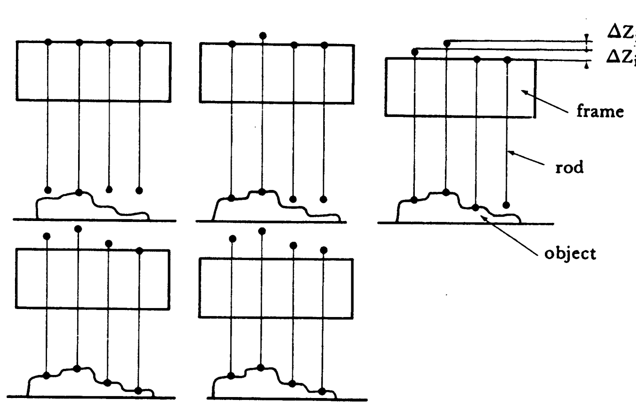

Figure 12.2(b) (Coiffet) The Page sensor: for every increment of frame movement the rods that have undergone movement Δ Zi are counted.

12.3). The outer rings were wired in parallel four at a time to form four rows. The center rings were likewise wired to form four columns. Thus, any sensor could be x-y addressed.

A current was allowed to flow from the inner to outer selected rings, through the elastomers. By measuring the current-voltage ratio, the local conductivity of the elastomer could be determined, and hence the applied force.

The authors then applied pattern recognition techniques to determine edges, points, and other features.

The major problem reported by these authors, as well as others who have experimented with these materials, is the repeatability of the measurement. Once compressed, the material takes a very long time to recover its original characteristics.

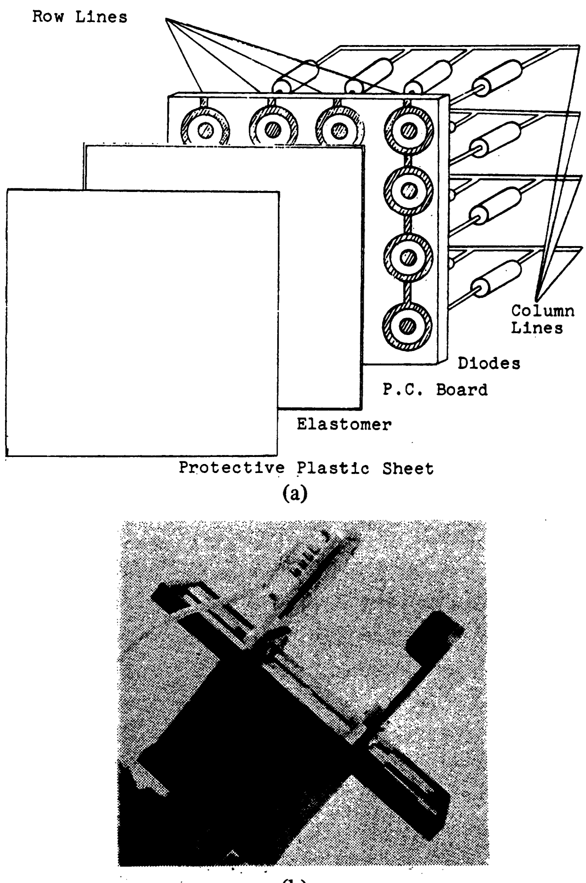

Figure 12.3 (St. Clair & Snyder) (a) Exploded view of the sensor. (b) The tactile sensor. (*Courtesy 1978 IEEE*)

12.2 PROXIMITY SENSORS

In this section, we will discuss devices that allow the robot to determine some properties of a surface without actually contacting that surface. The property most often detected is simply the presence or absence of a surface. This function provides collision avoidance. In addition, proximity sensors provide information about approach conditions, so that appropriate deceleration and maneuvering may be performed prior to grasping.

12.2.1 Optical Proximity Detectors

An optical proximity detector such as the one depicted in Figure 12.4 can provide a simple binary signal, indicating the presence of an object. Calibration is required for each object, since the distance at which the sensor's output goes true will depend on the reflectivity of the surface. Such a sensor can be used either for collision avoidance or to signal the robot when it has reached a precise distance from the object.

12.2.2 Optical Ranging Using Reflectance

By projecting a calibrated light source onto the object and measuring the reflected intensity, one could conceivably determine the distance from the sensor to the object. Successful use of such a sensor requires some understanding of the ways in which light is reflected from a surface.

The most familiar form of reflection, purely specular reflection, is shown in Figure 12.5(a). In specular reflection, the emitted light ray forms an angle with the surface normal exactly equal to the incident ray.

If the incident and emitted angles are not identical, then some *scattering* is said to have occurred. The most often discussed form of scattering, *Lambertian scattering*, is depicted in Figure 12.5(b). In a surface which exhibits Lambertian scattering, the net effect of all the

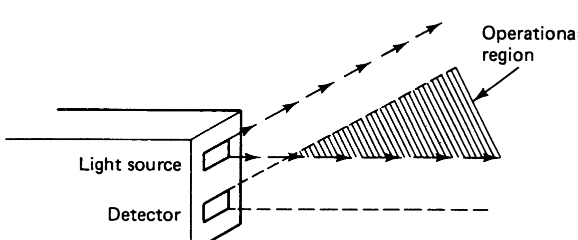

Figure 12.4 Optical proximity detector containing a light source (typically an LED), and a light detector.

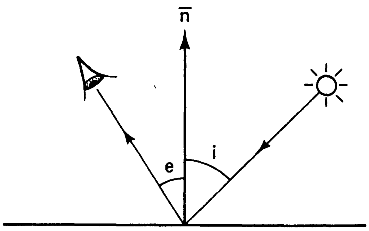

Figure 12.5(a) Specular reflection.

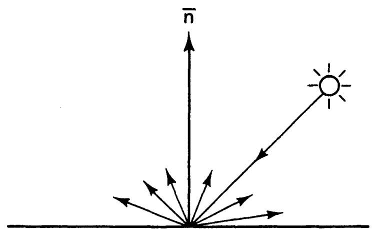

Figure 12.5(b) Lambertian scattering.

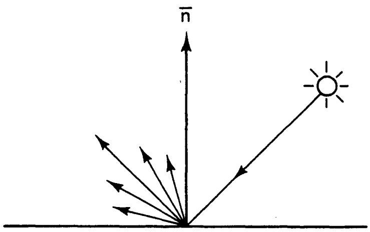

Figure 12.5(c) Forward scatter.

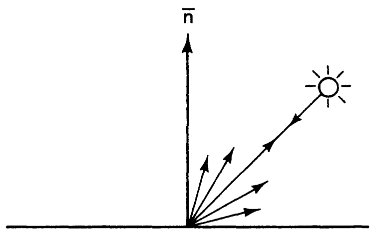

Figure 12.5(d) Backscatter.

processes occurring is that the brightness observed is independent of viewing angle and depends only on the angle between the surface normal and the incident ray. That is, $E = a_0 I \cos i$, where E is the observed brightness, I is the incident light intensity, and i is the angle between the incident ray and the surface normal. This fact is utilized in some computer vision work to determine surface orientation. See Horn (1975) or Ray (1981) for details.

Other types of scattering are shown in Figures 12.5(c) and (d). In fact, most surfaces exhibit a mixture of these reflectivity properties. This fact, coupled with other difficulties in modeling, makes it more effective to calibrate a proximity sensor than to attempt to develop a good analytic model. Figure 12.6 shows such a sensor, with both light

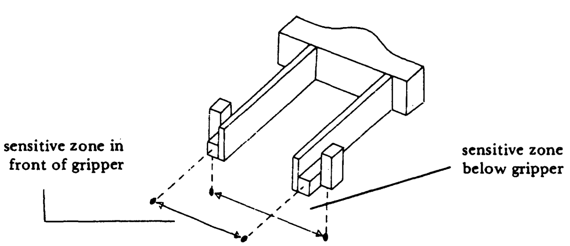

Figure 12.6 (Coiffet) Example of sensors attached to a manipulator gripper.

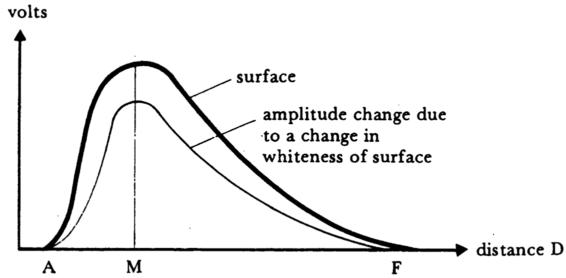

Figure 12.7 (Coiffet) Typical response of an infrared detector as a function of distance from a surface.

source and detector mounted on the gripper. Figure 12.7 shows a typical response characteristic of such a sensor. This curve will be slightly distorted if the surface is not plane. Coiffet (1983) points out three difficulties in using such a sensor:

1. The whiteness of the surface (by trial and error) has to be known. This is usually the case in industrial applications.
2. Except for the singularity at the top of the curve, the same signal can denote two possible distances.
3. The axis of the sensor must be normal to the surface.

. . . these proximity sensors are mostly used for the detection of the presence of an object in the volume, scanned only in rare cases to measure distance, and exceptionally, in recognition.

Bejczy (1980) however, reports on an improved sensor that eliminates the double-valued reading and provides improved performance by using fiber optics and more sophisticated signal processing. That sensor provides an effective sensing range of 7 to 8 cm.

12.2.3 Triangulation Proximity Sensors

If a plane of light is projected on a scene at a known angle and is observed from a known position, the light source, sensor, and object form a *range triangle* as shown in Figure 12.8(a). The projection angle and light source–sensor distance are known, and the observation angle is measured. From this, the distance, d, to the object may be determined.

This technique, known as *light striping*, is very popular in industrial machine vision. The same technique may be scaled down as shown in Figure 12.8(b) to a sensor mounted on the hand, utilizing a CCD sensor and a single light stripe.

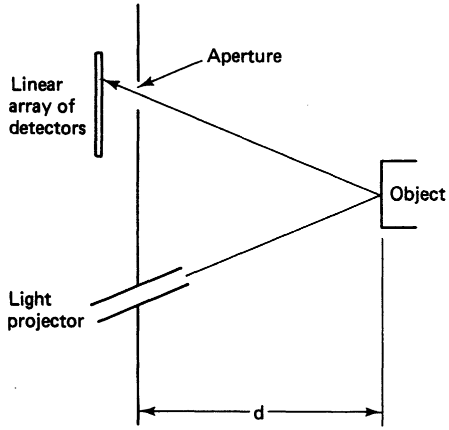

Figure 12.8(a) Range triangle.

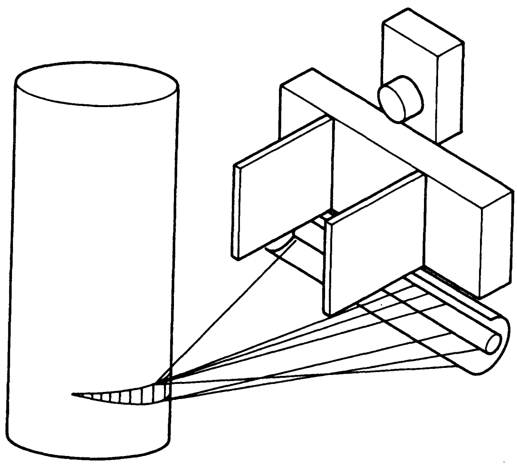

Figure 12.8(b) Camera and light source mounted on hand.

12.3 ULTRASONIC RANGING

An ultrasonic transducer emits a pulse of high-frequency sound and then listens for the echo. Since sound in air travels at slightly under 1 foot per millisecond, the elaspsed time between initial transmission and echo detection can then be converted to distance.

The material or the topography could cause a pulse at any particular frequency to be canceled and, therefore, not echoed. For this reason, most transducers actually transmit a "chirp" consisting of a range of frequencies. For example, the Polaroid electrostatic transducer transmits a chirp consisting of four ultrasonic frequencies, 60 kHz (kilohertz), 57 kHz, 53 kHz, and 50 kHz.

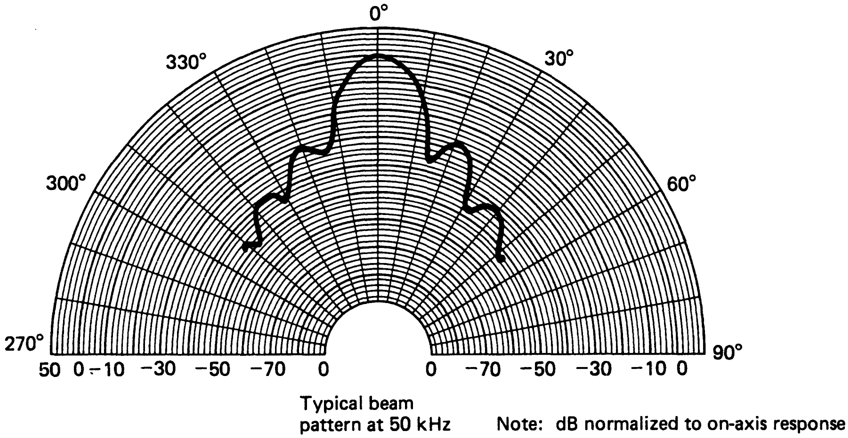

Figure 12.9 Typical beam pattern at 50 kHz. Note: db normalized to on-axis response. Note: curves are representative only. Individual responses may differ. (*Courtesy Polaroid*)

Attenuation of an ultrasonic pulse depends on frequency and path length. Specifically, the sound pressure level at a distance D from the sensor is

$$p = p_0 \frac{1}{D} e^{-\alpha D}.$$

where α is the absorption coefficient in air. α increases with increasing frequency. At 50 kHz, for example, the signal power returned at 3 feet is a million times stronger than is the signal returned at 35 feet. For this reason a variable gain receive amplifier is a requirement.

Figure 12.9 shows the beam pattern of the Polaroid transducer. In general, any object subtending an angle of 2–4° with respect to the sensor will cause a return. More specifically, Polaroid* specifies the performance test as follows:

At 4 feet, a sphere 2 inches in diameter will be detected within an acceptance angle of 8–14°, and at 15 feet, a sphere 12 inches in diameter will be detected within an acceptance angle of 8–19°.

The accuracy of this transducer is better than 1 percent of the range. That is, an object 3 feet away can consistently be located to within $\frac{1}{2}$ inch.

Such sensors are most appropriate in robotic applications for detecting potential collisions and avoiding them and for approximate ranging, in the absence of vision. For example, an ultrasonic sensor

*The author is grateful to Mr. Olin Brown of Polaroid for his assistance in describing the ultrasonic range sensor.

could get the gripper fairly close to the object, and then an optical proximity detector mounted on the hand could be used to provide fine ranging for precise positioning.

12.4 CONCLUSION

In this chapter, we have described several sensors and their potential applications in robotics. Ultrasonic sensors provide a look at the object from a distance of several feet and allow the robot to position the hand relatively close to the part, close enough for devices such as optical proximity detectors to become active. Such detectors can be used to position the hand until it is almost contact with the part. Finally, touch sensors, either pressure transducers, arrays of switches, or a mix of the two, can identify the part surface contours.

Both ultrasonic and optical proximity detectors can make serious errors when confronted with parts that have unusual shapes. For example, the part in Figure 12.10 has a small rod extending above the surface. That rod may be too small to be detected by an ultrasonic sensor and may escape the narrow field of view of a proximity detector. Such problems may be handled on an ad hoc basis by, for example, sweeping the hand in a spiral path searching for the rod or, in some cases, by computer vision, the topic of the next chapter.

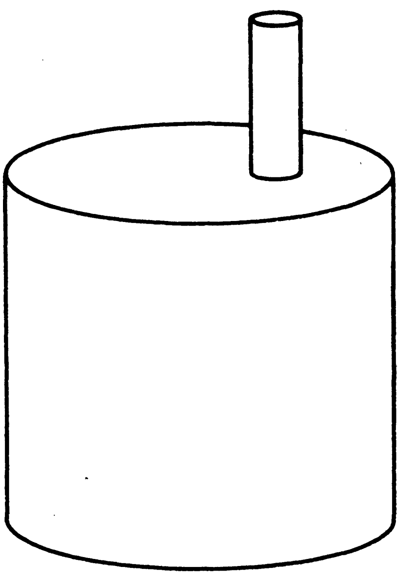

Figure 12.10

12.5 SYNOPSIS

Vocabulary

You should know the definition and application of the following terms:

artificial skin
cutaneous
elastomer
kinesthetic
Lambertian
light striping
optical proximity detector
reflectance ranging
scattering
specular
transduction
triangulation
ultrasonic

12.6 REFERENCES

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12.7 PROBLEMS

1. Analyze carefully using a robot to pick oranges. Under what conditions could vision help? What type of tactile sensor would seem appropriate and on what kind of gripper?
2. Propose an application of robotics that could make use of a sensor that provides only information about the cutaneous sense.
3. Propose an application of robotics that could make use of a sensor that provides only kinesthetic information.
4. Analyze the feasibility of the sensor shown in Figure 12.1(b). What are its limitations? Compare that sensor with the sensor of Figure 12.3. Which do you think is more robust? Why? (You might consider such properties as hysteresis, work hardening, reliability, and maintainability.)
5. Consider the problem of using an optical proximity detector to detect the presence of metallic parts. Describe the properties of the metallic surface which would allow such a device to be effective or not effective.
6. In Section 12.3, the claim is made that "At 50 kHz, the signal power returned at 3 feet is a million times stronger than the signal returned at 35 feet." Verify this.