7.4. Repeat Problem 7.3, but suppose the maximum torque this motor can provide is 0.9 Nm. Therefore, a new motor must be picked. Two other motors are available, one with the inertia of 0.009 Kgm^2 and torque of 0.85 Nm, one with inertia of 0.012 Kgm^2 and torque of 1 Nm. Which one would you use?

7.5. Estimate how much the torque/inertia ratio of a disk motor might be if it can go from zero to 2000 rpm in one millisecond, and compare it to the motor of Problem 7.1.

7.6. Using a timer circuit, design a pulse generating circuit that will deliver a range of 5–500 pulses per second to a stepper motor driver.

7.7. Calculate the gear ratio for a Harmonic drive if $N_L = 100$, $N_F = 95$, $N_2 = 90$, $N_3 = 95$.

7.8. Write a program to generate a variable pulse stream to drive a motor with pulse-width-modulated voltages of 1, 2, 3, 4, and 5 volts for a 5-volt input.

7.9. Write a program to generate a sinusoidal pulse-width-modulated output for a constant input voltage.

7.10. If you have access to a microprocessor and electronic components such as transistors, make an H-bridge and write a control program to drive a motor in either direction or to brake it. Be mindful of the problems associated with an H-bridge's transistors turning on and off at inappropriate times.

CHAPTER 8

Sensors

8.1 Introduction

In robotics, sensors are used for both internal feedback control and external interaction with the outside environment. Animals and humans have similar distinct sensors. For example, when you wake up, even before you open your eyes, you know where your extremities are; you do not have to look to know that your arm is beside you, or that your leg is bent. This is because neurons in the muscles send signals to the brain, and as they are stretched or relaxed with the contracting, stretching, or relaxing muscles, the signal changes and the brain determines the state of each muscle. Similarly, in a robot, as the links and joints move, sensors such as potentiometers, encoders, and resolvers send signals to the controller, allowing it to determine joint values. Additionally, as humans and animals possess senses of smell, touch, taste, hearing, vision, and speech to communicate with the outside world, robots may possess similar sensors that allow them to communicate with the environment. In certain cases, the sensors may be similar in function to that of humans such as vision, touch, and smell. In other cases, the sensors may be something humans lack such as a radioactive sensor.

There is a huge array of sensors available for measuring almost any phenomenon. However, in this chapter, we will only discuss sensors used in conjunction with robotics and automatic manufacturing.

8.2 Sensor Characteristics

To choose an appropriate sensor for a particular need, we have to consider a number of different characteristics. These characteristics determine the performance, economy, ease of application, and applicability of the sensor. In certain situations, different types of sensors may be available for the same purpose. Therefore, the following may be considered before a sensor is chosen:

- **Cost:** The cost of a sensor is an important consideration, especially when many sensors are needed for one machine. However, the cost must be balanced with other requirements of the design such as reliability, importance of the data they provide, accuracy, life, and so on.
- **Size:** Depending on the application of the sensor, the size may be of primary importance. For example, the joint displacement sensors have to be adapted into the design of the joints and move with the robot's body elements. The available space around the joint may be limited. Additionally, a large sensor may limit the joint's range. Therefore, it is important to ensure that enough room exists for the joint sensors.
- **Weight:** Since robots are dynamic machines, the weight of a sensor is very important. A heavy sensor adds to the inertia of the arm and reduces its overall payload. Similarly, a heavy camera mounted on a robotic insect airplane will severely limit its flying capabilities.
- **Type of output (digital or analog):** The output of a sensor may be digital or analog and, depending on the application, this output may be used directly or have to be converted. For example, the output of a potentiometer is analog, whereas that of an encoder is digital. If an encoder is used in conjunction with a microprocessor, the output may be directly routed to the input port of the processor, while the output of a potentiometer has to be converted to digital signal with an analog-to-digital converter (ADC). The appropriateness of the type of output must be balanced with other requirements.
- **Interfacing:** Sensors must be interfaced with other devices such as microprocessors and controllers. The interfacing between the sensor and the device can become an important issue if they do not match or if other add-on components and circuits become necessary (including resistors, transistor switches, power source, and length of wires involved).
- **Resolution:** Resolution is the minimum step size within the range of measurement of the sensor. In a wire-wound potentiometer, it will be equal to the resistance of one turn of the wire. In a digital device with n bits, the resolution will be:

$$Resolution = \frac{Full\ Range}{2^n} \tag{8.1}$$

  As an example, an absolute encoder with 4 bits can report positions up to $2^4 = 16$ different levels. Therefore, its resolution is $360/16 = 22.5°$.
- **Sensitivity:** Sensitivity is the ratio of a change in output in response to a change in input. Highly sensitive sensors will show larger fluctuations in output as a result of fluctuations in input, including noise.
- **Linearity:** Linearity represents the relationship between input variations and output variations. This means that in a sensor with linear output, the same change in input at any level within the range will produce a similar change in output. Almost all devices in nature are somewhat nonlinear, with varying degrees of nonlinearity. Some devices may be assumed to be linear within a certain range of their operation. Others may be linearized through assumptions. A known nonlinearity in a system may be overcome by proper modeling, equations, or additional electronics. For example, suppose a displacement sensor has an output that varies as a second-order equation. Using the square root of the signal, either through programming or by a simple electronic circuit, will yield a linear output proportional to the displacement. Therefore, the output will be as if the sensor were linear.

- **Range:** Range is the difference between the smallest and the largest outputs the sensor can produce, or the difference between the smallest and largest inputs with which it can operate properly.
- **Response time:** Response time is the time that a sensor's output requires to reach a certain percentage of the total change. It is usually expressed in percentage of total change, such as 95%. It is also defined as the time required to observe the change in output as a result of a change in input. For example, the response time of a simple mercury thermometer is long, whereas a digital thermometer's response time, which measures temperature based on radiated heat, is short. A special response time of 63.2% is called *time constant* τ. Similarly, rise time is the time required between 10% and 90% of the final value and settling time is the time between 0% and 98% rise.
- **Frequency response:** Suppose you attach a very high-quality radio tuner to a small, cheap speaker. Although the speaker will reproduce the sound, its quality will be very low, whereas a high-quality speaker system with a woofer and tweeter can reproduce the same signal with much better quality. This is because the frequency response of the two-speaker system is very different from the single, cheap speaker. The natural frequency of a small speaker is high, and therefore, it can only reproduce high frequency sounds. On the other hand, the speaker system with at least two speakers will run the signal into both the tweeter and woofer speakers, one with high natural frequency and one with low natural frequency.

  The summation of the two frequency responses allows the speaker system to reproduce the sound signal with much better quality (in reality, the signals are filtered for each speaker). All systems can resonate at around their natural frequency with little effort. As the input frequency deviates from the natural value, the response falls off. The frequency response is the range in which the system's ability to resonate (respond) to the input remains relatively high. The larger the range of the frequency response, the better the ability of the system to respond to varying input. Otherwise, the phenomenon measured may vary quickly, before the sensor has a chance to respond and send a signal. Therefore, it is important to consider the frequency response of a sensor and determine whether or not the sensor's response is fast enough under all operating conditions (we will discuss this in more detail in Chapter 9).
- **Reliability:** Reliability is the ratio of how many times a system operates properly, divided by how many times it is used. For continuous, satisfactory operation it is necessary to choose reliable sensors that last a long time while considering the cost and other requirements.
- **Accuracy:** Accuracy is defined as how close the output of the sensor is to the expected value. If for a given input, the output is expected to be a certain value, accuracy is related to how close the sensor's output is to this value. For example, a thermometer should read $100°C$ when placed in pure boiling water at sea level.
- **Repeatability:** If the sensor's output is measured a number of times in response to the same input, the output may be different each time. Repeatability is a measure of how varied the different outputs are relative to each other. Generally, if a sufficient number of tries are made, a range can be defined that includes all results around the nominal value (the radius of a circle that encompasses all results). This range is defined as repeatability. In general, repeatability is more important than accuracy, since in most cases, inaccuracies are systematic and can be corrected or compensated because they

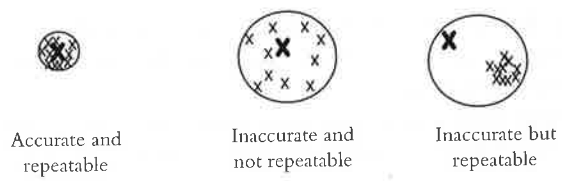

Figure 8.1 Accuracy versus repeatability.

can be predicted and measured. Repeatability is generally random and cannot be easily compensated (see Figure 8.1).

The following is a review of some sensors used in robotics, mechatronics, and automation.

8.3 Sensor Utilization

Figure 8.2(a) shows a basic sensor circuit with a voltage source. As the sensor turns on and off, due to the back-emf principle, the wires act as inductors and, consequently, a voltage spike is generated in the wires that can create false readouts. To prevent this, it is advisable to add a monolithic-type capacitor to the circuit, as shown in Figure 8.2(b). The capacitor should be placed as close to the sensor as possible.

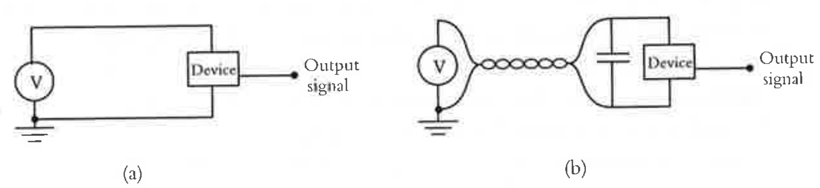

Figure 8.2 Application of a capacitor, added to prevent voltage spikes in reading sensors.

Similarly, if long wires (longer than a few inches) are used to connect a sensor to a voltage source or to where the signal is read, the wires can act as antennae and interfere with the signal. The solution is to use shielded or coaxial wires or to twist the wires together.

By the way, the above is true in other cases too. For example, long wires that connect a motor to a voltage source can also act as antennae, and therefore, it is better to twist the wires together. Similarly, voltage spikes can create problems with integrated circuit chips. Therefore, it is advisable to place a capacitor between the voltage-in and ground pins of an IC chip as close to it as possible (for example, next to, or under, the chip).

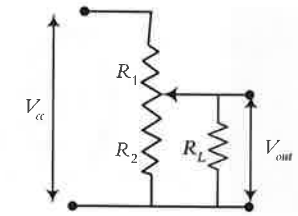

Figure 8.3 A potentiometer as a position sensor.

8.4 Position Sensors

Position sensors are used to measure displacements, both angular and linear, as well as movements. In many cases, such as in encoders, the position information may also be used to calculate velocities. The following are common position sensors used in robotics:

8.4.1 Potentiometers

A potentiometer converts position information into a variable voltage through a resistor. As the sliding contact (wiper) slides on the resistor due to a change in position, the proportion of the resistance before or after the point of contact with the wiper compared to the total resistance varies (Figure 8.3). The resistive external load R_L is in parallel with R_2, and both are in series with R_1. Since in this capacity, the potentiometer acts as a voltage divider, the output will be proportional to the resistance as:

$$V_{out} = \frac{R_2 R_L}{R_1 R_L + R_2 R_L + R_1 R_2} \cdot V_{cc} \tag{8.2}$$

Assuming that R_L is large, the quantity $R_1 R_2$ can be ignored, and the equation simplifies to:

$$V_{out} = V_{cc} \frac{R_2}{R_1 + R_2} \tag{8.3}$$

Example 8.1

Assume that $R_1 = R_2 = 1\ k\Omega$. Calculate the difference between the values of V_{out} based on Equations (8.2) and (8.3) if (a) $R_L = 10\ k\Omega$ and (b) $R_L = 100\ k\Omega$.

Solution:

a. $V_{out} = \frac{10}{10+10+1} \cdot V_{cc} = \frac{10}{21} V_{cc} = 0.476 V_{cc}$ and $V_{out} = \frac{1}{2} \cdot V_{cc} = 0.5 V_{cc}$

b. $V_{out} = \frac{100}{100+100+1} \cdot V_{cc} = \frac{100}{201} V_{cc} = 0.498 V_{cc}$ and $V_{out} = \frac{1}{2} \cdot V_{cc} = 0.5 V_{cc}$

Clearly, it is crucial that the resistive load be large enough for acceptable accuracy. ■

Potentiometers can be rotary or linear, and therefore, can measure linear or angular motions. Rotary potentiometers can also be multiple-turn, enabling the user to measure many revolutions of motion.

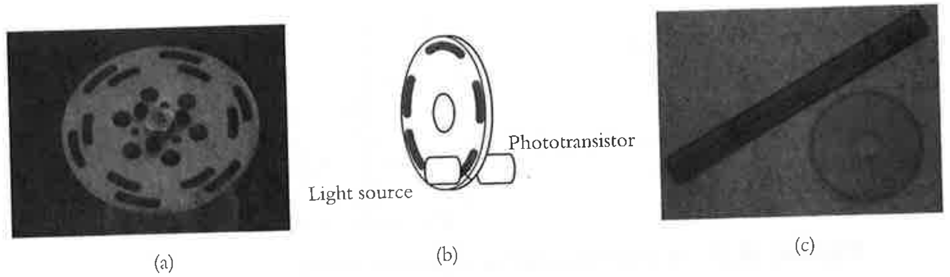

Figure 8.4 (a) A simple rotary incremental encoder disk mounted on a motor shaft. This encoder measures angular rotations. (b) Schematic of a rotary encoder arrangement. (c) A reflective-type linear absolute encoder that can measure linear movements and a rotary incremental encoder disk with 1024 slots.

Potentiometers are either wire-wound or use a conductive polymer resistor paste—a deposit of a thin film of resistive carbon particles in a polymer or ceramic and metal mix called *cermet* on a phenolic substrate. The major benefit of conductive polymers is that their output is continuous, and therefore, less noisy. As a result, it is possible to electronically differentiate the output of this type of resistor to find velocity. However, since the output of a wire-wound potentiometer is stepwise, it cannot be differentiated.

Potentiometers are generally used as internal feedback sensors in order to report the position of joints and links. Potentiometers are used both alone as well as together with other sensors such as encoders. In this case, the encoder reports the current position of joints and links, whereas the potentiometer reports the startup positions. As a result, the combination of the sensors allows minimal input requirement with maximum accuracy. This will be discussed in more detail later.

8.4.2 Encoders

An encoder is a simple device that can output a digital signal for each small portion of a movement. To do this, the encoder disk or strip is divided into small sections, as in Figure 8.4. Each section is either opaque or transparent (it can also be either reflective or nonreflective). A light source, such as an LED on one side, provides a beam of light to the other side of the encoder disk or strip, where it is seen by a light-sensitive sensor, such as a phototransistor. If the disk's angular position (or in the case of a strip, the linear position) is such that the light is revealed, the sensor on the opposite side will be turned on and will have a high signal. If the angular position of the disk is such that the light is occluded, the sensor will be off and its output will be low (therefore, a digital output). As the disk rotates, it can continuously send signals. If the signals are counted, the approximate total displacement of the disk can be measured at any time.

Incremental Encoders There are two basic types of encoders: incremental and absolute. Figures 8.4(a) and 8.4(b) are incremental encoders. In this type of encoder, the areas (arcs) of opaque and transparent sections are all equal and repeating. Since all arcs are the same size, each represents an equal angle of rotation. If the disk is divided into only two portions, each portion is 180 degrees, its resolution will also be 180 degrees, and

within this arc, the system is incapable of reporting any more accurate information about the displacement or position. If the number of divisions increases, the accuracy increases as well. Therefore, the resolution of an optical encoder is related to the number of arcs of transparent/opaque areas. Typical incremental encoders can have 512 to 1024 arcs, reporting angular displacements with a resolution of 0.7 to 0.35 degrees. High resolution encoders with thousands of pulses per revolution (PPR) are also available.

Optical encoders are either opaque disks with the material removed for transparent areas (Figure 8.4(a) and 8.4(c)) or are clear material like glass with printed opaque areas. Many encoder disks are also etched, such that they either reflect the light or do not reflect the light. In that case, the light source and the pick-up sensor are both on the same side of the disk.

An incremental encoder is like an integrator. It only reports changes to angular position (it reports the change in location, which is the displacement). However, it cannot report or indicate directly the actual value of the position. In other words, an incremental encoder can only tell how much movement is made. But unless the initial location is known, the actual position cannot be discerned from the sensor. An incremental encoder acts as an integrator, because the controller actually counts the number of signals the encoder sends, determining the total positional change, and consequently, it is integrating the position signal. Unless the controller knows the start-up position, it can never determine where the robot is. In all systems that track positions with incremental encoders, it is necessary to reset the system at the beginning of operations (or at wake-up). The controller will subsequently know the displacements at all times, so long as the reset position is known. (In some Adept robots, a 16-bit encoder is used together with a Hall-effect sensor to provide $\pm 20\mu$ accuracy).

Most photodetectors are analog devices. This means that as the magnitude of the light varies, their output varies too. Therefore, as one section on the encoder disk approaches the detector and the projected light intensity increases to a maximum, the output of the detector rises before falling again as it departs. Consequently, a squaring circuit is used to condition the signal. Figure 8.5 shows the output of an incremental encoder. If only one

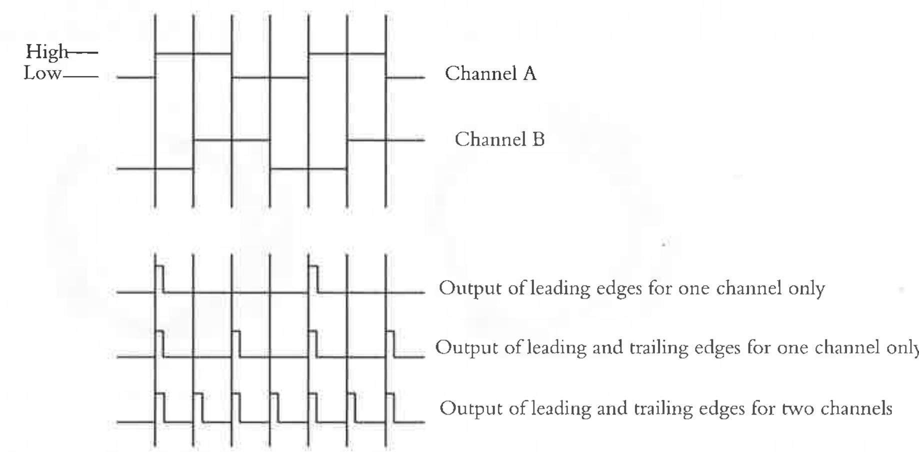

Figure 8.5 Output signals of an incremental encoder.

set of slots is used, it will be impossible to determine whether the disk is rotating clockwise or counterclockwise. To remedy this, encoder disks have two sets of slots (two channels), 1/2 step out of phase with each other (Figure 8.4(a)). As a result, the output signals of the two sets of slots are also a 1/2 step out of phase with each other. The controller can compare the two signals and determine which one changes from high to low or vice versa before the other signal. Through this comparison, it is possible to determine the direction of rotation of the disk.

By counting both the leading edges as well as the trailing edges of the output signals of the encoders on both channels, it is actually possible to increase resolution of the output of incremental encoders without increasing the number of slots.

Note that it is crucial to set up your system to look for *changes* in the signal, not whether the signal is high or low. If your circuit keeps counting when the signal is high, it may register a significantly high false count, especially if your system is fast or if the shaft rotates slowly. Only counting when there is a change (high to low or low to high) ensures that a correct number of signals are registered and counted.

Absolute Encoders An alternative to incremental optical encoders is an absolute encoder. Each portion of the encoder disk's angular displacement has a unique combination of clear/opaque sections that give it a unique signature. Through this unique signature, it is possible to determine the exact position of the disk at any time, without the need for a starting position. In other words, even at start time, the controller can determine the position of the disk by considering the unique signature of the disk at that location. As shown in Figure 8.6, there is a multiple row of sections, each one different from the others. The first row may have only one clear and one opaque section (one on, one off). The next row has 4 (or 2^2), followed by 8 (or 2^3), and so on. Each row must have its own light source and light detector assembly. Each sensor assembly sends out one signal. Therefore, two rows require two inputs to the controller (2 bits), three rows require 3 bits, and so on.

As shown in Figure 8.6, an encoder with 4 rows can have $2^4=16$ distinct combinations, each section covering an angle of 22.5°. This means that within this section of 22.5°, the controller cannot determine where the encoder is. Therefore, the resolution is only 22.5°. To increase the resolution, there would have to be more sections, or bits. An encoder with 1024 divisions on one row has 10 ($1024 = 2^{10}$) bits of information that must

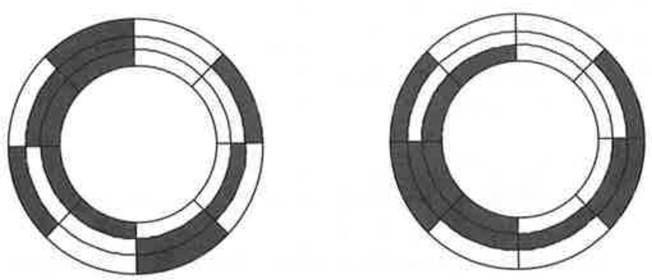

Figure 8.6 Each portion of the angular position of an absolute encoder has a unique signature. Through this signature, the angular position of the encoder can be determined.

Table 8.1 *Binary and Gray Codes.*

#	Gray Code	Binary Code	#	Gray Code	Binary Code
0	0000	0000	6	0101	0110
1	0001	0001	7	0100	0111
2	0011	0010	8	1100	1000
3	0010	0011	9	1101	1001
4	0110	0100	10	1111	1010
5	0111	0101	11	1110	1011

be communicated to the controller. With 10-bit resolution, a robot with 6 joints would require 60 input lines to the controller. Consequently, it is necessary to consider the advantages and disadvantages of incremental and absolute encoders. Commercial encoders with as high as 15–16 bits are available.

Another method to increase the resolution of encoders is to add a supplemental light sensing device to it. In one rendition,[1] a faceted mirror was attached to the encoder shaft, which reflected a laser light onto a low-line-density diffraction grating. The diffracted light was projected onto an array of 200–8000 photodiodes. Depending on the angle of the shaft, the light reflected by the mirror onto the grating would change, therefore changing the output signals from the array. A combination of signals from the encoder and the photodiode array increases the resolution significantly, but at a great cost.

Figure 8.6 also shows the difference between a binary code and a gray code. In the binary code system, there are many instances where more than one set of bits change sign simultaneously, whereas in gray code, at any particular location, there is always only one bit-change to go back or forth. The importance of this difference is that in digital measurements, unlike popular perception, the values of signals are not constantly read, but the signal is measured (sampled) and held until the next sample reading. In binary code, where multiple bits change simultaneously, if all changes do not happen exactly at the same time, they may not all register. In gray code, since there is only one change, the system will always find it. Table 8.1 lists the gray code for numbers 0–11.

8.4.3 Linear Variable Differential Transformer (LVDT)

A linear variable differential transformer (or transducer) is actually a transformer whose core moves with the distance measured and that outputs a variable analog voltage as a result of this displacement. In general, a transformer is an electric-to-electric energy converter that changes the voltage/current ratio. Except for losses, the total input energy to the device is the same as the total output energy. As a transformer increases or decreases a voltage in proportion to the number of turns in its coils, the corresponding current changes inversely with it. This occurs because there are two coils with different numbers of turns. The electrical energy into one coil creates a flux, which induces a voltage in the second coil proportional to the ratio of the number of turns in the windings. As the number of turns in the secondary coil increases, the voltage increases proportionally, and consequently, the current decreases proportionally. However, the induction of voltage in the secondary is very much a function of the strength of the flux. If no iron core is present, the flux lines can disperse, reducing the strength of the magnetic field. As a result, the induction of voltage in the secondary will be minimal. In the presence of an iron core, the flux lines are gathered

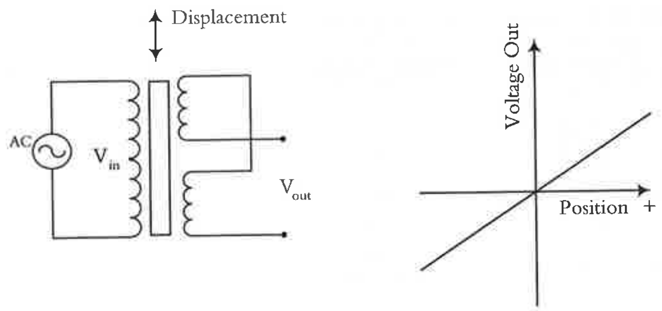

Figure 8.7 Linear Variable Differential Transformer.

inward, increasing the density of the field, and consequently, the induced voltage. This is used to create the variable output voltage in the LVDT, as in Figure 8.7. The output of an LVDT is very linear and proportional to the input position of the core.

8.4.4 Resolvers

Resolvers are very similar to LVDTs in principle, but are used to measure an angular motion. A resolver is also a transformer, where the primary coil is connected to the rotating shaft and carries an alternating current, either through slip rings or from a brushless transformer within it (Figure 8.8). There are two secondary coils, placed 90° apart from each other. As the rotor rotates, the flux it develops rotates with it. When the primary coil in the rotor is parallel to either of the two secondary coils, the voltage induced in that coil is maximum, while the other secondary coil perpendicular to it does not develop any voltage. As the rotor rotates, eventually the voltage in the first secondary coil goes to zero, while the second coil develops its maximum voltage. For all other angles in between, the two secondary coils develop a voltage proportional to the sine and cosine of the angle between the primary and the two secondary coils. Although the output of a resolver is analog, it is equal to the sine and cosine of the angle, eliminating the necessity to calculate these values later. Resolvers are reliable, robust, and accurate.

8.4.5 (Linear) Magnetostrictive Displacement Transducers (LMDT or MDT)

In this sensor, a pulse is sent through a conductor, which bounces back as it reaches a magnet. The time of travel to the magnet and back is converted to a distance if the speed of travel is known. By attaching the moving part to either the magnet or the conductor,

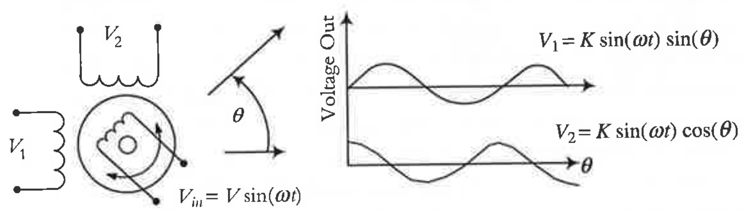

Figure 8.8 Schematic of a resolver.

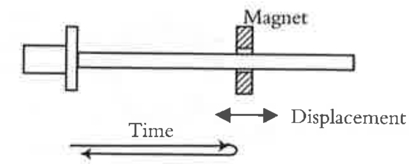

Figure 8.9 Schematic drawing of a magnetostrictive displacement sensor.

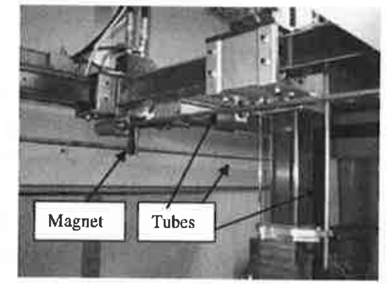

Figure 8.10 The IBM 7565 magnetostrictive displacement transducers. A pulse generated at one end of a long tube travels within the tube until it reaches a magnet and bounces back. The time of travel of the signal is converted to position information.

the displacement can be measured. A simple schematic of the sensor is shown in Figure 8.9. The IBM 7565 hydraulic gantry robot displacement sensors were of this type, as shown in Figure 8.10.

8.4.6 Hall-effect Sensors

A Hall-effect sensor works on the Hall-effect principle, where the output voltage of a conductor that carries a current changes when in the presence of a magnetic field. Therefore, the output voltage of the sensor changes when a permanent magnet or a coil that produces a magnetic flux is close to the sensor. A Hall-effect transducer's output is analog and must be converted for digital applications. It is used in many applications, including the sensing of the position of the permanent magnet rotors of brushless DC motors.

8.4.7 Other Devices

Many other devices can be used as position sensors, some novel and hi-tech, some simple and old. For example, in order to measure the angles of finger joints in a glove (such as in a virtual-reality glove), conductive elastomer strips were attached to the glove above the fingers. Conductive elastomer is a urethane-based synthetic rubber filled with conductive carbon particles. Its electrical resistance decreases as the tension on it increases. Therefore, as the finger bends within the glove, it stretches the strip, changing its resistance, which can be measured and converted to a position signal.[2]

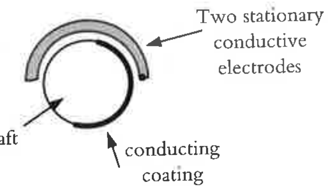

Figure 8.11 Shaft-angle measuring device based on a tunnel-diode oscillator and capacitance between a shaft and stationary electrodes.[3]

In another device, one-half side of a nonconductive shaft is coated with a conducting material. Two ½-cylinder conductive electrodes with radii slightly larger than the shaft's are mounted concentrically over the shaft, creating a capacitor between the shaft and the stationary electrodes (Figure 8.11). As the shaft rotates, the capacitance changes, too. Used as a capacitor within a tunnel-diode oscillator circuit, the output frequency varies as the capacitance varies relative to the shaft position. Therefore, by measuring the frequency of the oscillation, the position of the shaft can be measured.[3]

8.5 Velocity Sensors

The following are the more common velocity sensors used in robotics. Their application is very much related to the type of position sensor used. Depending on the type of position sensor used, there may not even be a need to use a velocity sensor.

8.5.1 Encoders

If an encoder is used for displacement measurement, there is in fact no need to use a velocity sensor. Since encoders send a known number of signals for any given angular displacement, by counting the number of signals received in a given length of time *dt* velocity can be calculated. A typical number for *dt* may be 10 ms. However, if the encoder shaft rotates slowly, the number of signals received may be too small for an accurate calculation of velocity. On the other hand, if the time is increased in order to increase the total number of signals per cycle, the rate at which velocity is updated and sent to the controller will decrease. This will diminish the accuracy and effectiveness of the controller. In some systems, the cycle time *dt* is varied depending on the angular velocity of the encoder shaft. A smaller number is used if it rotates fast, increasing the effectiveness of the controller, and a larger number is used otherwise to gather enough data.

8.5.2 Tachometers

A tachometer is in fact a generator that converts mechanical energy into electrical energy. Its output is an analog voltage proportional to the input angular speed. It may be used along with potentiometers to estimate velocity. Tachometers are generally inaccurate at very low speeds.

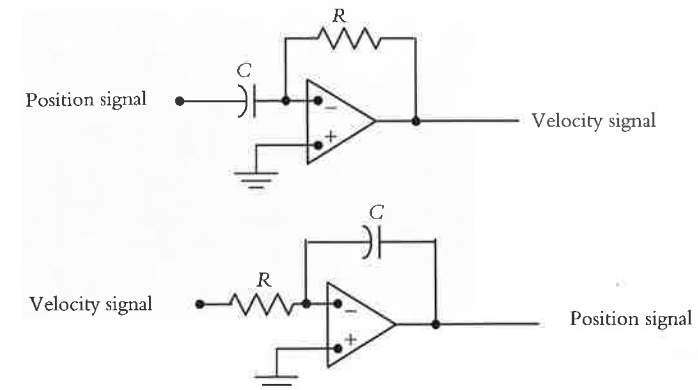

Figure 8.12 Schematics of differentiating and integrating *R-C* circuits with an op-amp.

8.5.3 Differentiation of Position Signal

If the position signal is clean, it is actually possible, and simple, to differentiate the position signal and convert it to velocity signal. To do this, it is necessary that the signal be as continuous as possible to prevent the creation of large impulses in the velocity signal. Therefore, it is recommended that a resistor with conductive polymer film be used for position measurement, as a wire-wound potentiometer's output is piecewise and unfit for differentiation. However, differentiation of a signal is always noisy and should be done very carefully. Figure 8.12 shows a simple R-C circuit with an op-amp that can be used for differentiation, where the velocity signal is:

$$V_{out} = -RC\frac{dV_{in}}{dt} \tag{8.4}$$

Similarly, the velocity (or acceleration) signal can be integrated to yield position (or velocity) signals as:

$$V_{out} = -\frac{1}{RC}\int V_{in}dt \tag{8.5}$$

8.6 Acceleration Sensors

Accelerometers are very common sensors for measuring accelerations. However, in general, accelerometers are not used with industrial robots. Recently, acceleration measurements have been used for high precision control of linear actuators[4] and for joint feedback control of robots.[5]

8.7 Force and Pressure Sensors

8.7.1 Piezoelectric

Piezoelectric material compresses if exposed to a voltage and produces a voltage if compressed. This was used in devices such as the phonograph to create a voltage from the

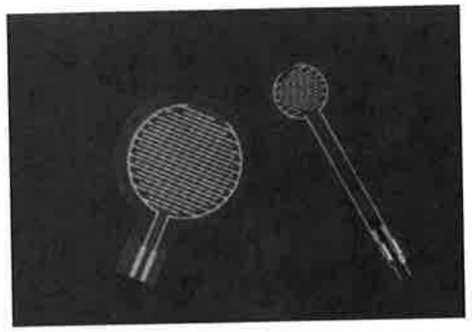

Figure 8.13 A typical force sensing resistor (FSR). The resistance of this sensor decreases as the force acting on it increases.

variable pressure caused by the grooves in the record. Similarly, a piece of piezoelectric can be used to measure pressures, or forces, in robotics. The analog output voltage must be conditioned and amplified for use.

8.7.2 Force Sensing Resistor

The Force Sensing Resistor (FSR) is a polymer thick-film device that exhibits a decreasing resistance with increasing force applied perpendicular to its surface. In one particular model, the resistance changes from about 500 $k\Omega$ to about 1 $k\Omega$ for forces of 10 to 10,000 gr (refer to References 6, 7, and 8 for more information about UniForce™ sensors and others). Figure 8.13 shows a typical force sensing resistor.

8.7.3 Strain Gauge

A strain gauge can also be used to measure force. The output of the strain gauge is a variable resistance, proportional to the strain, which itself is a function of applied forces. Therefore, measuring the resistance, we can determine the applied force. Strain gauges are used to determine the forces at the end effector and the wrist of a robot. Strain gauges can also be used for measuring the loads on the joints and links of the robot, but this is not very common. Figure 8.14(a) is a simple schematic drawing of a strain gauge. Strain gauges are used within a Wheatstone bridge, as shown in Figure 8.14(b). A balanced Wheatstone bridge would have similar potentials at points A and B. If the resistance in any of the four resistors changes, there will be a current

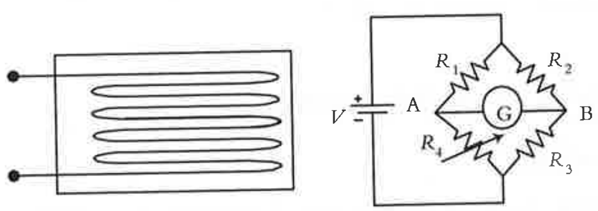

Figure 8.14 (a) A strain gauge and (b) a Wheatstone bridge.

flow between these two junctions. Consequently, it is necessary to first calibrate the bridge for zero flow in the galvanometer. Assuming that R_1 is the strain gauge, when under stress, its value will change, causing an imbalance in the Wheatstone bridge and a current flow between A and B. By carefully adjusting the resistance of one of the other resistors until the current flow becomes zero, the change in the resistance of the strain gauge can be determined from:

$$\frac{R_1}{R_4} = \frac{R_2}{R_3} \tag{8.6}$$

Strain gauges are sensitive to changes in temperature. To remedy this problem, a dummy strain gauge can be used as one of the four resistors in the bridge to compensate for temperature changes.

8.7.4 Antistatic Foam

The antistatic foam used for transporting IC chips is conductive and its resistance changes due to an applied force. It can function as a crude and simple, yet inexpensive, force and touch sensor. To use a piece of antistatic foam, insert a pair of wires into two sides of it and measure the voltage or resistance across it.

8.8 Torque Sensors

Torque can be measured by a pair of strategically placed force sensors. Suppose that two force sensors are placed on a shaft, opposite of each other, on opposite sides. If a torque is applied to the shaft, it generates two opposing forces on the shaft's body, causing strains in opposite directions. The two force sensors can measure the forces, which can be converted to a torque. To measure torques about different axes, three pairs of mutually perpendicular sensors must be used. However, since forces can also be measured with the same sensors, a total of six force sensors can generally report forces and torques about three axes, independent of each other, as depicted in Figure 8.15. Pure forces generate

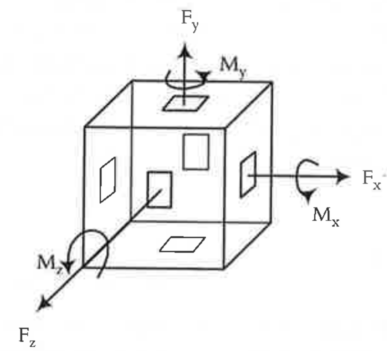

Figure 8.15 Arrangement of three pairs of strain gauges along the three major axes for force and torque measurements.

Figure 8.16 Typical industrial force/torque sensors. (IP65 Gamma and Mini 85, printed with permission from ATI Industrial Automation.)

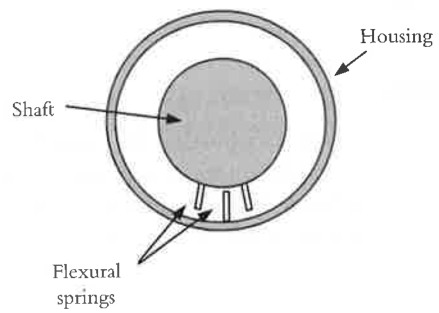

Figure 8.17 The torque can be measured by measuring the changes in the frequency of oscillation of a tunnel-diode oscillator when the capacitance of the flexural springs changes due to the applied torque.

similar signals in a pair, while torques generate pairs of signals with opposite signs. Figure 8.16 shows typical industrial force-torque sensors.

A miniature load sensor, designed to be used as fingertips for anthropomorphic robot hands, uses a spring instrumented with at least six strain gauges. The wires are attached to a small interface board at the base of the spring. The sensor is attached to an A/D converter as close to the sensor as possible. The data is transmitted to the controller by wires, routed at the neutral axis of the fingers.[9]

Figure 8.17 shows a schematic depiction of a system in which flexural springs, attached to a shaft, form a pair of capacitors used as part of a tunnel-diode oscillator circuit. As the shaft rotates slightly under the load, the capacitance of each pair changes, causing a change in the oscillation frequency of the circuit. By measuring the frequency of oscillations, the torque can be determined.[10]

8.9 Microswitches

Microswitches, though extremely simple, are very useful and common in all robotic systems. They cut off the electrical current, and therefore, can be used for safety purposes, for determining contact, for sending signals based on displacements, and many other uses. Microswitches are robust, simple, and inexpensive.

8.10 Visible Light and Infrared Sensors

These sensors react to the intensity of light projected onto them by changing their electrical resistance. If the intensity of light is zero, the resistance is at maximum. As the light intensity increases, the resistance decreases, and consequently, the current increases. These sensors are inexpensive and very useful. They can be used for making optical encoders and other devices as well. They are also used in tactile sensors, as will be discussed later.

A phototransistor can also be used as a light sensor, where in the presence of a certain intensity of light, it will turn on; otherwise, it will be off. Phototransistors are usually used in conjunction with an LED light source.

A light sensor array can be used with a moving light source to measure displacements as well. This has been used to measure deflections and small movements in robots and other machinery.[11] Light sensors are sensitive to the visible light range. Infrared sensors are sensitive to infrared range. Since infrared is invisible to human eyes, it will not disturb humans. For example, if a device needs light to measure a large distance for navigation purposes, infrared can be used without attracting attention or disturbing anyone. Simple infrared remote control devices are also available that can be used to establish remote control communication links between devices and robots. Refer to Reference 8 for specifications.

8.11 Touch and Tactile Sensors

Touch sensors are devices that send a signal when physical contact has been made. The simplest form of a touch sensor is a microswitch, which either turns on or off as contact is made. The microswitch can be set up for different sensitivities and ranges of motion. As an example, a strategically placed microswitch can send a signal to the controller if a mobile robot reaches an obstacle during navigation. More sophisticated touch sensors may send additional information. For example, a force sensor used as a touch sensor may not only send touch information, but also report the magnitude of the contact force.

A tactile sensor is a collection of touch sensors which, in addition to determining contact, can also provide additional information about the object. This additional information may be about the shape, size, or type of material. In most cases, a number of touch sensors are arranged in an array or matrix form, as shown in Figure 8.18. In this design, an array of six touch sensors is arranged on each side of a tactile sensor. Each touch

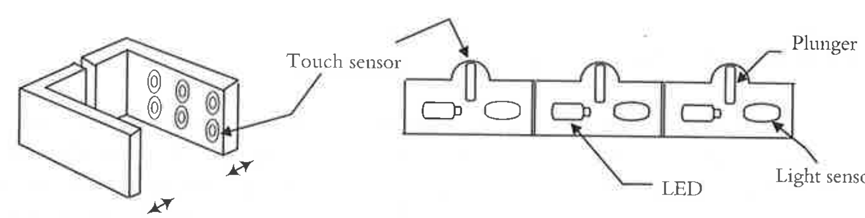

Figure 8.18 Tactile sensors are generally a collection of simple touch sensors arranged in an array form with a specific order to relay contact and shape information to the controller.

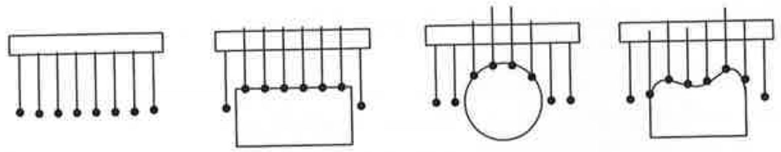

Figure 8.19 A tactile sensor can provide information about the object.

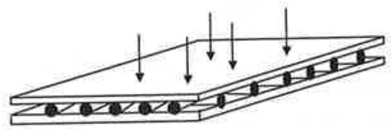

Figure 8.20 Skin-like tactile sensor.

sensor is made up of a plunger, an LED, and a light sensor. As the tactile sensor closes and the plunger moves in or out, it blocks the light from the LED projecting onto the light detector. The output of the light sensor is proportional to the displacement of the plunger. As you can see, these touch sensors are in fact displacement sensors. Similarly, other types of displacement sensors may be used for this purpose, from microswitches to LVDTs, pressure sensors, magnetic sensors, and so on.

As the tactile sensor comes in contact with an object, depending on the shape and size of the object, different touch sensors react differently at a different order. This information is then used by the controller to determine the size and the shape of the object. Figure 8.19 shows three simple set-ups, one touching a cube, one touching a cylinder, and one touching an arbitrary object. As can be seen, each object creates a different unique signature that can be used for detection.

Attempts have also been made to create somewhat of a continuous skin-like tactile sensor that could function similarly to human skin. In most cases, the design revolves around a matrix of sensors embedded between two polymer-type layers, separated by a mesh, as shown schematically in Figure 8.20. As a force is applied to the polymer, it is distributed between a few surrounding sensors, where each one sends a signal proportional to the force applied to it. For low resolution, these tactile sensors work satisfactorily.[12] Other designs include a similar polymer-type substrate populated with capacitive sensors. A microprocessor reads the sensors sequentially in order to determine the shape of the object and the contact force at each location. In another design, a flexible circuit board, populated with proximity sensors (see Section 8.12) provides a skin-like covering to help robots avoid collisions.[13]

8.12 Proximity Sensors

A proximity sensor is used to determine that an object is close to another object before contact is made. This noncontact sensing can be useful in many situations, from measuring the speed of a rotor to navigating a robot. There are many different types of proximity sensors, such as magnetic, eddy current and Hall-effect, optical, ultrasonic, inductive, and capacitive. The following is a short discussion of some of these sensors.

8.12.1 Magnetic Proximity Sensors

These sensors are activated when they are close to a magnet. They can be used for measuring rotor speeds (and the number of rotations) and turning a circuit on or off.[8] Magnetic proximity sensors may also be used to count the number of rotations of wheels and motors, and therefore, be used as position sensors. Imagine a mobile robot, where the total displacement of the robot is calculated by counting the number of times a particular wheel rotates, multiplied by the circumference of the wheel. A magnetic proximity sensor can be used to track wheel rotations by mounting a magnet on the wheel (or its shaft) and having the sensor stationary on the chassis. Similarly, the sensor can be used for other applications, including safety. For example, many devices have a magnetic proximity sensor that sends a signal when the door is open to stop the rotating or moving parts.

8.12.2 Optical Proximity Sensors

Optical proximity sensors consist of a light source called emitter (either internal to the sensor, or external to it), and a receiver, which senses the presence or the absence of light. The receiver is usually a phototransistor and the emitter is usually an LED. The combination of the two creates a light sensor, and is used in many applications, including optical encoders.

As a proximity sensor, it is set up such that the light, emitted by the emitter, is not reflected to the receiver unless an object is within range. Figure 8.21 is a schematic drawing of an optical proximity sensor. Unless a reflective object is within the range of the switch, the light is not seen by the receiver; therefore, there will be no signal.

Figure 8.22 shows another variation of an optical proximity sensor. In this simple system that can determine both proximity as well as short-range distance (and therefore

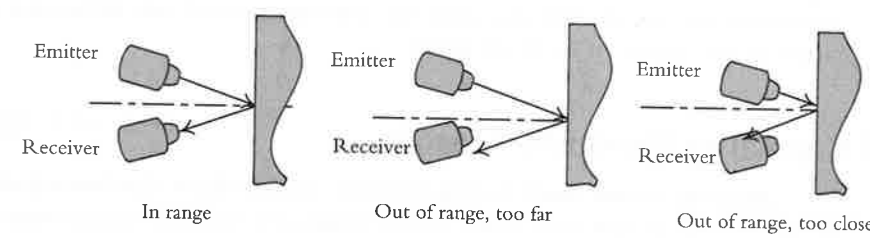

Figure 8.21 Optical proximity sensor.

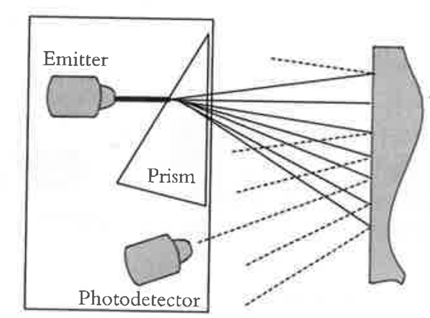

Figure 8.22 An alternative optical proximity sensor.

act as a range finder for short distances), a beam of light is passed through a prism that refracts the light into its constituent primary colors. Depending on the distance of the object from the sensor, one particular color of light is reflected back to the sensor's photodetector. By measuring the energy of the reflected light, the distance can be determined and reported.

8.12.3 Ultrasonic Proximity Sensors

In ultrasonic proximity sensors, an ultrasonic emitter emits frequent bursts of high frequency sound waves (usually in the 200 kHz range). There are two modes of operation for ultrasonic sensors, namely, opposed mode and echo (diffused) mode. In opposed mode, a receiver is placed in front of the emitter; in echo mode, the receiver is either next to, or integrated into, the emitter and receives the reflected sound wave. If the receiver is within range, or if the sound is reflected by a surface close to the sensor, it is sensed and a signal is produced. Otherwise, the receiver will not sense the wave and there is no signal. All ultrasonic sensors have a blind zone near the surface of the emitter in which the distance and presence of an object cannot be detected. Ultrasonic sensors cannot be used with surfaces such as rubber and foam that do not reflect the soundwaves in echo mode. For more information about ultrasonic sensors, refer to section 8.13.1. Figure 8.23 is a schematic drawing of this type of sensor.

8.12.4 Inductive Proximity Sensors

Inductive proximity sensors are used to detect metal surfaces. The sensor is a coil with a ferrite core, an oscillator/detector, and a solid state switch. In the presence of a metal object in the close vicinity of the sensor, the amplitude of the oscillation diminishes. The detector senses the change and turns the solid state switch off. When the part leaves the range of the sensor, it turns on again.

8.12.5 Capacitive Proximity Sensors

The capacitive sensor reacts to the presence of any object that has a dielectric constant more than 1.2. In that case, when within range, the material's capacitance raises the total

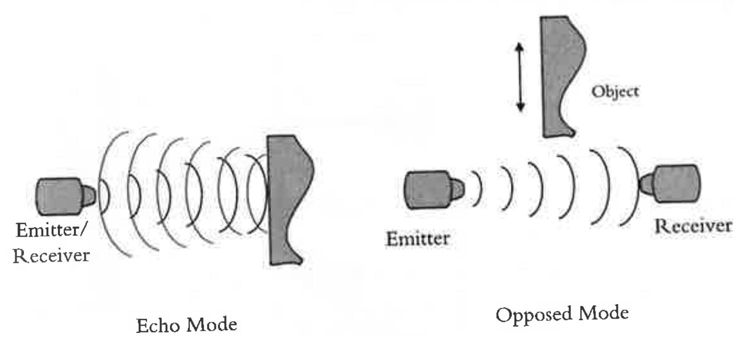

Figure 8.23 Ultrasonic proximity sensors.

Table 8.2 *Dielectric Constants for Select Materials.*

Air	1.000	Porcelain	4.4–7
Aqueous solutions	50–80	Cardboard	2–5
Epoxy resin	2.5–6	Rubber	2.5–3.5
Flour	1.5–1.7	Water	80
Glass	3.7–10	Wood, dry	2–7
Nylon	4–5	Wood, wet	10–30

capacitance of the circuit. This triggers an internal oscillator to turn on the output unit which will send out an output signal. Consequently, the sensor can detect the presence of an object within a range. Capacitive sensors can detect nonmetal materials such as wood, liquids, and chemicals. Table 8.2 shows dielectric constants for select materials.

8.12.6 Eddy Current Proximity Sensors

As we discussed in Chapter 7, when a conductor is placed within a changing magnetic field, an electromotive force (emf) is induced in it that causes a current to flow in the material. This current is called eddy current. An eddy current sensor typically has two coils, where one coil generates a changing magnetic flux as reference. In the close proximity of conducting materials, an eddy current is induced in the material, which in turn creates a magnetic flux opposite of the first coil's, effectively reducing the total flux. The change in the total flux is proportional to the proximity of the conducting material and is measured by the second coil. Eddy current sensors are used to detect the presence of conductive materials as well as the nondestructive testing of voids and cracks, thickness of materials, and so on.

8.13 Range Finders

Unlike proximity sensors, range finders are used to find larger distances, to detect obstacles, and to map the surfaces of objects. Range finders are meant to provide advance information to the system. Range finders are generally based on light—visible light, infrared light, or laser—and ultrasonics. Two common methods of measurement are triangulation and time-of-flight or lapsed time.

Triangulation involves illuminating the object by a single ray of light that forms a spot on the object. The spot is seen by a receiver such as a camera or photodetector. The range or depth is calculated from the triangle formed between the receiver, the light source, and the spot on the object, as shown in Figure 8.24.

As is evident from Figure 8.24(a), the particular arrangement between the object, the light source, and the receiver only occurs at one instant. At this point, the distance d can be calculated by:

$$\tan\beta = \frac{d}{l_1}, \quad \tan\alpha = \frac{d}{l_2} \quad \text{and} \quad L = l_1 + l_2$$

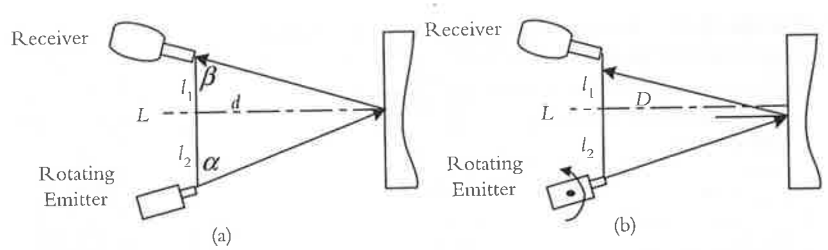

Figure 8.24 Triangulation method for range measurement. The receiver will only detect the spot on the object when the emitter is at a particular angle, which is used to calculate the range.

Substituting and manipulating the equation will yield:

$$d = \frac{L \tan\alpha \tan\beta}{\tan\alpha + \tan\beta} \tag{8.7}$$

Since L and β are known, if α is measured, d can be calculated. You can see from Figure 8.24(b) that except at that instant, the receiver will not see the reflected light. Consequently, it is necessary to rotate the emitter and, as soon as the reflected light is observed by the receiver, record the angle of the emitter and use it to calculate range. In practice, the emitter's light (such as laser) is rotated continuously by a rotating mirror and the receiver is checked for signal. As soon as the light is observed, the angle of the mirror is recorded.

Time of flight or **lapsed time** ranging consists of sending a signal from a transmitter that bounces back from an object and is received by a receiver. The distance between the object and the sensor is half the distance traveled by the signal, which can be calculated by measuring the time of flight of the signal and by knowing its speed of travel. This time measurement must be very fast to be accurate. For small distance measurements, the wavelength of the signal must be very small.

8.13.1 Ultrasonic Range Finders

Ultrasonic systems are rugged, simple, inexpensive, and low powered. They are readily used in cameras for focusing, in alarm systems for motion detection, and in robots for navigation and range measurement. Their disadvantage is in their limited resolution which is due to the wavelength of the sound and natural variations of temperature and velocity in the medium, and in their maximum range which is limited by the absorption of the ultrasound energy in the medium. Typical ultrasonic devices have a frequency range of 20 kHz to above 2 MHz.

Most ultrasonic devices measure the distance using the time-of-flight technique, in which, a transducer emits a pulse of high-frequency ultrasound that is reflected back when it encounters a separation in the medium and a receiver that receives the reflected signal. The distance between the transducer and the object is half the distance traveled, which is equal to the time-of-flight times the speed of sound. Of course, the accuracy of the measurement depends on the wavelength of the signal and the accuracy of the time measurement and the speed of sound. The speed of sound in a medium is dependent on

the frequency of the wave (at above 2 MHz level) and the density and temperature of the medium. To increase the accuracy of the measurement, a calibration bar is usually placed about an inch in front of the transducer, which is supposed to calibrate the system for varying temperatures. This is only good if the temperature is uniform throughout the traveled distance, which may or may not be true.

Time measurement accuracy is also very important for accurately measuring distance. Usually, the worst case error in time measurement is $\pm 1/2$ wavelength if the clock is stopped as soon as the receiver receives the returned signal at a minimum threshold. Therefore, higher frequency ultrasound devices yield better accuracy. For example, for 20 kHz and 200 kHz systems, the wavelengths will respectively be about 0.67 and 0.067 inches (17 and 1.7 mm) yielding a minimum worst case accuracy of 0.34 and 0.034 inches (8.5 and 0.85 mm). Cross correlation, phase comparison, frequency modulation, and signal integration methods have been used to increase the resolution and accuracy of ultrasonic devices. However, although higher frequencies yield a better resolution, they attenuate much faster than the lower frequency signals, which severely limits their range. On the other hand, the lower frequency transducers have wide beam angles and a severely deteriorated lateral resolution. Consequently, there is a tradeoff between the lateral resolution and signal attenuation in relation with the beam frequency.

Background noise is another problem with ultrasonic sensors. Many different industrial and manufacturing operations and techniques produce soundwaves that contain ultrasonics as high as 100 kHz, which can interfere with the ultrasonic device operation. As a result, it is recommended that frequencies above 100 kHz be utilized in industrial environments.

Ultrasonics can be used for distance measurement, mapping, and flaw detection. A single-point distance measurement is called *spot checking*, versus *range array acquisition* for multiple data point acquisition techniques used for 3-D mapping. In this case, a large number of distances to different locations on an object are measured. The collection of distance data provides a 3-D map of the surface of the object. It should be noted that since only half the surface area of a 3-D object can be ranged, these measurements are also referred to as 2.5-D. The backside of the object or areas obscured by other parts cannot be ranged.

8.13.2 Light-Based Range Finders

Light (including infrared and laser)-based range finders measure the distance from an object by three different methods: direct time delay measurement, indirect amplitude modulation, and triangulation. The direct time delay measurement method measures the time required for a collimated beam of light (usually laser, since it does not divert) to travel to an object and back, similar to an ultrasonic sensor. Since the speed of light in air is 186,000 miles/sec (300,000 km/sec), it travels about 1 ft (30 cm) in 1 ns. Therefore, extremely high speed electronics and high resolutions are required to use this method.

In one indirect method, the time delay is measured by modulating a long burst of light with a low-frequency sinusoidal wave (Time-to-Amplitude Converter, TAC) and measuring the phase difference between the modulations between the emitted light and the backscattered light. This, in effect, is slowing down the wave speed to measurable scales by substituting the speed of light with low-speed modulations, but still taking advantage of the long travel range of laser lights.

Triangulation is the common technique used in range finding using light beams. For shorter distances encountered in navigation, triangulation yields the most accurate and best resolution among the three different techniques.

Another technique for measuring range with light sources is stereo imaging, which we will discuss in Chapter 9. A variation to this technique involves the use of a small laser pointer along with a single camera.[14] In this technique, the location of the laser light within the camera image is measured relative to the center of the image. Since the laser light and the axis of the camera are not parallel, the location of the laser dot within the image is a function of the distance between the object and the camera.

LIDAR (Light Detection and Ranging) is similar to radar, but uses light instead of radio waves. A beam of light (laser or infrared) is fired toward the target, and the properties of scattered light are measured to find the range and/or other information about a distant target. To gather information on a continuous basis, thousands of pulses of light are reflected by a rotating mirror. In a system developed by Velodyne Lidar, Inc., a set of 64 laser emitters fire thousands of pulses per second while the unit rotates between 5–15 Hz. It can collect data about the environment at 360 degrees azimuth and 27 degrees elevation, with a range of 120 meters.[15] Another time-of-flight laser-based sensor that measures distances up to 30 meters at a resolution of 0.25 degrees costs several thousands of dollars.

8.13.3 Global Positioning System (GPS)

This positioning system is based on a radio-navigation system for civilian use, freely available to anyone. With a GPS receiver, we can determine a global position and time that can be used for navigation and mapping. The system includes 29 satellites orbiting the Earth, a control and monitoring station on Earth, and the GPS receivers. The receiver uses the transmitted data from the satellites to calculate its position. This information can be sent directly to the control system of a mobile robot for positioning purposes and navigation.

Each satellite sends signals at precise intervals with information about the time the signal was sent and location of the satellite. The GPS unit reads the signals sent by four satellites and, using the difference between the current time and the time at which each signal was sent (which is contained in the message received), calculates the distance to the satellite. Each distance forms a sphere centered at the satellite, on which the GPS unit resides. The intersection between these spheres is the location of the GPS unit.

In theory, signals from only three satellites should suffice; the GPS unit should be able to determine its location relative to three satellites (two spheres intersect at a circle, and the circle generally intersects the third sphere at two points; the one closer to the Earth's surface is the desired location). However, because the signals move at the speed of light, the accuracy of the system is greatly dependent on the accuracy of the GPS unit's clock. The commercially mass-produced GPS clocks are not accurate enough to yield precise positioning. Therefore, the signal from a fourth satellite is also used to increase the accuracy of the system from about 100 meters to about 20 meters. Military devices use a more accurate clock and high performance signals for improved positional accuracy.

A GPS unit can be integrated into a robotic system for navigation and positioning. The position information is fed into the microprocessor which uses it to decide the succeeding

actions or motions. A 3-D roll-pitch-yaw compass may also be used for global direction and navigation. Although this compass is not a GPS system, it can provide directional information about the three axes of motion, and therefore, aid in controlling a robot's position and orientation.

8.14 Sniff Sensors

Sniff sensors are similar to smoke detectors. They are sensitive to particular gases and send a signal when they detect the gas. They are used for safety purposes as well as for search and detection purposes.[16,17]

8.15 Taste Sensors

A taste sensor is a device that determines the composition of particles in a medium. One device uses an array of potentiometric sensors to evaluate the five basic tastes of sweetness, bitterness, sourness, saltiness, and umami (although no smell has been integrated into the system yet). To distinguish different varieties of wine, a wine-tasting artificial tongue uses an array of ion-sensitive field-effect transistors within a single chip to measure relative levels of ions of sodium, potassium, calcium, copper, and silver. These are used to evaluate and classify samples of wine.[18] Another sensor uses ion-specific electrodes, oxidation/reduction sensor pairs, an electrical conductivity sensor, and an array of galvanic cells to measure the presence of contaminants such as copper, zinc, lead, and iron ions in water as low as 10 ppm.[19] This information can either be used directly, or in combination with other data, in robotic systems and automated activities.

8.16 Vision Systems

Vision systems are perhaps the most sophisticated sensors used in robotics. Due to their importance and complexity, they will be discussed separately in Chapter 9. However, note that vision systems are, in fact, sensors, and that they relate the function of a robot to its environment as do all other sensors.

8.17 Voice Recognition Devices

Voice recognition involves determining what is said and taking an action based on the perceived information. Voice recognition systems generally work on the frequency content of spoken words. As you may remember from other courses, any signal may be decomposed into a series of sines and cosines of different frequencies at different amplitudes, which will reconstruct the original signal if combined. (We will discuss this in more detail in Chapter 9.) However, it is useful to realize that all signals have certain major frequencies that constitute a particular spectrum and that this spectrum is generally different for other signals. In voice recognition systems, it is assumed that every word (or letter or sentence), when decomposed into its constituent frequencies, will have a unique signature composed of its major frequencies, which allow the system to recognize the word.

To do this, the user must train the system by speaking the words *a priori* to allow the system to create a look-up table of the major frequencies that represent the spoken words. Later, when a word is spoken and its frequencies are determined, the result is compared to the look-up table. If a close match is found, the word is recognized. For better accuracy, it is necessary to train the system with more repetitions. On the other hand, a more accurate list of frequencies will reduce allowable variations. This means that if the system tries to match many frequencies for better accuracy, in the presence of any noise or any variations in the spoken words, the system will not be able to recognize the word. On the other hand, if a limited number of frequencies is matched in order to allow for variations, the system may recognize a similar, but incorrect, word. A universal system that recognizes all accents and variations in speaking may not be either possible or useful. Many robots have been equipped with voice recognition systems in order to communicate with the users. In most cases, the robot is trained by the user and can recognize words that trigger a certain action in response. For example, a particular word may be programmed to relate to a certain position and orientation. When the voice recognition system recognizes the word, it will send a signal to the controller which, in turn, will run the robot to the desired location and orientation. This has been particularly useful with robots that aid the disabled as well as for medical robots.

8.18 Voice Synthesizers

Voice synthesis is accomplished in two different ways. One way is to re-create the words by combining phonemes and vowels. In this case, each word is recreated when the phonemes and vowels are combined. This can be accomplished with commercially available phoneme chips and a corresponding program. Although this type of system can reproduce any word, it sounds unnatural and machine-like. As an example of the difficulty encountered by this kind of system, consider the two words "power" and "mower." Although both words are written very similarly, they are pronounced differently. This kind of a system will not be able to recognize this (unless every conceivable exception is programmed into the chip).

The alternative is to record the words that the system may need to synthesize and to access them from memory as needed. Telephone announcements, video games, and many other machine voices are pre-recorded and accessed as needed. Although this system sounds very natural, it is limited. As long as all the words the machine needs to say are known *a priori*, this system can be used. With advances in computer technology, voice recognition and synthesis will be advanced significantly in the future.

8.19 Remote Center Compliance (RCC) Device

Although this device is not an actual sensor, it is discussed here because it acts as a sensing device for misalignments and provides a means of correction for robots. However, remote center compliance (RCC) devices, also called *compensators*, are completely passive and there are no input or output signals.

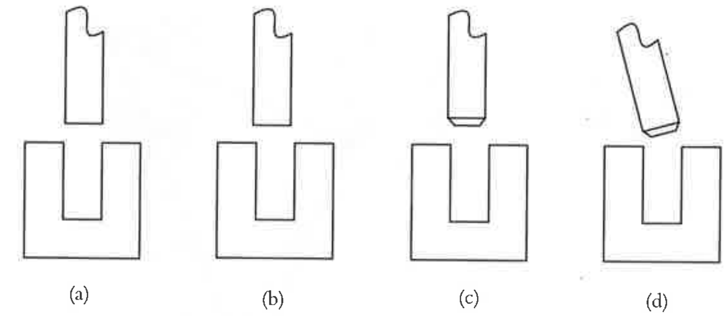

Figure 8.25 Misalignment of assembling elements.

An RCC device is an attachment added to the robot between the wrist and the end effector. It is designed to provide a means of correction for misalignments between the end effector and a part.

Suppose a robot is to push a peg into a hole in a part, as shown in Figure 8.25. If the hole and the peg are exactly the right sizes, and if they are exactly aligned, both laterally and axially, the robot may push the peg into the hole. However, this is often impossible to achieve. Imagine the hole is slightly off such that the centerline of the hole and the peg are a small distance apart, as in Figure 8.25(b).

If the robot is in position-control mode, it will attempt to push the peg into the hole even if there is a misalignment. As a result, either the robot or the part will deflect or break. A stiffer robot, a sign of a "good" robot, worsens this problem. If the robot has some compliance, it is actually possible to cut a chamfer (Figure 8.25(c)) around the hole (or the peg, or both) to allow the robot to move laterally to align itself with the hole and prevent deflections or breakage. Alternately, it is possible to allow the part to move to align itself with the robot.

Now assume that instead of an axial misalignment, there is an angular (cocking) misalignment between the two centerlines (as in Figure 8.25(d)). In this case, even if the peg and the hole are exactly aligned at the mouth of the hole, if the peg is pushed in, one of the two will have to either deflect or break, unless one is allowed to move. However, a compliant robot that "gives" enough to prevent breakage will probably have unacceptable accuracy.

Imagine that in order to resolve these problems, a spring is used to connect the end effector to the robot wrist. In this case, the misalignment can be overcome, but the compliant connection between the robot and the part does not allow insertion of the peg into the hole; the spring simply compresses instead. Therefore, a device is needed that can provide selective compliance to the end effector to allow the robot to correct itself in directions where correction is needed but without affecting its accuracy in other directions. A remote center compliance device provides this selective compliance through a simple 4-bar mechanism.

To understand how the RCC device works, consider a simple 4-bar mechanism as shown in Figure 8.26. In a mechanism, there are a total of $M = n \times (n-1)/2$ instantaneous centers of zero velocity, where n is the number of links, including the ground. Each instantaneous center of zero velocity is a point where the instantaneous velocity of one body *relative* to another is zero. In a 4-bar mechanism, there will be a total

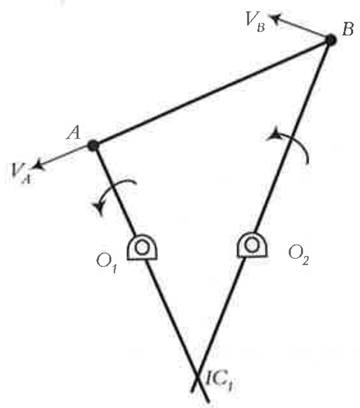

Figure 8.26 Instantaneous centers of zero velocity for a 4-bar mechanism.

of six such centers. Each of the two pin joints O_1 and O_2 attached to the ground is a center of rotation for the two links attached to the ground. The other two pin joints A and B are centers of rotation (or zero velocity) of the coupler AB relative to links O_1A and O_2B, and vice versa. However, in addition to these, there are two more centers of instantaneous zero velocity, one between the ground and the coupler and one between the two links O_1A and O_2B.

To find the instantaneous center of zero velocity for the coupler (in which we are interested for this subject), we need to find the velocities of two arbitrary points on it. The instantaneous center of zero velocity for the coupler will be at the intersection of two lines perpendicular to the velocities of the two points on the coupler, such as points A and B. This is true because, since $\bar{V} = \bar{\omega} \times \bar{\rho}$, the velocity of any point is normal to its radius of curvature $\bar{\rho}$. As a result, the instantaneous center of zero velocity must be somewhere on the normal-to-velocity line (which is along the length of each link), where two such lines intersect. Since this point has a zero instantaneous velocity, it means that at this instant, it is not moving, and consequently, the body *must* be rotating about it. Therefore, at the instant shown, the coupler link AB is rotating about point IC_1. This point will be at another location in the next instant, and as a result, its acceleration cannot be zero.

Now consider a parallelogram 4-bar mechanism as shown in Figure 8.27(a). Since the two normals to the two velocities at A and B are parallel, the instantaneous center of zero

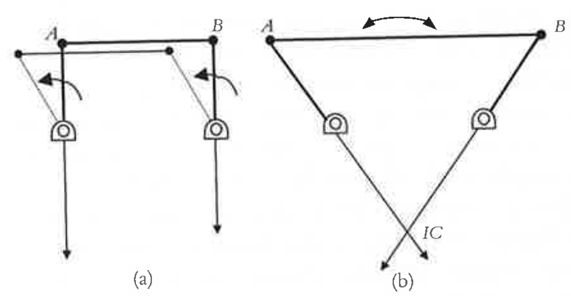

Figure 8.27 Special 4-bar mechanisms, the basis for a remote-center compliance device.

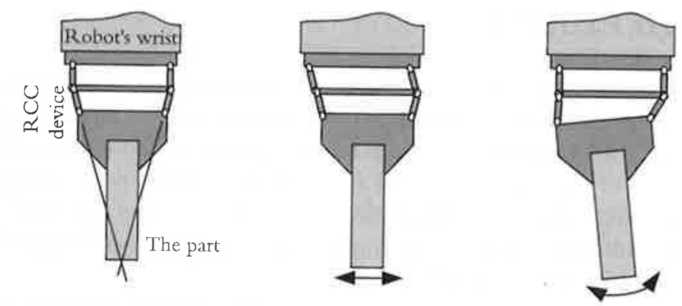

Figure 8.28 Schematic depiction of how an RCC device operates.

velocity for the coupler will be at infinity, indicating that the coupler is not rotating but is in pure translation. This means that the coupler will always translate to the left or right without any rotation (although its motion is curvilinear). Figure 8.27(b) shows a 4-bar mechanism with two links of equal lengths and the instantaneous center of zero velocity for its coupler which allows an instantaneous rotation of the coupler link about the IC. These two mechanisms can provide simple translation or rotation about a remote center when needed. An RCC device is a combination of these two mechanisms such that when needed, it can provide slight translation or rotation of the object about a distant point (therefore remote-center compliance). The distant point is the point of contact between the two parts, such as the peg and the hole, which is remote from the robot. However, you realize that this compliance is only lateral (or angular), where it is needed. The robot is still axially stiff, since the mechanism does not provide any motion in the direction normal to the coupler. As a result, it provides a selective compliance in the direction needed, without reducing the robot's stiffness, and consequently, its accuracy.

Figure 8.28 is a schematic drawing of how an RCC device works. In reality, each device provides a certain stiffness (or compliance) in lateral and axial directions, or in bending and cocking directions, and must be picked based on need. Each device also has a given center-to-center distance, which determines its remote center location relative to the center of the device. Therefore, there may be a need for multiple RCC devices if more than one part or operation is performed, and it must be picked accordingly.[20] Figure 8.29 shows a commercial RCC device.

Figure 8.29 A commercial RCC device. (Printed with permission from ATI Industrial Automation Corporation.)

8.20 Design Project

At this point, you may want to incorporate into your robots as many sensors as you want or have available to you. Some of the sensors will be necessary for feedback, which are essential if you are to control the robots. Others are added based on need and availability. This is a very interesting part of any robotic project. You may experiment with different sensors for different applications—and even come up with your own. You may experiment with other sensors that have not been mentioned here but are available from electronic warehouses.

Similarly, you may integrate sensors to the rolling-cylinder or sphere robot rovers for control and added intelligence. For example, visible light and infrared sensors located in the center of their platform will allow you to communicate with the rover by projecting a visible or infrared light beam through the gap between the cylinders. Similarly, you may route a sensor's wires through the central shaft of the robot and connect to the microprocessor. This way, without the need for slip-rings, you can have sensors outside of the robots. Proximity sensors and range finders can also be used to determine proximity or distance to walls and other obstacles and for navigating in different environments.

Summary

In this chapter, we discussed a variety of different sensors used in conjunction with robots and robotic applications. Some of these sensors are used for internal feedback. Others are used for communication between the robot and the environment. Some sensors are easy to use and inexpensive while others are expensive, difficult to use, and require a lot of support circuitry. Each sensor has its own advantages and disadvantages. As an example, an incremental encoder can provide simple, digital, position, and velocity information with minimum input requirements. However, the absolute position cannot be measured with it. An absolute encoder provides absolute position information in digital form but requires many lines of input that may not be available. A potentiometer can also provide absolute position information, is very simple to use, and is very inexpensive, but its output is in analog form and must be digitized before a microprocessor can use it. However, in some applications, an encoder and a potentiometer are used together, one to report the absolute position at wake-up and one to accurately report the changes in the position. Together, they provide all the information needed to run the system. It is the role of the design engineer to decide what type of sensor is needed or is best suited for a particular application.

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