Part III

Automatic Control in Manufacturing

Automatic control in manufacturing refers to forcing a device or a system achieve a desired output in an autonomous manner through intelligent instrumentation. Control is carried out at multiple levels and at different modes. At the lowest level, the control of individual devices for the successful execution of their required individual tasks is achieved in the continuous-time domain. At one level above, the control of a system (e.g., a multidevice manufacturing workcell), for the correct routing of parts within it, is achieved in an event-based control mode. In both cases, however, automatic control relies on accurate and repeatable feedback received from individual device controllers and a variety of sensors.

In Chap. 13, the focus is on the description of various sensors that can be used for automatic control in manufacturing environments. A brief generic introduction to the control of devices in the continuous-time domain precedes the discussion of various pertinent analog- and digital-transducer based sensors (e.g., motion sensors, force sensors). Machine vision for two-dimensional image analysis is also addressed in this chapter. A variety of actuators are described in the conclusion of the chapter as the "executioners" of closed-loop control systems.

In reprogrammable flexible manufacturing, it is envisaged that individual machines carry out their assigned tasks with minimal operator intervention. Such automatic device control normally refers to forcing a servomechanism to achieve (or yield) a desired output parameter value in the continuous-time domain. In Chap. 14, our focus will thus be on the automatic control of two representative classes of production and assembly machines: material removal machine tools and industrial robotic manipulators. For the former class of machines, numerical control (NC) has been the norm for the control of the movement of the cutting tool and/or the workpiece since the early 1960s. In this context, issues such as motion trajectory interpolation, *g*-code programming, and adaptive control will be discussed in this chapter.

The planning and control of the motion of industrial robots will also be discussed in Chap. 14. Robotic manipulators can be considered the most complex assembly devices in existence. Thus solutions valid for their control would be applicable to other assembly machines. Regardless of their geometry classification (serial or parallel), industrial robotic manipulators carry out tasks that require their end effector (gripper or specialized tool) to move in point-to-point or continuous-path mode, just as do NC machine tools. Unlike NC motion interpolation for machining, however, trajectory planning for industrial robots is a complex matter owing to the dynamics of open-chain manipulators moving payloads in three-dimensional Cartesian space subject to gravitational, centrifugal, and inertial forces. In this context, the following issues are discussed in Chap. 14: robot kinematics/dynamics, trajectory planning and control, and motion programming.

In a typical large manufacturing enterprise, there may be a number of flexible manufacturing systems (FMSs) each comprising, in turn, a number of flexible manufacturing workcells (FMCs). An FMC is a collection of production/assembly machines, commonly configured for the manufacturing of families of parts with similar processing requirements, under the control of a host supervisor. The focus of Chap. 15 is thus the autonomous supervisory control of parts, flow within networked FMCs; in contrast to time-driven (continuous-variable) control of the individual devices in a FMC, the supervisory control of the FMC itself is event driven.

There are three interested parties to the FMC-control problem: users, industrial controller developers, and academic researchers. The users have been always interested in controllers that will improve productivity, in response to which industrial controller vendors have almost exclusively relied on the marketing of programmable logic controllers (PLCs). The academic community, on the other hand, has spent the past two decades developing effective control theories that are suitable for the supervisory control of manufacturing systems. In Chap. 15, we will thus first address two of the most successful discrete-event system control theories developed by the academic community: Ramadge-Wonham automata theory and Petri-nets theory. The description of PLCs, used for the autonomous DES-based supervisory control of parts flow in FMCs, will conclude this chapter.

Quality control refers to the establishment of closed-loop control processes capable of measuring conformance (as compared to desired metrics) and varying production parameters, when necessary, to maintain steady-state control. The final manufacturing issue thus addressed in this part of the book, in Chap. 16, is quality control with specific emphasis on on-line statistical control (versus postprocess sampling). Quality management strategies and measurement technologies targeted specifically to quality control are addressed in Chap. 16 as a preamble to a discussion on common statistical tools, such as statistical process control. A brief discussion of ISO 9000 is also presented in this chapter.

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Instrumentation for Manufacturing Control

In flexible manufacturing systems (FMSs), control is carried out on multiple levels and in different modes. On the lowest level, our interest is in the control of individual devices (e.g., milling machine, industrial robot) for the successful execution of their required individual tasks. One level above, our concern would be with the control of a collection of devices working in concert with each other [e.g., a multidevice flexible manufacturing workcell (FMC)]. Here, the primary objective is the sequencing of tasks through the correct control of part flow. In both cases, however, automatic control relies on accurate and repeatable feedback, in regard to the output of these processes, achieved through intelligent instrumentation.

Automatic device control normally refers to forcing a servomechanism to achieve (or yield) a desired output parameter value in the continuous-time domain. Requiring a milling machine to cut through a desired workpiece contour is a typical manufacturing example. Motion sensors measuring the displacement and speed of the individual axes of the milling machine table provide the closed-loop control system with necessary feedback about the process output. Automatic supervisory control of FMCs, on the other hand, means forcing the system to behave within legal bounds of task sequencing based on observable events that occur within the system. This type of event-based control is primarily achieved based on feedback information received from individual device controllers and device-independent (workcell) sensors.

The principal element of any sensor is the transducer—a device that converts one form of energy into another (e.g., light into electrical current). The combination of a transducer and a number of signal-conditioning and processing elements forms a sensor. In this chapter, the focus is on the description of various sensors that can be used for automatic control in manufacturing environments. A brief generic introduction to the control of devices in the continuous-time domain will precede the discussion of various pertinent manufacturing sensors. The control of machine tools and robots will be discussed in greater detail in Chap. 14; an in-depth discussion of event-based manufacturing system control is presented in Chap. 15. Quality control issues will be addressed in Chap. 16.

13.1 PROCESS CONTROL AND CONTROLLERS

Closed-loop (feedback) control continuously adjusts the variable parameters of a process in order to yield an output of desired value. As shown Fig. 1, the actual output parameter value, *c*, is measured via a sensor and fed back to a comparator (summing junction) for the computation of the error, *e*, with respect to the desired output value, *r*. Based on this error value, $e = r - c$, a controller decides on an appropriate corrective action and instructs an actuator (or multiple ones) to carry out this response.

For a dynamic process, all process variables would be functions of time, where the primary objective of the control system is to reduce the output error to as close as possible to zero in the fastest manner. Although different controller designs will achieve this objective in varying transient-response ways, all must thrive to yield stable systems with minimum steady-state errors.

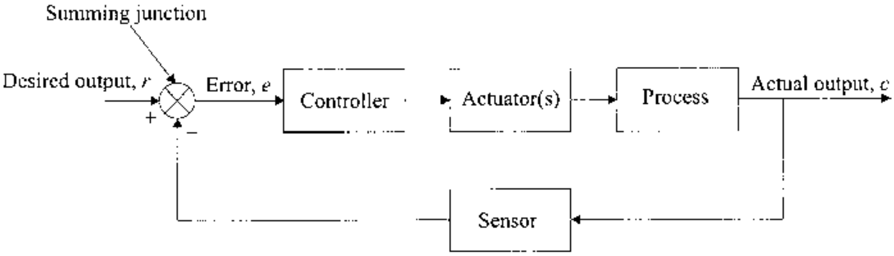


FIGURE 1 Closed-loop control block diagram.

Controllers have often been classified as analog versus digital. Analog systems are, naturally, more prone to electronic noise than their digital counterparts which utilize analog-to-digital-to-analog (AD/DA) converters for analog inputs/outputs.

In digital control, the digital processor (a computer) can be used in two different configurations:

Supervisory control: A microprocessor (computer) is utilized as a (digital) monitoring device and provides the control system with new desired output values (Fig. 2a). The control is still analog in nature. The microprocessor can be used to control several systems.

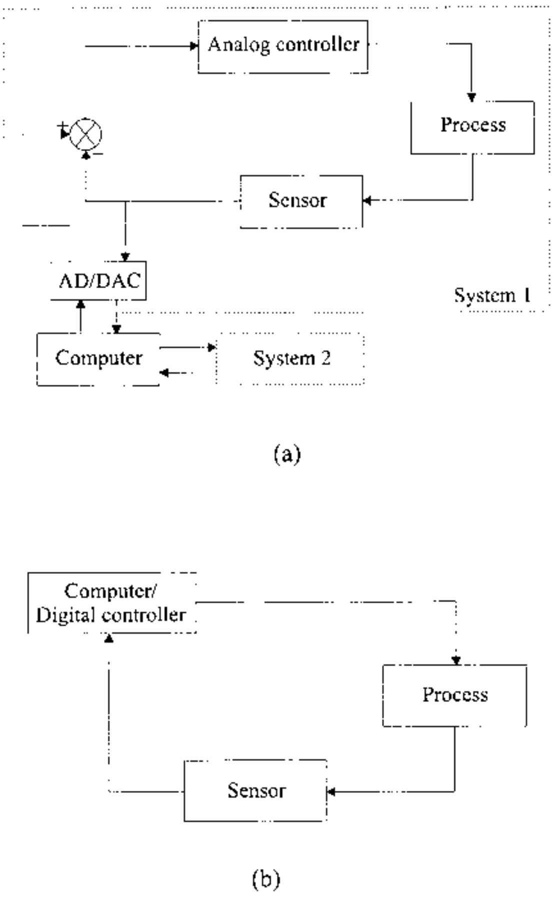


FIGURE 2 Digital control: (a) supervisory; (b) direct.

Direct control: A microprocessor replaces completely the analog controller and the comparator as the sole control device. All (computer) inputs and outputs are digital in nature (Fig. 2b).

13.1.1 Controller Modes

Continuous controllers manipulate the (input) error signal for the generation of an output signal in several different modes, most commonly relying on proportionality:

Proportional-integral (PI) control: This composite control mode uses the following typical expression for determining the output signal value, p:

$$p = K_p e + K_p K_i \int_0^t e\,dt + P_o \tag{13.1}$$

where K_p and K_i are the proportional and integral gains, respectively, and p_o is the controller output with no error. The integral mode of the composite signal eliminates the inherent offset (residual error) that would have been produced by the proportional mode of control. PI controllers may yield large overshoots owing to integration time.

Proportional-derivative (PD) control: This composite control mode utilizes a cascade form of the two individual proportional and derivative control modes:

$$p = K_p e + K_p K_d \frac{de}{dt} + p_o \tag{13.2}$$

where K_d is the derivative gain. The derivative mode of a composite controller responds to changes in the error (the rate of change)—it is a predictive action generator.

Proportional-integral-derivative (PID) control: This three-mode composite controller is the most commonly used controller for industrial processes:

$$p = K_p e + K_p K_i \int_0^t e\,dt + K_p K_d \frac{de}{dt} + p_o \tag{13.3}$$

13.1.2 Controllers

Electronic analog controllers that use analog (current) signals are commonly employed in the automatic control of manufacturing devices. Op-amp circuits form the backbone of these controllers. Error signals are computed by measuring voltage differences and used for determining the output current signal of the controller, where gains are defined by specific resistor and capacitor values.

Digital controllers are computers that are capable to interact with external devices via I/O interfaces and AD/DA converters. Their reprogrammability with appropriate software greatly enhances their usability for automatic control. The primary advantages of using digital controllers include ease of interface to peripheral equipment (e.g., data storage devices), fast retrieval and processing of information, capability of using complex control laws, and transmission of noiseless signals.

13.2 MOTION SENSORS

Motion control is of primary interest for the majority of manufacturing processes: automatic control of a milling operation requires precise knowledge of the motion of the table, on which the workpiece is mounted; industrial robots need to know the exact location of a workpiece prior to its grasping; and so on. Motion sensors can provide the motion controllers of such manufacturing equipment with displacement, velocity, and acceleration measurements. Mostly, they carry out their measurement tasks without being in contact with the object.

Motion sensors use a variety of transducers that yield analog output signals. Electromagnetic, electro-optical, and ultrasonic transducers are the most common ones and will be discussed individually below. Some digital transducers will also be presented in this section.

13.2.1 Electromagnetic Transducers

The majority of electromagnetic-transducer-based noncontact sensors are used in manufacturing environments as detectors of presence, as opposed to absolute or relative measurement of motion, owing to their low-precision yield. Such sensors, although frequently called proximity (i.e., distance and orientation) sensors, simply detect the presence of an object in their close vicinity. Some exemplary sensors are briefly described below:

Potentiometers: Resistive-transducer-based contact displacement sensors are often referred to as potentiometers, or as pots. The transducer of a potentiometer, a wire or a film, converts mechanical displacement into voltage owing to the changing resistance of the transducer (Fig. 3).

Potentiometers can be configured to measure linear or rotary displacements. In both cases, however, owing to their contact mode, they add inertia and load (friction) to the moving object whose displacement they are measuring.

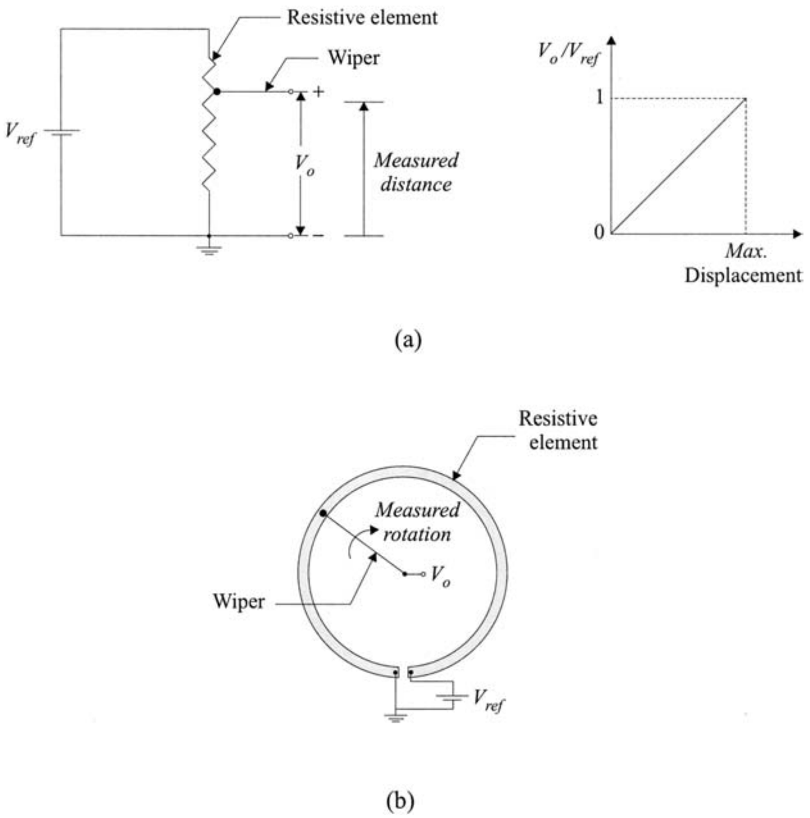


FIGURE 3 Resistive transducers for (a) linear; (b) rotary motions.

LVDT: The linear variable-differential transformer (LVDT) is a passive inductive sensor utilized for the contact measurement of linear displacement. This variable-reluctance transducer comprises a moving core that varies the magnetic flux coupling between two or more coils (Fig. 4). When the core is placed in the center, the output voltage is zero since the secondary voltages are equal and cancel each other. As the core is displaced in one direction or another, a larger voltage is induced in one or the other secondary coil, thus producing a voltage differential as a function of core displacement.

There also exist rotary variable-differential transformers (RVDTs) for rotational displacement measurements.

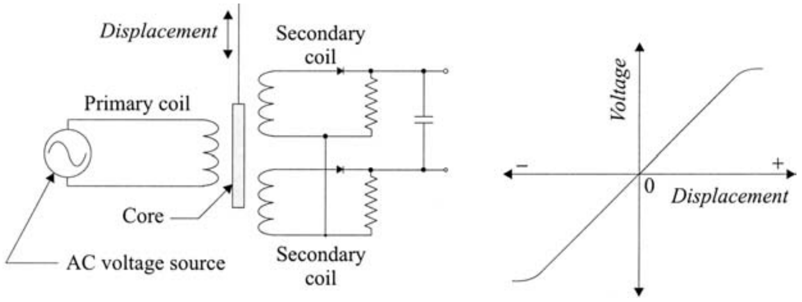


FIGURE 4 Linear variable-differential transformer.

Transverse inductive sensors: Inductive transducers can be configured to act as proximity or presence detection sensors, when only one coil is used. The flux generated by the coil is disturbed by a magnetic object in the close vicinity of the transducer (10 to 15 mm) (Fig. 5). Although the displacement of the object can be related to the amount of flux change, such sensors are rarely used for absolute (precision) measurements of displacement.

Capacitive sensors: Variations in capacitance can be achieved by varying the distance between the two plates of a flat capacitor. In capacitance displacement sensors for conducting material objects, the surface of the object forms one plate, while the transducer forms the other plate

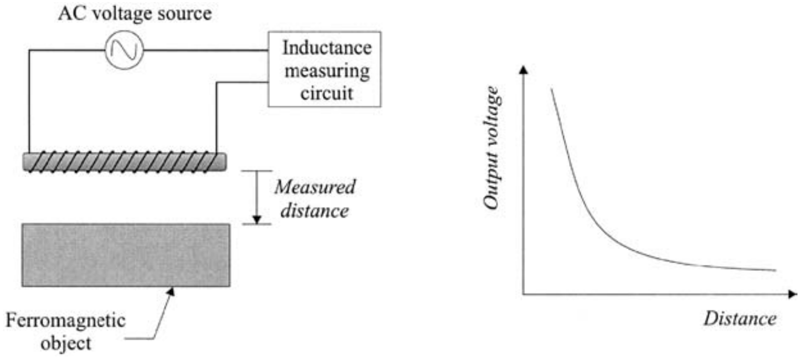


FIGURE 5 Inductive proximity sensor.

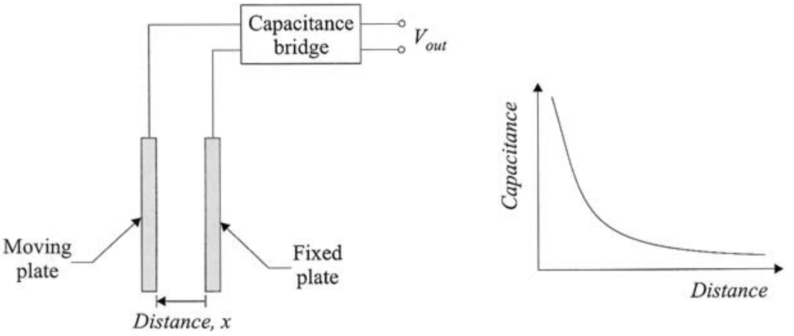


FIGURE 6 Capacitive sensors.

(Fig. 6). For dielectric objects, the capacitive sensor would have two live electrodes—the object does not need to be part of the sensing system (also called fringing capacitance).

As with transverse inductive sensors, the precise measurement of absolute motion is a difficult task for capacitive sensors. Thus they are commonly used only for the detection of the presence of conductive or dielectric objects close to the sensor (up to 30 to 40 mm).

13.2.2 Electro-Optical Transducers

Electro-optical-transducer-based sensors developed over the past three decades allow noncontact displacement measurement of the highest possible precision—for example, less than half a light wavelength for interferometers. Such sensors are also often used in the manufacturing industry for simply checking for the presence of an object. The common principle of all electro-optical sensors is the controlled emission of light, its reflection from the surface of an object, and the analysis and interpretation of the reflected light for absolute or relative position and, in some instances, orientation measurements.

Light Sources

The majority of electro-optical sensing devices in manufacturing utilize coherent or noncoherent light in the infrared range (0.76 to 100 μm wavelength). In some applications, the utilization of light in the visible range (0.4 to 0.76 μm wavelength) might be sufficient. Typical light sources include incandescent lamps, solid-state lasers, and light-emitting diodes (LEDs), the last developed in the early 1960s. LEDs are transducers that convert electrical current into light—namely, the opposite of light-detecting transducers.

Light Detectors

There are a variety of electro-optical transducers that can detect electromagnetic radiation based on the interaction of photons with semiconductor materials. These devices are often called photodetectors:

Photodiodes: These detectors operate in two distinct modes, photoconductive and photovoltaic. In the former mode, radiation causes change in the conductivity of the semiconductor material in terms of change in resistance. Photovoltaic detectors, on the other hand, generate a voltage proportional to the input light intensity. Photodiodes' primary advantage is their fast response time (as low as a few nanoseconds).

Phototransistors: These detectors produce electrical current proportional to input light intensity. Phototransistors provide higher sensitivity (i.e., higher current) than do photodiodes but operate at much lower response times (milliseconds versus nanoseconds).

Optical Fibers

Optical fibers allow remote placement of sensors that employ electro-optical transducers, as well as access to hard-to-reach places. They can be either plastic or glass and are normally protected by a cladding layer against potential damage and/or excessive bending. Fiber-optic cables can be easily coupled to light-emitting or light-receiving diodes—that is, they can be used to collect light reflected from a surface (normally, within a 20 to 30° cone) as well as emit coherent or noncoherent light onto desired surfaces.

Amplitude Modulation Proximity Sensors

In amplitude modulation electro-optical sensors, the magnitude of the light reflected from a surface can be utilized to determine the distance and orientation of the object. Such sensors usually comprise one light source and several photodetectors. Many utilize plastic optical fibers (typically, having a 0.3 to 2 mm core size) to reflect and collect light from objects' surfaces (Fig. 7a). The intensity of the light reflected from the surface is not a monotonic function of the distance. Thus the minimum operating distance of the transducer ($x_{\min}$) is usually limited to a value that will guarantee a monotonic response (Fig. 7b).

For the measurement of surface orientation, a symmetrical three-fiber constellation can be used (Fig. 8a). In this configuration, the emitter is at the center and the two receivers are positioned symmetrically on either side. The light intensities detected by the receivers of this sensor, as a function of the surface orientation, are shown in Fig. 8b.

One must note that, although orientation measurements are not affected by variations in distance due to the normalization effect by the

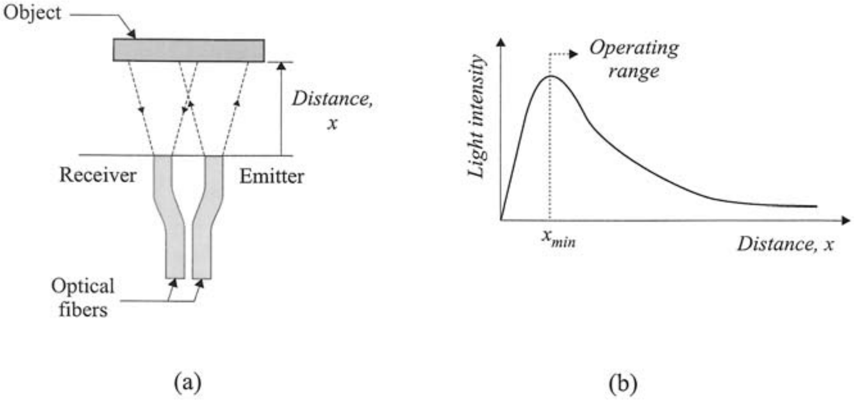


FIGURE 7 (a) Y-guide transducer; (b) Y-guide response for distance measurement.

symmetrical receivers, distance measurements are significantly affected by the orientation of the surface. Accordingly, in proximity sensing, an object's surface orientation is first estimated and subsequently the distance is determined. The accuracies of the measured distance and the orientation angle can be further improved by an iterative process.

A primary disadvantage common to all amplitude-modulation sensors is their dependence on the material of the object's surface. All distance/orientation versus light-intensity relationships must be calibrated with respect to the specific objects at hand.

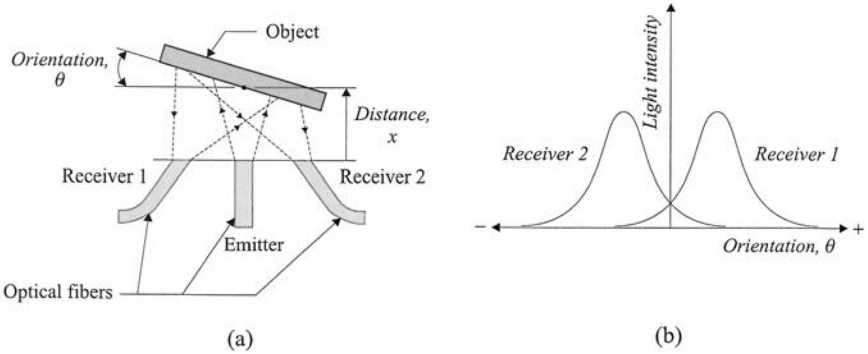


FIGURE 8 (a) Typical receiver pair constellation for orientation measurements; (b) the light intensity detected by each receiver as a function of orientation (θ).

Phase Modulation Proximity Sensors

A phase modulation proximity sensor usually comprises two light sources and one or more photodetectors. The light sources are driven by modulated sinusoidal signals having a 90° phase relationship (Fig. 9). The signal detected by the receiver is a superposition of the two reflected signals. The signal attenuation is a function of the geometrical and electrical parameters of the sensor, the reflectivity characteristics of the object's surface, and the surface's distance and orientation with respect to the sensor.

Triangulation Proximity Sensors

Triangulation proximity sensors can be used to determine the position of an object by examining the geometrical attributes of the reflected and incident light beams. In its basic configuration, a triangulation sensor comprises a laser light source and a linear array of photodetectors (Fig. 10). A narrow light beam reflected from the object's surface is detected by several of these detectors; the one detector that receives the maximum light intensity is considered as the vertex of the base of the triangle shown in Fig. 10. The geometry of the ray trajectory, then, provides the basic information for the estimation of the object's distance (x).

It is accepted that a triangulation sensor has the following properties:

The influence of irregularities, reflectivity, and orientation of the object is negligible.

The distance measurement is not affected by illumination from the environment and luminance of the object. Their influence is eliminated by comparison of two sensor signals obtained in successive on-and-off states of the light source.

The sensor's physical configuration can be sufficiently small for use in manufacturing applications.

Interferometers

All the above-mentioned electro-optical sensors can be configured to provide highly repeatable measurements, though the precision of measurements is inversely proportional to the operational range of these sensors. There are commercial sensors that can provide 2 to 5 μm precision, whose range, however, is less than 10 to 15 mm. Increased operational ranges would come at the expense of measurement precision (e.g., 10 to 20 μm precision for a 50 to 100 mm range). Laser interferometers capable of providing distance measurements with less than half a wavelength precision are thus the preferred choice of electro-optical sensors for high-precision applications (e.g., milling machines).

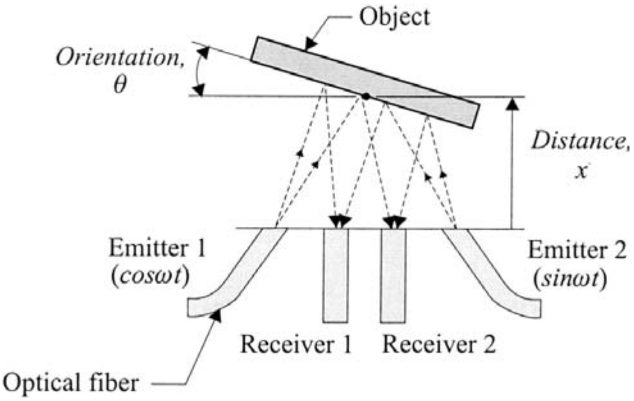


FIGURE 9 The basic phase modulation proximity sensor configuration.

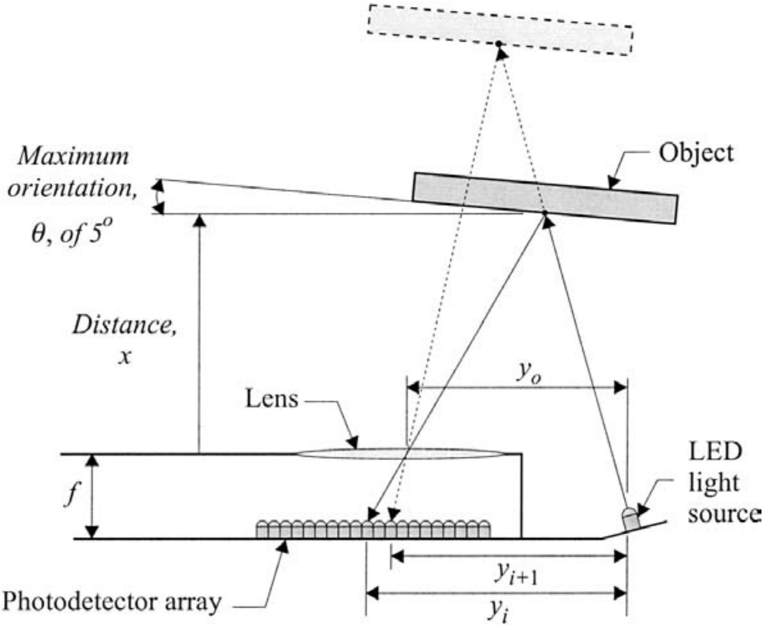


FIGURE 10 Basic principle of a triangulation sensor for measuring distance.

Interference of two light beams separated by a phase of 180° yields a total black fringe. Interferometers utilize this principle by superimposing two light beams, one reflected from a fixed mirror and one from the surface of a moving object, and count the fringes to determine the distance traveled by the object (Fig. 11). The distance traveled by the object is measured as a multiple of half wavelengths of the light source used. Modern interferometers can measure relative phase changes in a light wave to a precision of as a low as 1/52nd of the wavelength.

Nonproximity Sensors

LEDs and photodetectors can be arranged into a variety of configurations for the detection of presences of objects, finding their edges, etc. (Fig. 12). These sensors do not attempt to find the distance or orientation of the object's detected surface or its edges.

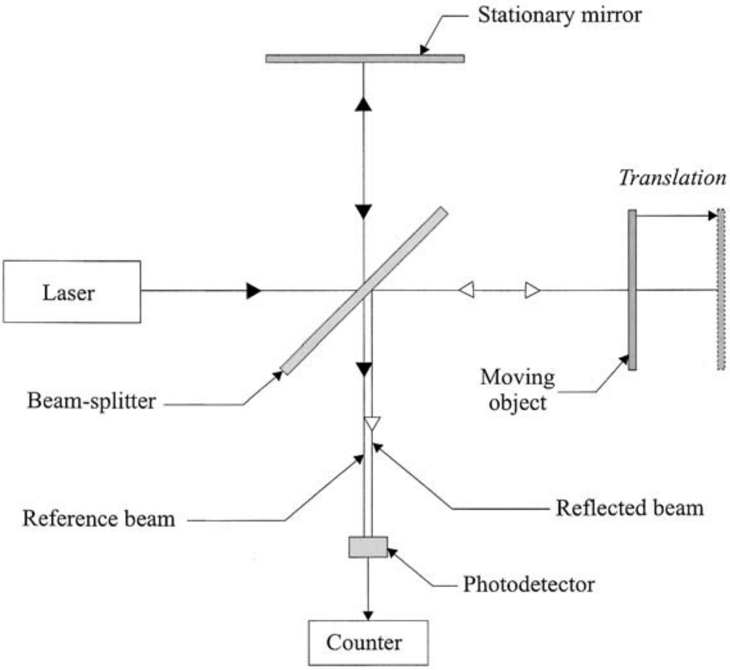


FIGURE 11 Interferometry.

13.2.3 Ultrasonic Transducers

Ultrasonic transducers can be configured using several emitters and receivers to measure the relative proximity of an object's surface. Acoustic waves above the 20 kHz range are labeled as ultrasonic—beyond the capability of humans to perceive. In industrial settings, ultrasonic transducers can emit acoustic waves with a frequency of as high as 200 kHz, and they can be used both as emitters and as receivers.

There are several time-of-flight methods for distance measurements:

Pulse-echo: The time elapsed from the emission of an ultrasonic acoustic pulse to the reception of the returned echo (reflection from the object's surface) can be utilized to calculate distance, when one logically assumes a constant signal velocity over relatively short distances (less than a few meters) (Fig. 13).

Phase-angle: The phase angle between emitted and received acoustic waves can be used to measure a distance normally less than the length of the ultrasonic wave.

Frequency modulation: Frequency modulated signals reflected from an object's surface, with no change in signal shape, except for the frequency shift, can be utilized accurately to calculate distance.

Piezoelectric transducers, which convert mechanical displacement into electrical current and vice versa, are the most commonly used devices in ultrasonic sensors. Ceramics and some polymers can be polarized to act as natural piezoelectric materials (e.g., natural crystals). Other ultrasonic transducers include electrostatic (i.e., plate capacitors with one free and one fixed plate), magneto-restrictive (based on dimensional changes of ferromagnetic rods), and electromagnetic (e.g., loudspeakers and microphones).

In some cases, ultrasonic transducers can also be utilized to detect the presence of objects that could not be achieved with electromagnetic or electro-optical sensors owing to large distances and reflectivity problems.

13.2.4 Digital Transducers

Transducers that output data in digital form, as discrete pulses or coded information, are classified as digital transducers. Such sensors' output can be directly interpreted by microprocessor-based controllers (with no need for analog-to-digital data conversion). Digital counters must be utilized when the output signal is in pulse form.

In this section, our focus will be on two popular digital transducers, encoders and tachometers, for displacement and velocity measurements, respectively.

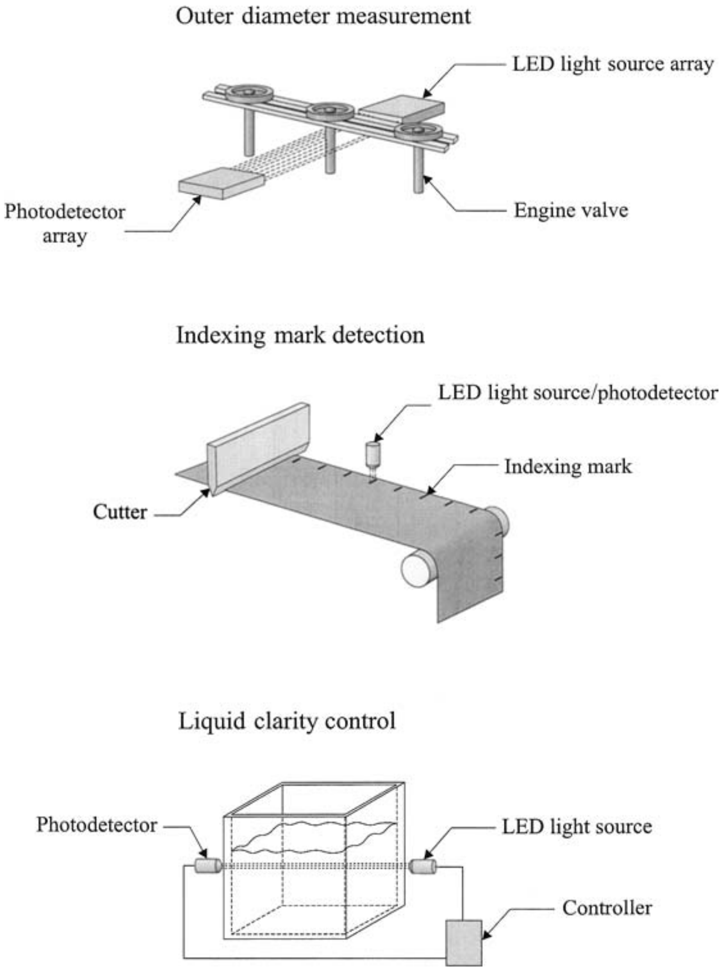


FIGURE 12 Some industrial applications of electro-optical proximity sensors.

Encoders

Digital encoders can be configured to measure linear or rotary displacement. They utilize physical contact, magnetic disturbance or optics for the detection of movement. Optical encoders are most commonly used owing to their high-accuracy manufacturability. They can be in incremental form (pulsed information) or absolute form (coded information). All, however,

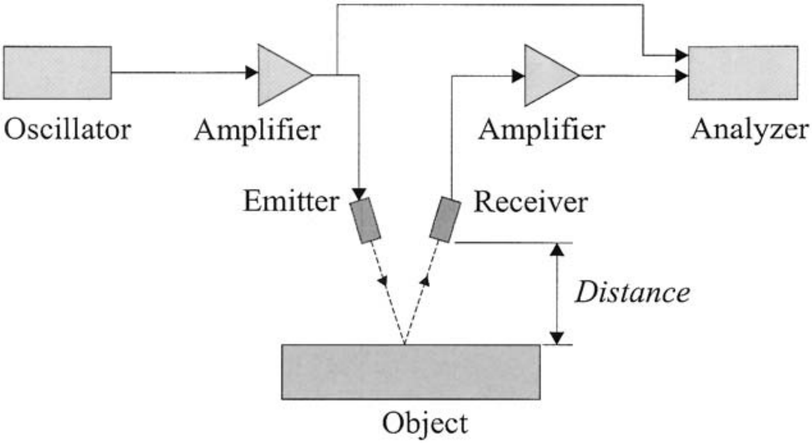


FIGURE 13 Ultrasonic sensor.

comprise two basic components: a marked grating (scale) component and a detection system.

Rotary encoders employ a disk-shape grating device with radial markings (also called "shaft encoders"), while in linear encoders the (linear) scale comprises one or more sets of parallel lines. The former will be discussed first because of their use in almost all motion-control systems (linear or rotary motion).

Optical rotary encoders use one of three methods to detect the motion of the (grating) disk:

Geometric masking is based on allowing light to pass through unmasked slits (grating) and be detected by photodetectors on the other side of the disk (Fig. 14).

Moiré fringes are generated by employing two disks with similar periodic patterns in (rotary) motion with respect to each other.

Diffraction effects, due to coherent light passing through a pattern of slits (a few wavelengths wide), can be utilized for very-high-precision encoding.

Figure 15 illustrates the basic principle of the incremental quadrature rotary encoder with four distinct outputs, $n = 4$. Two photodetectors are placed one half slit-width apart, thus detecting the rotary motion of the outer ring with a 90° phase, while a third detector registers a reference signal per each revolution of the disk by noting a reference slit on an inner

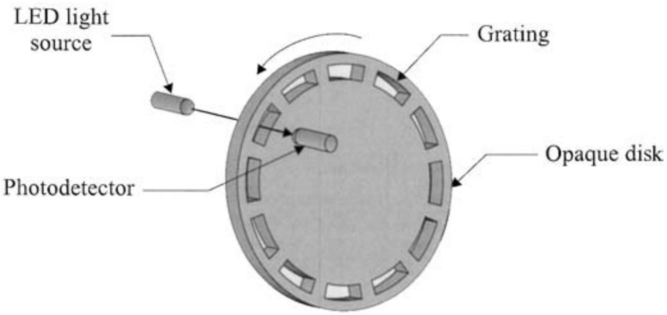


FIGURE 14 Geometric masking for rotary encoding.

track on the disk. A counter counts the number of slits detected for relative displacement calculations.

Figure 16 shows the basic principle of an absolute encoder with four rings, yielding sixteen distinct outputs, $n = 16$, employing the Gray coding scheme (versus the binary coding scheme) (Table 1). The use of the Gray code allows transition of only one bit of data between two consecutive sector numbers, thus minimizing ambiguity and requiring simpler electronics. Each of the four tracks (rings) is monitored by a separate photodetector as in the case of incremental encoders.

Optical linear encoders are normally of incremental form and utilize geometric masking as the encoding technique. Some commercial linear encoders also utilize the principles of diffraction for higher resolution measurements.

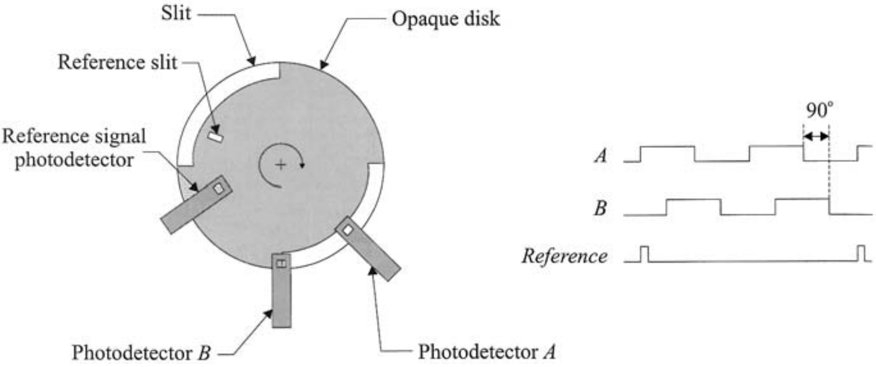


FIGURE 15 Incremental rotary encoding.

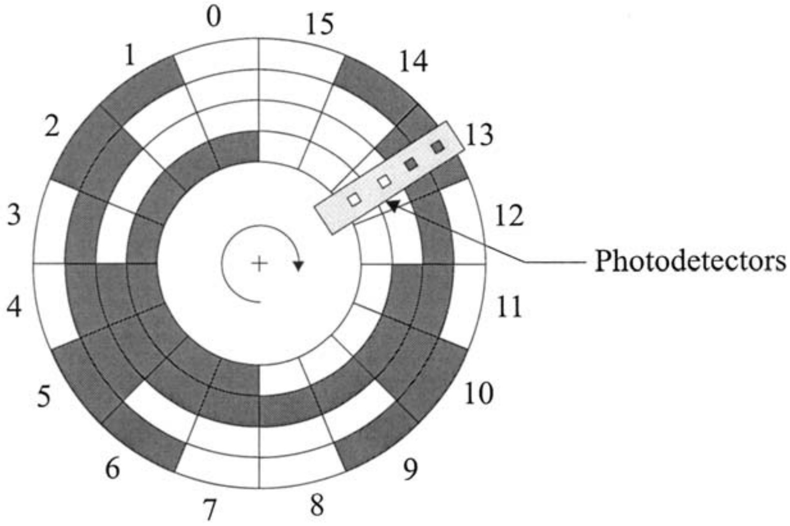


FIGURE 16 Absolute rotary encoding.

Rotary incremental optical encoders can have from fifty thousand up to several millions of steps per revolution, while their absolute counterparts can have from 512 up to 131,072 steps per revolution. Linear encoders can have a resolution from 0.005 μm to 5 μm.

Digital Tachometers

Angular speed can be measured using a tachometer, which is normally considered an analog transducer that converts mechanical energy into electromagnetic energy. A DC tachometer generates a voltage proportional to the speed of a rotating coil coupled to a shaft, whose rotational speed we want to determine. An AC tachometer generates a voltage with a frequency proportional to the rotational speed of a rotor.

Electromagnetic tachometers can also be configured to generate a pulsed-output signal; for example, the rotational speed of a ferromagnetic

TABLE 1 Gray Coding for Four-Bit Words

0	1	2	3	4	...	13	14	15
0111	0110	0100	0101	0001	...	1100	1110	1111

gear would induce pulsed signals as the individual teeth pass in close proximity to a magnetic sensor (Fig. 17a). The frequency of the output voltage is directly proportional to the speed of the gear.

An electro-optical version of a pulsed tachometer is shown in Fig. 17b. This configuration forms the basis of digital tachometers: as in quadrature rotary encoders, a couple of pulsed signals, with a 90° phase shift, are counted for velocity measurement. Based on this principle, one may simply use an encoder for measuring both displacement and velocity.

13.3 FORCE SENSORS

Most manufacturing operations involve direct interactions between a tool and a workpiece. It is expected that the mechanical fabrication device exerts force on a workpiece in a tightly controlled fashion. Instruments for detecting and measuring such interactions are classified as force, torque, and tactile sensors. The most commonly used transducers for these sensors are strain gages, piezoelectric films, piezoresistive films or strips, and capacitive detectors. In this section, our focus will be only on the first three types of transducers.

13.3.1 Strain Gage Transducers

Strain gages, whose resistance changes under deformation, are utilized in the majority of force sensing applications owing to their simplicity. They are manufactured in the form of flat coils bonded onto a nonconducting elastic sheet of paper or plastic. The flat coil is normally a metallic element (e.g.,

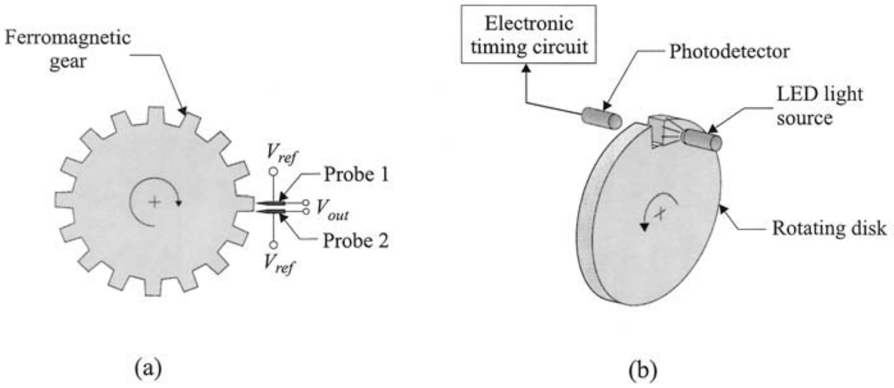


FIGURE 17 (a) Electromagnetic; (b) electro-optical pulsed tachometer.

copper–nickel alloy), though there are strain gages that are semiconductor elements. Strain gages are cemented onto the surface of an object whose strain we want to measure, as part of a bridge type circuitry. During this placement of the strain gages, we must ensure appropriate directionality. Most strain gages are designed to measure strain in one direction, although they can be configured for multidirectional measurement as well (Fig. 18).

Based on the principle of force-inducing strain, which in turn can be measured by strain gages, a large number of force and torque sensors (also known as load cells) have been built and commercialized in the past several decades. The most commonly used load cell is a rigid structure that elastically deforms under applied force. Cantilever-beam type cells are utilized for low-load cases, while ring-shaped cells are designed for large forces (Fig. 19a, 19b, respectively). Load cells placed on torsion members of mechanical devices can also effectively measure torque.

Strain gages have been occasionally used in the construction of tactile sensors for the detection and measurement of distributed forces along a two-dimensional contact surface between an object and the transducer. Such sensors are also capable of detecting and measuring slippage.

13.3.2 Piezoelectric and Piezoresistive Transducers

Piezoelectric materials generate an electric charge when subjected to an external force. The electric charge is collected by a capacitor and used to measure the magnitude of the force. Common piezoelectric materials are quartz crystals, lithium sulphate, lead zirconate titanate, and a number of synthetic materials (e.g., PVF_2).

There are also force-sensitive resistor (FSR) transducers used in the construction of force sensors. These materials, as do strain gages, alter their resistance to electrical current when subjected to an external force.

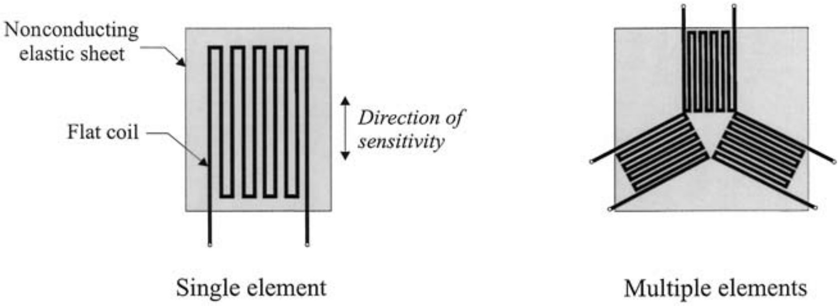


FIGURE 18 Strain gages: single- and multiple-element types.

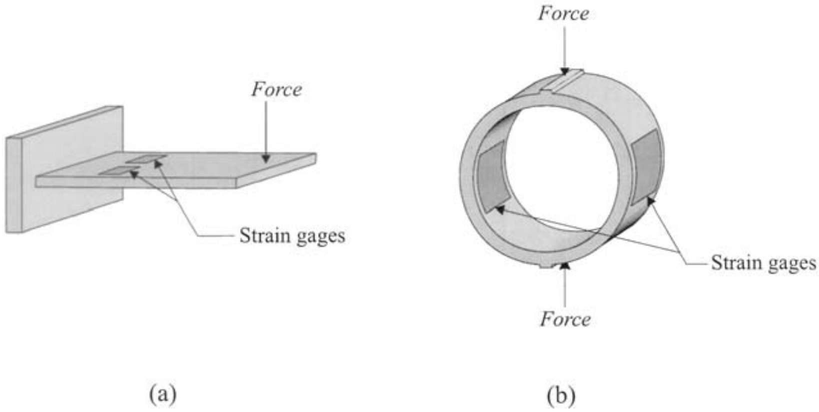


FIGURE 19 (a) Beam type; (b) ring type load cells.

They are fabricated using conductive elastomers such as silicon rubber and polyurethane impregnated with conductive particles/fibers (e.g., carbon powder). FSR-based transducers in the form of (overlapping) thin strings can be formed into a matrix configuration for tactile-sensing applications (Fig. 20).

13.4 MACHINE VISION

Machine vision is defined as the use of optical devices for noncontact acquisition of object/scene images and their automatic analysis for quality-

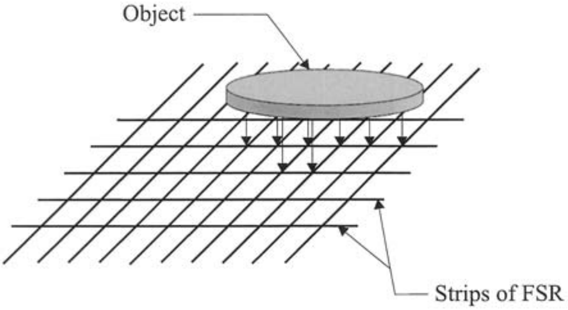


FIGURE 20 A force-sensitive resistive-based tactile sensors.

control or process-control purposes. In contrast to computer vision, targeted for three-dimensional imaging of unstructured environments, machine vision is utilized for two-dimensional imaging of objects in structured environments. Information about three-dimensional objects and/or scenes is interpreted from their two-dimensional images. Although range information can be deduced from multiple images, machine vision is primarily used for object recognition purposes and only in a limited number of cases for positional feedback to device controllers (e.g., position and orientation feedback provided to the controllers of electronic-component placement machines).

Machine vision applications can be traced back to the late 1930s and early 1940s, when analog systems were used in the U.S. for food sorting and inspection of refillable bottles for possible cracks. With the introduction of computers in the late 1950s and early 1960s into manufacturing environments, the utilization of machine vision rapidly expanded. By the early 1970s, several companies started to commercialize machine vision systems for inspection and control purposes. Diffracto, Canada, was one of these first such successful companies. Today, machine vision imaging principles are commonly used in the analysis of internal features of objects using x-ray based computed tomography, ultrasonics, and so on. Image acquisition is no longer restricted to the visible or even infrared wavelength region of the light spectrum.

Typical examples of machine vision use include high-speed bottle/can inspection, solder paste deposition inspection, dimensional verification of body in white in the automotive industry, label inspection, robot guidance in electronic component placement, welding seam tracking and mechanical assembly, and the dimensional measurement of machined parts for in-process control. The fundamental components of every machine vision system used in these and other applications are shown in Fig. 21. They include illumination devices, one or more imaging sensors (cameras) equipped with appropriate optical lenses/filters, image capture devices, and a computer. Image preprocessing/conditioning and image analysis/interpretation are tasks normally carried in software within the computer.

13.4.1 Image Acquisition

Image acquisition is to the capturing of light reflection from an illuminated scene by an electro-optical sensor and conversion of this data into a digital image. Machine vision systems must thus be provided with best possible illumination subsystems for the acquisition of sufficiently illuminated, shadow-free images with maximum contrast.

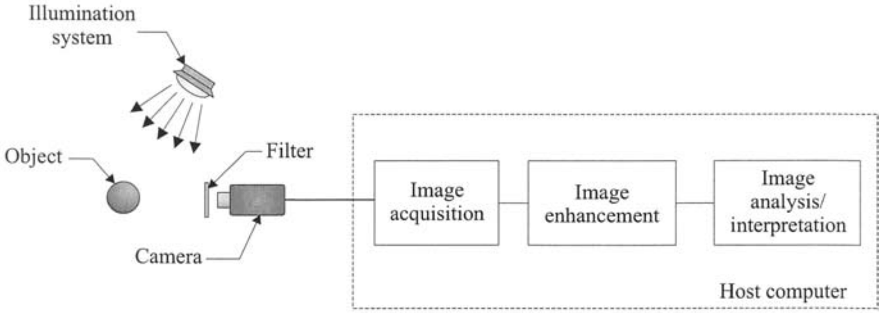


FIGURE 21 Basic machine vision system architecture.

Lighting

A variety of light sources (incandescent, quartz halogen, fluorescent, etc.) can be used to illuminate the scene in the form of diffused or collimated lighting (Fig. 22). The latter form is especially useful for backlighting; that is, providing the imaging sensor with a silhouette of the object. Fiber-optic cables are often used to illuminate hard-to-reach regions. Beam splitting can be also employed in providing an illumination direction in line with the optical axis of the sensing system (i.e., camera) (Fig. 22).

The image of an object is sensed as a mixture of the three primary colors red (R), green (G), and blue (B). All colors can be derived from these primary additive colors by varying their emission intensity (brightness): no light corresponds to black, while white is obtained by proportional mixing of red, green, and blue (Fig. 23a). Although most image sensors are based on the RGB color system, we may also note the existence of an alternative color space that is similar to human perception: hue, saturation, and brightness/intensity (HSB) (Fig. 23b). The hue component describes the color spectrum, the saturation component reflects the purity of the color, and the brightness component describes how close the color is to white (i.e., maximum brightness).

Cameras

Machine vision systems' reliability was significantly increased with the introduction of solid-state imaging sensors in the early 1970s: the charge-coupled device (CCD), charge-injection device (CID), metal-oxide semiconductor (MOS), and so on. CCD-based (matrix and linear) cameras have been the most widely utilized imaging sensors.

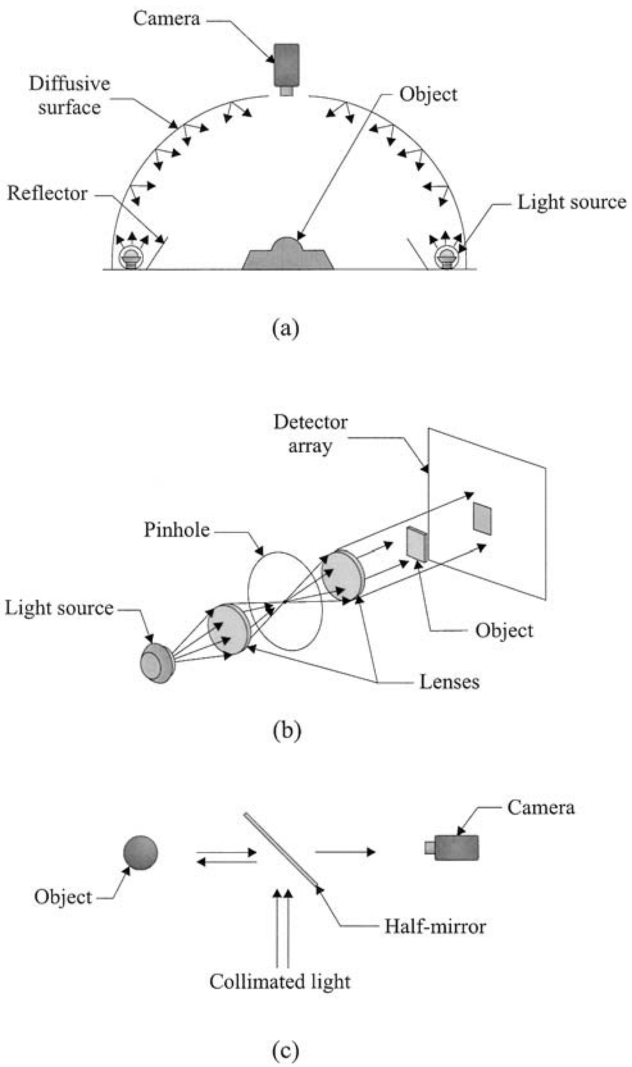


FIGURE 22 (a) Diffused; (b) collimated; (c) in-line lighting.

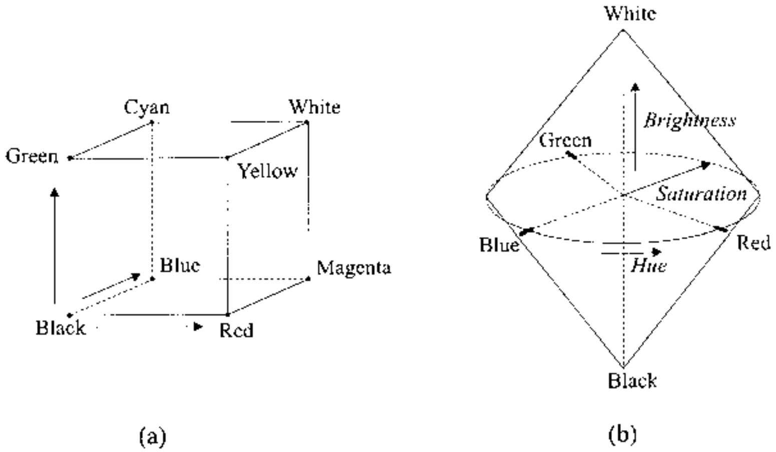


FIGURE 23 (a) RGB; (b) HSB color space.

CCD was invented in 1969 in the Bell Laboratories, U.S.A., by W. S. Boyle and G. E. Smith—a decade before the first CCD color camera was commercialized by Sony. The principle of operation of a CCD imaging sensor involves the following steps: conversion of light energy into electrical charge at discrete sites (pixels), transfer of the packets of charge through the silicon substrate, and conversion of individual charges into voltages by floating diffusion amplifiers.

Frame transfer–based CCDs utilize photogates (photoactive MOS capacitors) as photodetectors, while interline transfer CCDs use photodiodes (coupled to transfer gates) for photodetection and movement of charge. In the former type of CCDs, the whole frame of information is transferred simultaneously into a storage area, while in the latter type, the charge packets are transferred line by line. In both cases, however, the image is transferred out horizontally in a serial mode. The obvious advantage of frame transfer–based CCDs is the capture of the next image frame as soon as the previous frame is transferred to the storage area.

The latest use of CMOS (complementary MOS) technology in CCD cameras provides two further advantages: on-chip processing (leading to smaller sensors) and allowing random access to individual (active) pixels. The technology also prevents overflowing of charge into neighboring pixels (“blooming”).

There are single- and three-array CCD cameras for the acquisition of color images. Single-array sensors use an arrangement of filters to detect the primary colors of collected light signals by individual (distinct) neighboring pixels. In most cameras, the number of pixels devoted to each color differ (most would have twice as many as green pixels than the red or blue pixels—e.g., for a horizontal line of 768 pixels, 384 would be devoted to the detection of green light, 142 to red, and 142 to blue, in an exemplary arrangement of GGRBGGRB . . .). In higher end cameras, three individual arrays are dedicated to detect red, green, and blue light.

The majority of CCD array cameras have an aspect ratio of 4:3, yielding pixel sizes in correspondence to the physical size of the overall array itself and the resolution of the array. For example for a 768×480 array, with a diagonal length of 4 mm, the pixel size would be 4.17×5 μm.

The NTSC (National Television Systems Committee) standard used in North America recommends video timing of 30 frames per second. The PAL (phase alteration line) and the SECAM (sequentiel color avec mémoire) standards, on the other hand, recommend a frequency of 25 Hz.

Cameras based on (noninterlaced) progressive-scan CCDs capture an image in its entirety instantaneously, in contrast to interlaced-scan CCDs that capture an image line by line. The former are thus very suitable for imaging moving objects, providing (an unsmeared) improved vertical resolution.

Image Grabbing

The last stage in image acquisition is the creation of the digital image by grabbing the analog image captured by the CCD camera (Fig. 21). For analog-output cameras, the analog image is grabbed by converting the voltage values of all the pixels into their corresponding digital levels, yielding a digital image. This digital image is then transferred into the memory of the computer (typically, the random-access memory RAM) for image analysis. Most commercial frame grabbers (also known as digitizers) can be mounted on the bus of the personal computer (PC).

A digital image would have a resolution of gray levels dictated by the resolution of the frame grabber (e.g., 256 gray levels per pixel for an 8-bit digitizer and 1024 gray levels for a 10-bit digitizer). For color cameras (versus monochrome cameras), we would need three separate digitizers, one per primary color, in order to carry out color imaging and analysis. A single digitizer linked to the green (or to the composite image) output of the color CCD camera could be used, if image analysis were to be carried out in the gray-scale mode.

13.4.2 Monochromatic Image Processing and Analysis

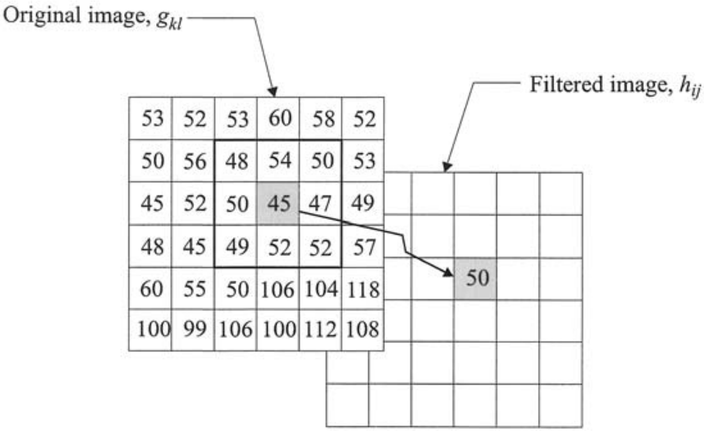
In this section, our focus is on the analysis of monochromatic images. Color image analysis is beyond the scope of this book. Analysis of digital images can be carried by directly using the acquired gray-scale representation or by first converting this representation into a binary (black and white) image and then using this limited representation for analysis. The objective of image analysis is either object identification and/or its dimensional verification or acquiring range information. The image analysis stage is normally preceded by the image preprocessing/enhancement stage.

Image Preprocessing

A digital image can be preprocessed for the removal of unwanted spatial frequencies—spatial filtering. Spatial convolution refers to spatial filtering through the use of neighborhood information obtained in the form of a window (or kernel) of size 3×3, 5×5, etc., whose center element coincides with the pixel we are examining.

The most common low-pass spatial filter is the mean filter used to yield a smoothing effect (attenuating the high-frequency elements), in which each pixel value is replaced by the average value of its neighbors within the kernel considered (Fig. 24):

$$h_{ij} = \frac{1}{N} \sum_{k=i-1}^{j+1} \sum_{l=j-1}^{j+1} g_{kl} \tag{13.4}$$



53	52	53	60	58	52
50	56	48	54	50	53
45	52	50	45	47	49
48	45	49	52	52	57
60	55	50	106	104	118
100	99	106	100	112	108

FIGURE 24 Mean filter.

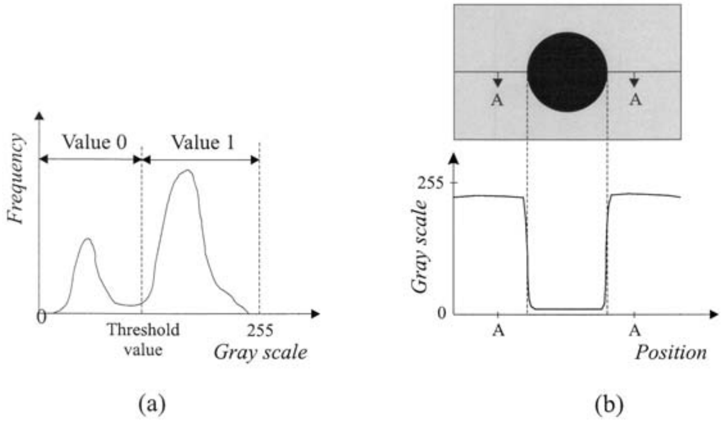
where g_{kl} represents the original image, h_{ij} represents the new (filtered) image and N is the total number of pixels in the kernel considered (e.g., for a 3×3 kernel, $N = 9$).

A high-pass spatial filter yields the opposite of a low-pass filter by attenuating the low-frequency elements. The result is a sharper image with clearly defined edges. A common 3×3 high-pass filter kernel is given here:

−1	−1	−1
−1	9	−1
−1	−1	−1

Once an image has been preprocessed through spatial convolution, the next step is determining the edges of the object captured in the digital image. As mentioned above, since image analysis can be carried out using gray-scale or binary images, we must choose one or the other before proceeding to the edge detection step. A binary image, if desired, can be obtained through a process called thresholding.

Thresholding is normally applied for faster image analysis, when the object in the image is accentuated in contrast to the background. A gray-scale image is converted into a binary (0,1) image by assigning the value zero to all the pixels with a value lower than a chosen threshold and assigning the value one to all others. A suitable threshold value can be chosen by examining the histogram of the gray-scale image (Fig. 25a).



(a) (b)

FIGURE 25 Thresholding.

Although for object identification, choosing the correct threshold value may not be that critical, for dimensional measurements, an incorrectly chosen threshold value would shift the edges of the object and thus yield an unreliable measurement (Fig. 25b).

For gray-scale image analysis, edge detection must be preceded by the application of an edge enhancer. One of the most commonly used edge enhancing filters is the Sobel operator. It uses two 3×3 kernels to calculate the new value of the pixel under consideration, h_{ij}:

$$h_{ij} = (S_x^2 + S_y^2)^{1/2} \tag{13.5}$$

where S_x and S_y are defined, respectively as

−1	0	1
−2	0	2
−1	0	1

1	2	1
0	0	0
−1	−2	−1

A thresholding process normally precedes the edge enhancement operation, such as the Sobel operator above, in order to enhance the detection of edges (Fig. 26).

The boundary of an object, whose edges have been determined using the tools described above, can be defined as a chain code. The objective is a concise representation to replace the boundary pixel coordinates with a sequence of numbers, each defining the relative location of the next boundary pixel. For example, the eight pixels neighboring a boundary point can be labeled by 1 to 8 (Fig. 27a). Using such a notation, an object boundary can be easily coded as a simple chain (Fig. 27b).

Image Analysis

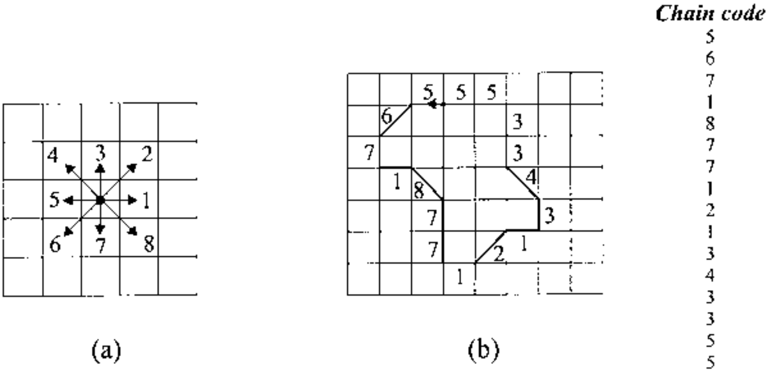
Image analysis is the extraction of necessary information from one or more digital images of an object or scene, for the purposes of object identification, dimensional measurement, and/or range and orientation determination. In regard to object identification (recognition), we will restrict our attention to two object-identification methods that impose minimal constraints on the placement of objects in the scene (i.e., their relative position and orientation). Both methods assume that the image has been segmented and objects do not overlap.

(a) (b) (c)

FIGURE 26 Edge detection process: (a) a gray-scale image; (b) a thresholded image; (c) object edges.

Model-based recognition: This method requires the modeling of objects in terms of several of their features that can be extracted from their acquired two-dimensional images. Features can include absolute measurements, such as area (total number of pixels included within the boundary of the object), perimeter, and maximum dimension; they can also include relative measurements or identification of certain geometrical features that would be scale-invariant (i.e., independent of the size of the image of the object), such as a circularity measure (area/perimenter^2), ratio of maximum dimension to minimum dimension, number of corners, number of holes, and so on.

The first task is to create individual models (feature vectors) for all the objects that we plan to recognize. The feature values in the vectors should correspond to the mean values of the potential measurements of dimensions,



(a) (b)

FIGURE 27 Chain coding; (a) directions; (b) example.

when these are distributed according to a Gaussian (normal) distribution owing to manufacturing variations (Chap. 16). Once the database of feature vectors is ready, on-line recognition can start.

For an object whose image we just acquired, the corresponding features are extracted and measured for the determination of the corresponding feature vector, U_i, $i = 1$ to m, where m is the number of features. This vector is then compared with all the feature vectors in our database, ${}^{j}O_i$, $j = 1$ to r, where r is the number of objects, for identifying a match. A match is established, by calculating a dissimilarity measure, D_j,

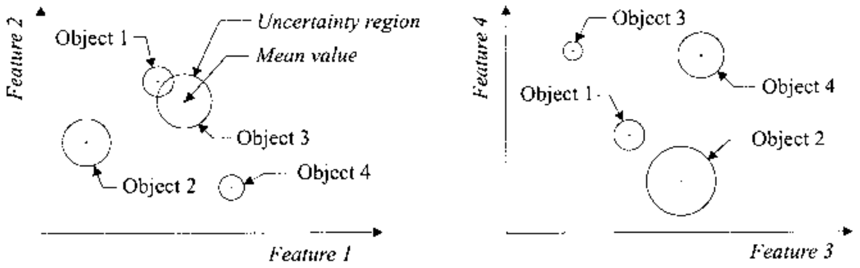
$$D_j = \sum_{i=1}^{m} (U_i - {}^{j}O_i)^2 \tag{13.6}$$

The smallest calculated D_j value, $(D_j)_{\min}$, indicates a potential match only if $(D_j)_{\min} \leq \varepsilon$, where ε indicates possible uncertainty due to imaging errors and/or manufacturing tolerances. Otherwise, the viewed object is labeled as unknown.

One should always attempt to form the smallest size feature vector (i.e., with minimum number of features) for the shortest possible processing time. However, the features chosen should provide maximum possible distinctiveness in order to prevent any potential ambiguity due to natural imprecisions (imaging errors dimensional tolerances, etc.). For example, in Fig. 28, four objects are first modeled using two features, Feature 1 and Feature 2. One notes that when using these two features the uncertainty regions of Object 1 and Object 2 overlap, thus yielding a potential ambiguity. In order to avoid this problem, the objects are remodeled using two new features, Feature 3 and Feature 4. These features do not yield ambiguity in the recognition of the four objects.

Shape recognition: An object's identity can be efficiently established by examining its outer boundary. Fourier transforms have been utilized to obtain approximate representations of objects' (periodic) contours and their subsequent identification through database comparison. Another popular method is the determination of a shape signature—"encoding." A polar-radii-signature-based encoding scheme is shown in Fig. 29. This scheme measures distances from the center of the object to all points (or a reduced representative set) on the boundary of the object yielding a unique signature. The centroid (center of mass) of any shape can be obtained by determining the balance point where the "mass" of the object's image is balanced with respect to both x and y axes.

As in model-based recognition, the shape signature of a viewed object must be compared with every one of the object boundaries stored in the database to determine a match. Since polar-radii signatures are not rotation



Poor feature vectors

Good feature vectors

FIGURE 28 Two-dimensional feature vectors.

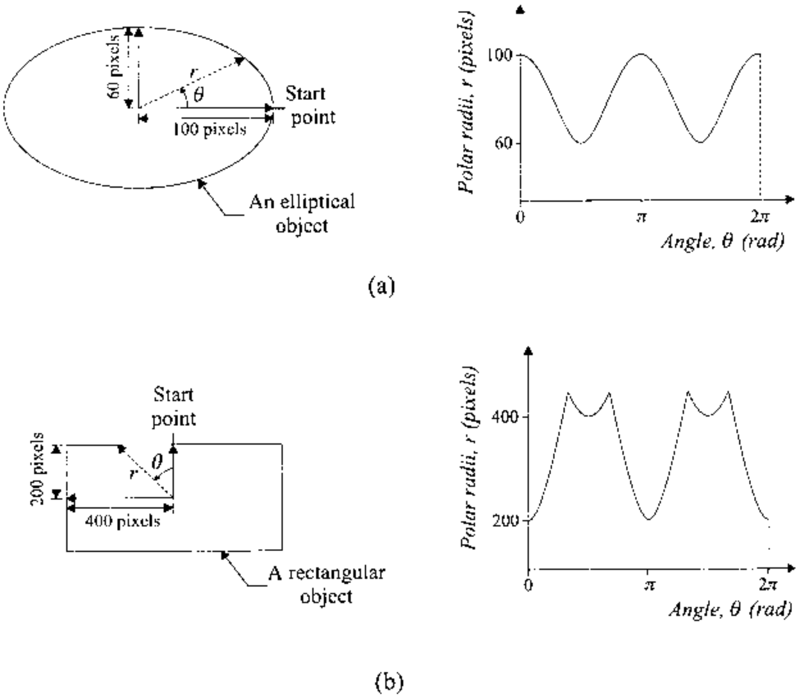


FIGURE 29 Polar radii signatures.

invariant, i.e., there is no established starting point for the generation of the signature, the alignment of signatures does present a challenge that must be addressed. Once an alignment is achieved, a dissimilarity measure can be calculated by summing up the absolute differences between the reference and the acquired signatures at every boundary point.

There are shape signatures that are rotation invariant—they utilize a characteristic ellipse unique to every shape in order to determine the starting point of the signature. The characteristic ellipse rotates together with the shape, where the intersection of its major axis with the shape boundary is always the same point.

13.4.3 Object Location Estimation

Machine vision can be used for estimating the position and orientation of objects, whose digital images have been acquired by one or more cameras. The task at hand is to relate the location of the object in the "image" plane to its actual location in a three-dimensional "world" coordinate frame. Such a process first requires the calibration of the camera used for image acquisition: determining the appropriate spatial transformation matrices by calculating the extrinsic (exterior orientation) and intrinsic (internal geometry) parameters of the camera. Once the camera has been calibrated, two images of the object must be acquired from different distances in order to calculate its range (one image could suffice, however, for determining its orientation).

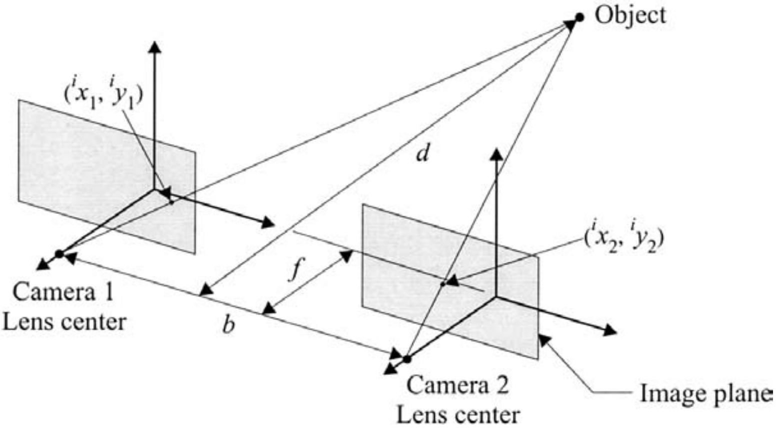


FIGURE 30 Stereo imaging.

A typical technique for range determination is stereo imaging (Fig. 30). The disparities of feature locations in two (separated) image planes, one of each camera, are utilized to extract depth information, d:

$$d = \frac{bf}{({}^{i}x_1 - {}^{i}x_2)} \tag{13.7}$$

where b is the separation distance of the two cameras (baseline), ${}^{i}x_1$ and ${}^{i}x_2$ are the x-axis image coordinates of the point feature as detected by Camera 1 and Camera 2, respectively, and f is the distance from the lens center to the image plane in both cameras.

13.5 ACTUATORS

Devices that execute motion commands generated by a controller are called actuators. Actuators convert energy input from an external source, typically electrical, hydraulic, or pneumatic, into mechanical (kinetic) energy and thus cause motion. Hydraulic actuators are normally reserved for large-load carrying applications, while pneumatic actuators are targeted for light-load carrying applications. Electrical actuators are the most versatile motion generators used for large-load carrying and minute-load carrying applications. They are quiet, easy to control, and easy to maintain, three favorable features in manufacturing applications. In a closed loop control environment actuator actions are monitored by sensors, like those mentioned in this chapter.

13.5.1 Electric Motors

Electrical actuators can be configured to provide rotary or linear motion. They are typically classified as AC (alternating current), DC (direct current) and stepper motors. Although a number of machines do use AC servomotors with voltage and frequency control via microelectronic drivers, the majority of manufacturing devices use DC motors and stepper motors:

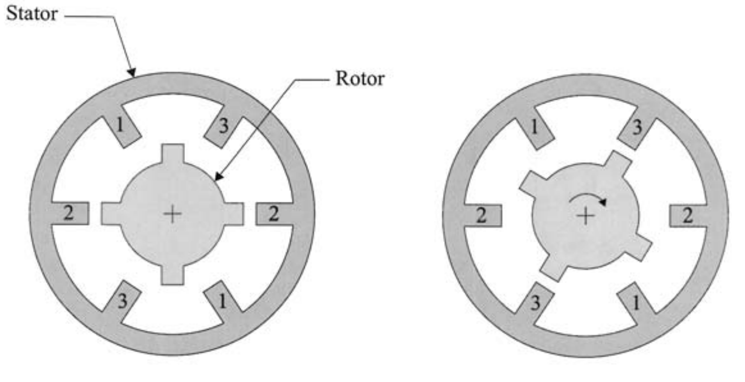
Rotary-motion (brush) DC motors utilize a (stationary) stator and a rotating core element (armature) placed inside the stator. Power transfer to the armature (commutation) is achieved through brushes placed on the rotary armature. The primary disadvantages of these motors are rapid wear out of the brushes and noise. Brushless DC motors, first introduced in the early 1980s, overcome these problems by utilizing electronic switching of the electrical current. Such motors can provide large torques over a range of speeds reached almost instantaneously

Linear motion can be achieved using rotary DC motors by coupling them to leadscrew drivers. For short-distance movements and light-load applications, however, one may choose to use linear DC motors, where a stage moves in a (stationary) channel. Power brushes are mounted on the stage for supplying the necessary current.

The displacement and velocity of DC servomotors must be controlled in a cascade (two-loop) architecture, tachometers measuring velocity in the inner-loop and encoders measuring displacement in the outer loop. Although the motion of a DC motor can be controlled by varying the input voltage, precise control cannot be achieved owing to the varying torque–speed relationship. Thus a desirable control mode would be adjusting the input current and thus controlling the torque applied—the voltage is manipulated to maintain a desired current.

Stepper motors, developed in the 1920s, provide accurate positioning through a stepping motion. That is, they provide incremental displacement (comprising equal length steps) in response to a sequence of precisely controlled digital pulses. As in DC motors, rotary motion is achieved by utilizing a stator and a rotor: a step motion is accomplished by the alignment of rotor poles with starter teeth through sequential alternating energizing of the teeth (Fig. 31).

The stepper motor has been generally targeted for use in an open loop control environment. A required displacement is achieved by a corresponding command of the necessary number of steps. Velocity is specified by varying



Pole Pair 3 is energized by an electrical current.

The rotor steps to the new position.

FIGURE 31 Step motion in variable reluctance stepper motor.

the rate of pulse input to the motor. Stepper motors, although desirable for high-positioning-accuracy tasks, would not be suitable for tasks with high torque/force resistance. In such cases, it would be necessary to utilize displacement sensors for feedback control to overcome step jumping (missing): rotary encoders for rotary and linear encoders for linear stepper motors.

13.5.2 Pneumatic and Hydraulic Actuators

Fluid power can be very effective in remote actuation. The power source is located a distance away from the output point, thus minimizing the weight carried by the manufacturing device. For example, an industrial robot with electric actuators incorporates the motors into the manipulator arm—the fifth joint carries the sixth motor, the fourth joint carries both the fifth and sixth motors, and so on. In fluid-power-based machines, on the other hand, the electrical pumps supplying the necessary pressurized fluid to all actuators are located in the exterior of the load-carrying mechanism.

Hydraulic actuators utilize incompressible (hydraulic) fluids to transfer energy to a desired output point. The incompressibility of the fluid allows them to output large forces/torques. Directional control valves and pressure control valves can be configured for the closed-loop control of hydraulic actuators. Linear cylinders can be utilized to output linear motion, while rotary pumps, such as the vane pump, can be utilized to output rotary motion (Fig. 32). In a vane motor, an eccentric rotor has chambers of unequal volume separated by spring-loaded vanes. Pressure differences between the chambers drive the rotor one way or another according to the direction of fluid input.

Pneumatic actuators are much easier to maintain than hydraulic actuators and are inexpensive. However, due to the compressibility of air, they cannot be used for large-load carrying applications and are only very

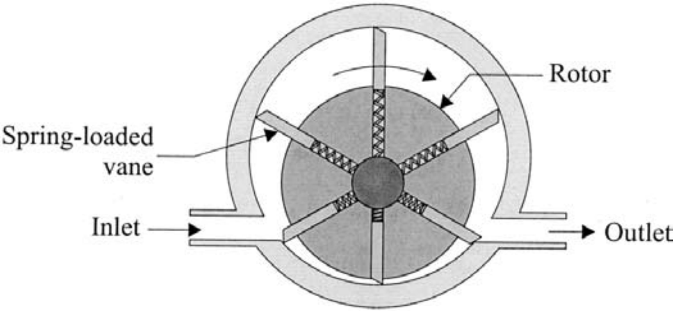


FIGURE 32 Vane motors.

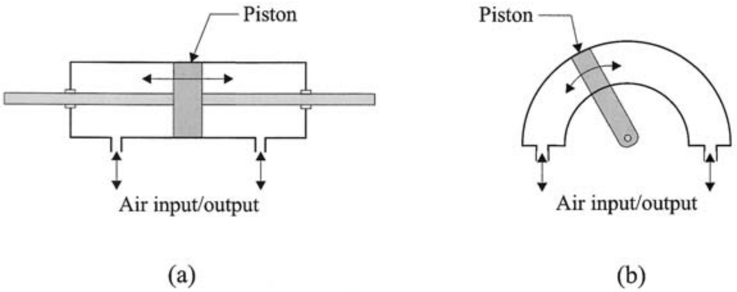


FIGURE 33 (a) Linear; (b) rotary pneumatic actuators.

infrequently used as servo systems (i.e., for motion control). They are primarily used in limit-to-limit motions (Fig. 33).

REVIEW QUESTIONS

1. Define the two primary levels of manufacturing control.
2. What is closed-loop process control?
3. Compare the different controller modes (i.e., PI, PD, and PID).
4. Compare analog controllers to digital controllers.
5. Describe the basic elements of a sensor.
6. Why is motion sensing of primary interest in many manufacturing processes?
7. Compare inductive transducers to capacitive transducers.
8. Noncontact sensing is considered a preferred mode of instrumentation for motion control. Discuss cases where a contact sensor, such as a linear variable-differential transformer (LVDT), would be the preferred choice.
9. Discuss amplitude-modulation-based (electro-optical) proximity sensing.
10. Compare amplitude-modulation-based proximity sensing to triangulation proximity sensing. Discuss advantages/disadvantages.
11. Explain the principle of interferometry and discuss some manufacturing application areas.
12. Compare ultrasonic proximity sensing to electro-optical proximity sensing.
13. Explain the principle of digital (absolute and relative) encoding and discuss some manufacturing application areas.
14. What are the most commonly employed transducers in force sensing?
15. Discuss machine vision versus computer vision.

16. Describe the primary steps of (digital) image acquisition and analysis.
17. Discuss the following issues in digital imaging: camera resolution, color versus monochromatic imaging, and the number of gray levels. In your discussion, you may refer to different manufacturing applications that would impact on the selection of these features.
18. What is image preprocessing? What are the advantages/disadvantages of image preprocessing?
19. For dimensional measurement purposes, would it be more accurate to utilize gray level images or (thresholded) binary images? Explain.
20. Discuss the use of model-based recognition versus (boundary) shape-based recognition in image analysis.
21. Discuss the use of DC motors versus stepper motors in manufacturing applications. Include some applications in your discussion.
22. Discuss the use of pneumatic actuators versus hydraulic actuators in manufacturing applications. Include some applications in your discussion.

DISCUSSION QUESTIONS

1. The factory of the future would be a totally networked enterprise. Information management in this enterprise would be a complex issue. In regards to planning, monitoring, and control, discuss the level of detail of information that the controllers (humans or computers) would have to deal with in such environments. For example, some argue that in a hierarchical information-management environment, activities are more of the planning type at the higher levels of the hierarchy and of the control type at the lower levels. It has also been argued that the level of details significantly decreases as you ascend the enterprise ladder.
2. The quality of a digital image is influenced by lighting conditions, electronic signal-transmission noise, and other image processing related problems. There exist numerous mathematical operators that can be utilized for the pre processing of such images. Discuss the advantages/disadvantages of using such operators in terms of specific manufacturing objectives: dimensional measurements versus pattern recognition.
3. In pattern recognition problems, an object (or a feature) can be identified by comparing its acquired image with a set of reference images in our database. Regardless of the analysis/identification technique utilized, two fundamental issues must be considered in the compilation of the database of reference object (image) models: Use of a dimensionally exact CAD-based object/feature model and the definition of statistical dimensional variations of the object's features that are

manufacturing-process dependent. Discuss both issues in the generation of a reliable set of reference object models for use in controllable/structured manufacturing environments. Furthermore, discuss how would one cope with (image) modeling problems in the absence of CAD-based object models.

4. Machine vision is a branch of computer vision targeted for inspection or guidance purposes in manufacturing environments. Such systems primarily operate in two-dimensional, static, uni color (gray scale) spaces for the autonomous measurement of geometric dimensions or recognition of patterns on viewed objects. The precision of the measurements is a direct function of the resolution of the camera's photodetector and the optics used. Discuss image processing time and measurement precision for several manufacturing applications. In this discussion, include a comparison on the suitability of machine vision for dimensional measurement versus pattern recognition in the context of manufacturing time and cost constraints.
5. The absence of accurate robot kinematic models, compounded with the absence of accurate geometric world models of their working environments, has often forced users to define Cartesian locations through manual teaching techniques (teleoperation). The robot end-effectors are moved to their desired destinations through teach pendants, and the controllers are required to memorize joint-encoder readings at these locations. The use of such playback-based robot motion techniques thus force objects always to be at their expected locations with very stringent tolerances. Discuss the potential of using a variety of visual and/or non visual task space sensors in controlling the robot motion that can lead to the relaxing of positioning requirements for objects that are static or those that are in motion.
6. Bin picking is a term used for the robotic grasping of a single component from an open bin that contains many randomly oriented, identical (and sometimes not identical) components. Discuss the difficulties associated with this operation from the machine vision point of view, assuming the robot can be directed to carry out such a picking operation, once it has been instructed about where the Cartesian location of the component is. Propose alternative solutions to robotic bin picking.
7. The supervisory control of a manufacturing process relies on timely and accurate sensory feedback. However, owing to the difficult production conditions (high temperatures, high pressures, physical obstructions, etc.), many production output parameters cannot be directly measured. Sensors instead observe and quantify certain physical phenomena (e.g., acoustic emissions) and relate these measurements to production

output parameters (e.g., tool wear) that we desire to monitor. Discuss the following and other issues in the context of effective autonomous process control: the availability of effective signal processing and pattern recognition techniques, the use of multiple sensors to monitor one phenomenon (i.e., sensor fusion), the decoupling of information obtained by a sensor whose outputs may have been influenced by several output parameters, and the availability of models that could optimally change a machine input parameter in response to changes monitored in one or more output parameters.

8. In machining, tool change (due to wear) may constitute a significant part of setup times. This is especially true in multipoint cutting, such as milling, where all the inserts have to be replaced together. Almost a century of work in the area of tool wear has yet to yield reliable models of the wear mechanisms, which would allow users to maximize the utilization of the tools and thus minimize the number of tool changes. Discuss the use of a variety of sensors and pattern recognition techniques for on-line intelligent machining in the absence of such models, or in support of approximate models.
9. Discuss the need of having effective tracking means, distributed throughout a manufacturing facility, which would provide users (and even customers) with timely feedback about the status and location of products in motion. Include several examples of such sensing and feedback devices in your discussion. Furthermore, discuss the advantages/disadvantages of using wireless solutions.
10. In the factory of the future, it is expected that manufacturing workcells will operate autonomously under the control of an overall computer-based supervisor. In such workcells, all devices, including fixtures and jigs, must be equipped with their own (device) controllers that can effectively communicate with the workcell supervisor. Discuss the integration of sensors and other communication components into intelligent fixtures that can be remotely controlled (via two-way communications) in the flexible manufacturing workcells of the future.

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