

THE COMPUTER SCIENCE AND ENGINEERING HANDBOOK

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33.7 Sensors

Sensors and actuators [Tzou and Fukuda 1992] function as *transducers*, devices through which the workcell planning, coordination, and control system interfaces with the hardware components that make up the workcell. Sensors are a vital element as they convert states of physical devices into signals appropriate for input to the workcell PC&C control system; inappropriate sensors can introduce errors that make proper operation impossible no matter how sophisticated or expensive the PC&C system, whereas innovative selection of sensors can make the control and coordination problem much easier.

The Philosophy of Robotic Workcell Sensors

Sensors are of many different types and have many distinct uses. Having in mind an analogy with biological systems, *proprioceptors* are sensors internal to a device that yield information about the internal state of that device (e.g., robot arm joint-angle sensors). *Exteroceptors* yield information about other hardware external to a device. Sensors yield outputs that are either analog or digital; digital sensors often provide information about the status of a machine or resource (gripper open or closed, machine loaded, job complete). Sensors produce inputs that are required at all levels of the PC&C hierarchy, including uses for:

- Servo-level feedback control (usually analog proprioceptors)
- Process monitoring and coordination (often digital exteroceptors or part inspection sensors such as vision)
- Failure and safety monitoring (often digital, e.g., contact sensor, pneumatic pressure-loss sensor)
- Quality control inspection (often vision or scanning laser).

Sensor output data must often be processed to convert it into a form meaningful for PC&C purposes. The sensor plus required signal processing is shown as a *virtual sensor* in Fig. 33:7; it functions as a *data abstraction*, that is, a set of data plus operations on that data (e.g., camera, plus framegrabber, plus signal processing algorithms such as image enhancement, edge detection, segmentation, etc.). Some sensors, including the proprioceptors needed for servo-level feedback control, are integral parts of their host devices, and so processing of sensor data and use of the data occurs within that device; then, the sensor data is incorporated at the servocontrol level or machine coordination level. Other sensors, often vision systems, rival the robot manipulator in sophistication and are coordinated by the job coordinator, which treats them as valuable shared resources whose use is assigned to jobs that need them by some priority assignment (e.g., dispatching) scheme. An interesting coordination problem is posed by so-called *active sensing*, where, e.g., a robot may hold a scanning camera, and the camera effectively takes charge of the coordination problem, directing the robot where to move it to effect the maximum reduction in entropy (increase in information) with subsequent images.

Types of Sensors

This section summarizes sensors from an operational point of view. More information on functional and physical principles can be found in Fraden [1993], Fu et al. [1987], Groover et al. [1986], and Snyder [1985].

Tactile Sensors. Tactile sensors [Nichols and Lee 1989] rely on physical contact with external objects. Digital sensors such as limit switches, microswitches, and vacuum devices give binary information on whether contact occurs or not. Sensors are available to detect the onset of slippage. Analog sensors such as

spring-loaded rods give more information. Tactile sensors based on rubberlike carbon- or silicon-based *elastomers* with embedded electrical or mechanical components can provide very detailed information about part geometry, location, and more. Elastomers can contain resistive or capacitive elements whose electrical properties change as the elastomer compresses. Designs based on LSI technology can produce *tactile grid pads* with, e.g., 64 × 64 *forcel* points on a single pad. Such sensors produce *tactile images* that have properties akin to digital images from a camera and require similar data processing. Additional tactile sensors fall under the classification of force sensors discussed subsequently.

Proximity and Distance Sensors. The noncontact proximity sensors include devices based on the Hall effect or inductive devices based on the electromagnetic effect that can detect ferrous materials within about 5 mm. Such sensors are often digital, yielding binary information about whether or not an object is near. Capacitance-based sensors detect any nearby solid or liquid with ranges of about 5 mm. Optical and ultrasound sensors have longer ranges.

Distance sensors include time-of-flight range finder devices such as sonar and lasers. The commercially available Polaroid sonar offers accuracy of about 1 in up to 5 ft, with angular sector accuracy of about 15°. For 360° coverage in navigation applications for mobile robots, both scanning sonars and ring-mounted multiple sonars are available. Sonar is typically noisy with spurious readings, and requires low-pass filtering and other data processing aimed at reducing the false alarm rate. The more expensive laser range finders are extremely accurate in distance and have very high angular resolution.

Position, Velocity, and Acceleration Sensors. Linear position-measuring devices include linear potentiometers and the sonar and laser range finders just discussed. Linear velocity sensors may be laser- or sonar-based Doppler-effect devices.

Joint-angle position and velocity proprioceptors are an important part of the robot arm servocontrol drive axis. Angular position sensors include potentiometers, which use dc voltage, and *resolvers*, which use ac voltage and have accuracies of ±15 min. Optical encoders can provide extreme accuracy using digital techniques. *Incremental optical encoders* use three optical sensors and a single ring of alternating opaque/clear areas, Fig. 33.18(a), to provide angular position relative to a reference point and angular velocity information; commercial devices may have 1200 slots per turn. More expensive *absolute optical*

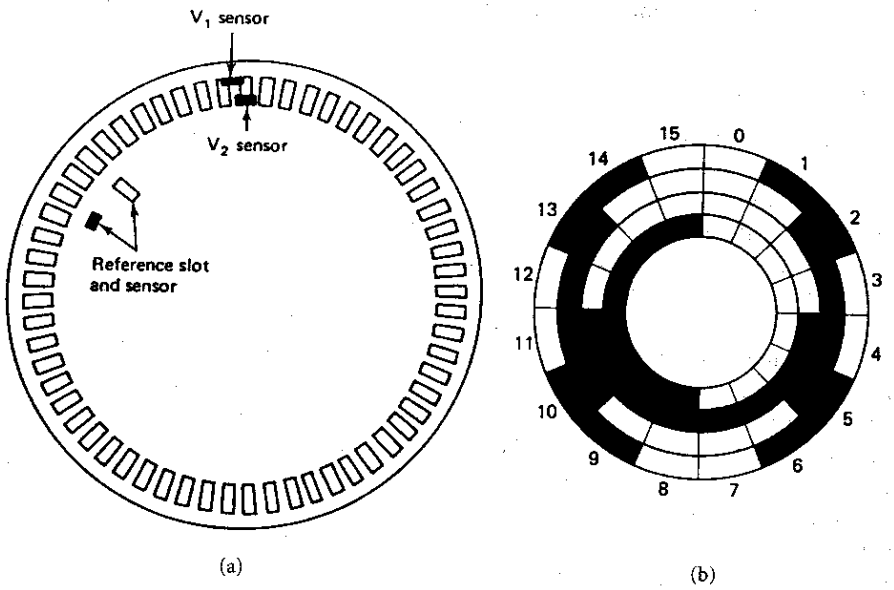


FIGURE 33.18 Optical encoders: (a) incremental optical encoder and (b) absolute optical encoder with $n = 4$ using Grey code (Snyder, W. E. 1985. *Industrial Robots: Computer Interfacing and Control.* Prentice–Hall, Englewood Cliffs, NJ. With permission.)

encoders, Fig. 33.18(b), have n concentric rings of alternating opaque/clear areas and require n optical sensors. They offer increased accuracy and minimize errors associated with data reading and transmission, particularly if they employ the *Grey code*, where only one bit changes between two consecutive sectors. Accuracy is $360°/2^n$, with commercial devices having $n = 12$ or so.

Gyros have good accuracy if repeatability problems associated with drift are compensated for. Directional gyros have accuracies of about $\pm 1.5°$; vertical gyros have accuracies of $0.15°$ and are available to measure multiaxis motion (e.g., pitch and roll). Rate gyros measure velocities directly with thresholds of $0.05°/s$ or so.

Various sorts of accelerometers are available based on strain gauges (next paragraph), gyros, or crystal properties. Commercial devices are available to measure accelerations along three axes.

Force and Torque Sensors. Various torque sensors are available, though they are often not required; for instance, the internal torques at the joints of a robot arm can be computed from the motor armature currents. Torque sensors on a drilling tool, for instance, can indicate when tools are dull. Linear force can be measured using load cells or strain gauges. A strain gauge is an elastic sensor whose resistance is a function of applied strain or deformation. The piezoelectric effect, the generation of a voltage when a force is applied, may also be used for force sensing. Other force sensing techniques are based on vacuum diodes, quartz crystals (whose resonant frequency changes with applied force), etc.

Robot arm force-torque wrist sensors are extremely useful in dextrous manipulation tasks. Commercially available devices can measure both force and torque along three perpendicular axes, providing full information about the Cartesian force vector **F**. Transformations such as Eq. (33.6) allow computation of forces and torques in other coordinates. Six-axis force-torque sensors are quite expensive.

Photoelectric Sensors. A wide variety of photoelectric sensors are available, some based on fiber optic principles. These have speeds of response in the neighborhood of 50 μs with ranges up to about 45 mm, and are useful for detecting parts and labeling, scanning optical bar codes, confirming part passage in sorting tasks, etc.

Other Sensors. Various sensors are available for measuring pressure, temperature, fluid flow, etc. These are useful in closed-loop servocontrol applications for some processes such as welding, and in job coordination and/or safety interrupt routines in others.

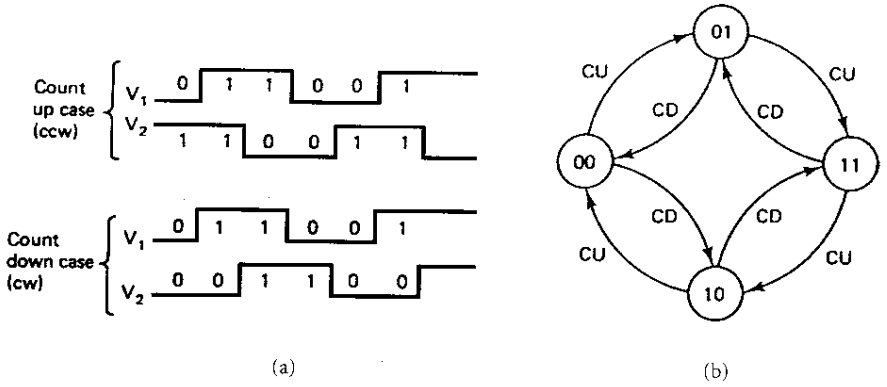
Sensor Data Processing

Before any sensor can be used in a robotic workcell, it must be *calibrated*. Depending on the sensor, this could involve significant effort in experimentation, computation, and tuning after installation. Manufacturers often provide calibration procedures though in some cases, including vision, such procedures may not be obvious, requiring reference to the published scientific literature. Time-consuming recalibration may be needed after any modifications to the system.

Particularly for more complex sensors such as optical encoders, significant sensor signal conditioning and processing is required. This might include amplification of signals, noise rejection, conversion of data from analog to digital or from digital to analog, and so on. Hardware is usually provided for such purposes by the manufacturer and should be considered as part of the sensor package for robot workcell design. The sensor, along with its signal processing hardware and software algorithms may be considered as a data abstraction and is called the *virtual sensor* in Fig. 33.7.

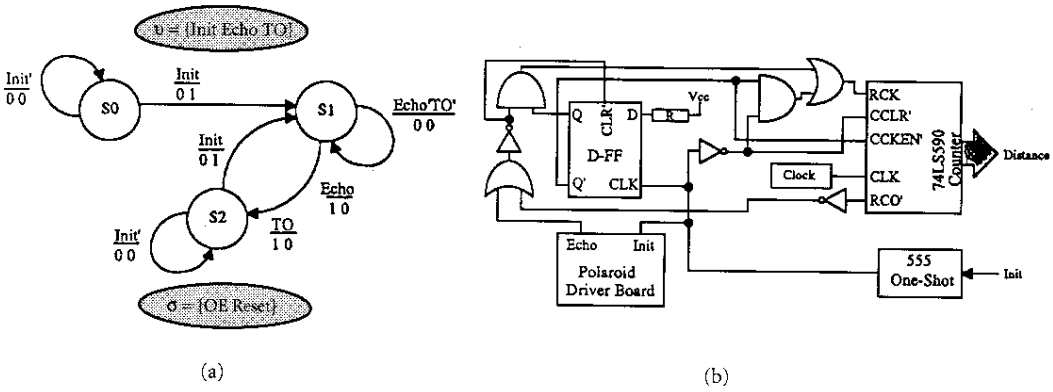
If signal processing does need to be addressed, it is often very useful to use *finite state machine (FSM) design*. A typical signal from an incremental optical encoder is shown in Fig. 33.19(a); a FSM for decoding this into the angular position is given in Fig. 33.19(b). FSMs are very easy to convert directly to hardware in terms of logical gates. A FSM for sequencing a sonar is given in Fig. 33.20(a); the sonar driver hardware derived from this FSM is shown in Fig. 33.20(b).

A particular problem is obtaining angular velocity from angular position measurements. All too often the position measurements are simply differenced using a small sample period to compute velocity. This is



(a) (b)

FIGURE 33.19 Signal processing using FSM for optical encoders: (a) phase relations in incremental optical encoder output and (b) finite state machine to decode encoder output into angular position. [Snyder 1985].



(a) (b)

FIGURE 33.20 Hardware design from FSM: (a) FSM for sonar transducer control on a mobile robot and (b) sonar driver control system from FSM.

guaranteed to lead to problems if there is any noise in the signal. It is almost always necessary to employ a low-pass-filtered derivative where velocity samples v_k are computed from position measurement samples $\mathbf{p}_k$ using, e.g.,

$$v_k = \alpha v_{k-1} + (1 - \alpha)(\mathbf{p}_k - \mathbf{p}_{k-1})/T \tag{33.18}$$

where T is the sample period and α is a small filtering coefficient. A similar approach is needed to compute acceleration.

Vision for Robotics

Computer vision is covered in Chapter 25 of this Handbook; the purpose of this section is to discuss some aspects of vision that are unique to robotics [Fu et al. 1987, Lee and Li 1991, Lee and Blenis 1994]. Industrial robotic workcells often require vision systems that are reliable, accurate, low cost, and rugged yet perform sophisticated image processing and decision making functions. Balancing these conflicting demands is not always easy. There are several commercially available vision systems, the most sophisticated of which may be the Adept vision system, which supports multiple cameras. However, it is sometimes necessary to design