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Introduction to Sensors and Actuators

M. Anjanappa
University of Maryland Baltimore County

K. Datta
University of Maryland Baltimore County

T. Song
University of Maryland Baltimore County

16.1 Sensors
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16.2 Actuators
Classification • Principle of Operation • Selection Criteria

Sensors and actuators are two critical components of every closed loop control system. Such a system is also called a *mechatronics system*. A typical mechatronics system as shown in Fig. 16.1 consists of a sensing unit, a controller, and an actuating unit. A sensing unit can be as simple as a single sensor or can consist of additional components such as filters, amplifiers, modulators, and other signal conditioners. The controller accepts the information from the sensing unit, makes decisions based on the control algorithm, and outputs commands to the actuating unit. The actuating unit consists of an actuator and optionally a power supply and a coupling mechanism.

16.1 Sensors

Sensor is a device that when exposed to a physical phenomenon (temperature, displacement, force, etc.) produces a proportional output signal (electrical, mechanical, magnetic, etc.). The term transducer is often used synonymously with sensors. However, ideally, a sensor is a device that responds to a change in the physical phenomenon. On the other hand, a transducer is a device that converts one form of energy into another form of energy. Sensors are transducers when they sense one form of energy input and output in a different form of energy. For example, a thermocouple responds to a temperature change (thermal energy) and outputs a proportional change in electromotive force (electrical energy). Therefore, a thermocouple can be called a sensor and or transducer.

Classification

Table 16.1 lists various types of sensors that are classified by their measurement objectives. Although this list is by no means exhaustive, it covers all the basic types including the new generation sensors such as smart material sensors, microsensors, and nanosensors.

TABLE 16.1 Type of Sensors for Various Measurement Objectives

Sensor	Features
	Linear/Rotational sensors
Linear/Rotational variable differential transducer (LVDT/RVDT)	High resolution with wide range capability Very stable in static and quasi-static applications
Optical encoder	Simple, reliable, and low-cost solution Good for both absolute and incremental measurements
Electrical tachometer	Resolution depends on type such as generator or magnetic pickups
Hall effect sensor	High accuracy over a small to medium range
Capacitive transducer	Very high resolution with high sensitivity Low power requirements Good for high frequency dynamic measurements
Strain gauge elements	Very high accuracy in small ranges Provides high resolution at low noise levels
Interferometer	Laser systems provide extremely high resolution in large ranges Very reliable and expensive
Magnetic pickup	Output is sinusoidal
Gyroscope	
Inductosyn	Very high resolution over small ranges
	Acceleration sensors
Seismic accelerometer	Good for measuring frequencies up to 40% of its natural frequency
Piezoelectric accelerometer	High sensitivity, compact, and rugged Very high natural frequency (100 kHz typical)
	Force, torque, and pressure sensor
Strain gauge	Good for both static and dynamic measurements
Dynamometers/load cells	They are also available as micro- and nanosensors
Piezoelectric load cells	Good for high precision dynamic force measurements
Tactile sensor	Compact, has wide dynamic range, and high
Ultrasonic stress sensor	Good for small force measurements
	Flow sensors
Pitot tube	Widely used as a flow rate sensor to determine speed in aircrafts
Orifice plate	Least expensive with limited range
Flow nozzle, venturi tubes	Accurate on wide range of flow More complex and expensive
Rotameter	Good for upstream flow measurements Used in conjunction with variable inductance sensor
Ultrasonic type	Good for very high flow rates Can be used for both upstream and downstream flow measurements
Turbine flow meter	Not suited for fluids containing abrasive particles Relationship between flow rate and angular velocity is linear
Electromagnetic flow meter	Least intrusive as it is noncontact type Can be used with fluids that are corrosive, contaminated, etc. The fluid has to be electrically conductive
	Temperature sensors
Thermocouples	This is the cheapest and the most versatile sensor Applicable over wide temperature ranges (-200∞C to 1200∞C typical)
Thermistors	Very high sensitivity in medium ranges (up to 100∞C typical) Compact but nonlinear in nature
Thermodiodes, thermo transistors	Ideally suited for chip temperature measurements Minimized self heating
RTD—resistance temperature detector	More stable over a long period of time compared to thermocouple Linear over a wide range

(*continued*)

TABLE 16.1 Type of Sensors for Various Measurement Objectives (Continued)

Sensor	Features
Infrared type	Noncontact point sensor with resolution limited by wavelength
Infrared thermography	Measures whole-field temperature distribution
	Proximity sensors
Inductance, eddy current, hall effect, photoelectric, capacitance, etc.	Robust noncontact switching action The digital outputs are often directly fed to the digital controller
	Light sensors
Photoresistors, photodiodes, photo transistors, photo conductors, etc.	Measure light intensity with high sensitivity Inexpensive, reliable, and noncontact sensor
Charge-coupled diode	Captures digital image of a field of vision
	Smart material sensors
Optical fiber	
As strain sensor	Alternate to strain gages with very high accuracy and bandwidth Sensitive to the reflecting surface's orientation and status
As level sensor	Reliable and accurate
As force sensor	High resolution in wide ranges
As temperature sensor	High resolution and range (up to 2000∞C)
Piezoelectric	
As strain sensor	Distributed sensing with high resolution and bandwidth
As force sensor	Most suitable for dynamic applications
As accelerometer	Least hysteresis and good setpoint accuracy
Magnetostrictive	
As force sensors	Compact force sensor with high resolution and bandwidth Good for distributed and noncontact sensing applications
As torque sensor	Accurate, high bandwidth, and noncontact sensor
	Micro- and nano-sensors
Micro CCD image sensor	Small size, full field image sensor
Fiberscope	Small (0.2 mm diameter) field vision scope using SMA coil actuators
Micro-ultrasonic sensor	Detects flaws in small pipes
Micro-tactile sensor	Detects proximity between the end of catheter and blood vessels

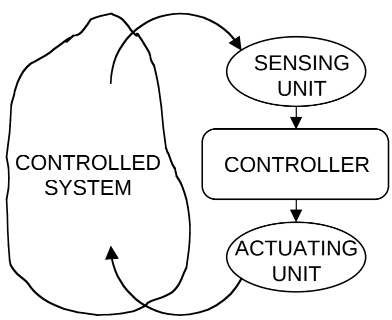

FIGURE 16.1 A typical mechatronics system.

Sensors can also be classified as *passive* or *active*. In passive sensors, the power required to produce the output is provided by the sensed physical phenomenon itself (such as a thermometer) whereas the active sensors require external power source (such as a strain gage).

Furthermore, sensors are classified as *analog* or *digital* based on the type of output signal. Analog sensors produce continuous signals that are proportional to the sensed parameter and typically require analog-to-digital conversion before feeding to the digital controller. Digital sensors on the other hand produce digital outputs that can be directly interfaced with the digital controller. Often, the digital outputs are produced by adding an analog-to-digital converter to the sensing unit. If many sensors are required, it is more economical to choose simple analog sensors and interface them to the digital controller equipped with a multi-channel analog-to-digital converter.

Principle of Operation

Linear and Rotational Sensors

Linear and rotational position sensors are two of the most fundamental of all measurements used in a typical mechatronics system. The most common type position sensors are listed in Table 16.1. In general, the position sensors produce an electrical output that is proportional to the displacement they experience. There are contact type sensors such as strain gage, LVDT, RVDT, tachometer, etc. The noncontact type includes encoders, hall effect, capacitance, inductance, and interferometer type. They can also be classified based on the range of measurement. Usually the high-resolution type of sensors such as *hall effect, fiber optic inductance, capacitance*, and *strain gage* are suitable for only very small range (typically from 0.1 mm to 5 mm). The *differential transformers* on the other hand, have a much larger range with good resolution. *Interferometer* type sensors provide both very high resolution (in terms of microns) and large range of measurements (typically up to a meter). However, interferometer type sensors are bulky, expensive, and requires large set up time.

Among many linear displacement sensors, strain gage provides high resolution at low noise level and is least expensive. A typical resistance strain gage consists of resistive foil arranged as shown in the Fig. 16.2. A typical setup to measure the normal strain of a member loaded in tension is shown in Fig. 16.3. Strain gage 1 is bonded to the loading member whereas strain gage 2 is bonded to a second member made of same material, but not loaded. This arrangement compensates for any temperature effect. When the member is loaded, the gage 1 elongates thereby changing the resistance of the gage. The change in resistance is transformed into a change in voltage by the voltage-sensitive wheatstone bridge circuit. Assuming that the resistance of all four arms are equal initially, the change in output voltage (Δv_o) due to change in resistance (ΔR_1) of gage 1 is

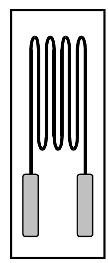

FIGURE 16.2 Bonded strain gage.

$$\frac{\Delta v_o}{v_i} = \frac{\Delta R_1/R}{4 + 2(\Delta R_1/R)}$$

Acceleration Sensors

Measurement of acceleration is important for systems subject to shock and vibration. Although acceleration can be derived from the time history data obtainable from linear or rotary sensors, the accelerometers whose output is directly proportional to the acceleration is preferred. Two common types include

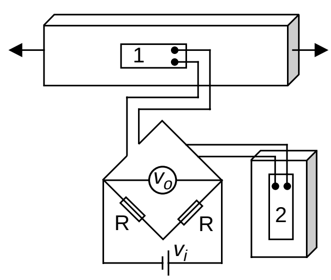

FIGURE 16.3 Experimental setup to measure normal strain using strain gages.

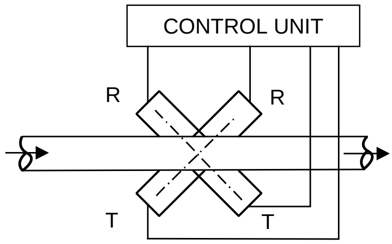

FIGURE 16.4 Ultrasonic flow sensor arrangement.

the *seismic mass* type and the *piezoelectric* accelerometer. The seismic mass type accelerometer is based on the relative motion between a mass and the supporting structure. The natural frequency of the seismic mass limits its use to low to medium frequency applications. The piezoelectric accelerometer, however, is compact and more suitable for high frequency applications.

Force, Torque, and Pressure Sensors

Among many type of force/torque sensors, the *strain gage dyanamometers* and *piezoelectric type* are most common. Both are available to measure force and/or torque either in one axis or multiple axes. The dynamometers make use of mechanical members that experiences elastic deflection when loaded. These types of sensors are limited by their natural frequency. On the other hand, the piezoelectric sensors are particularly suitable for dynamic loadings in a wide range of frequencies. They provide high stiffness, high resolution over a wide measurement range, and are compact.

Flow Sensors

Flow sensing is relatively a difficult task. The fluid medium can be liquid, gas, or a mixture of the two. Furthermore, the flow could be laminar or turbulent and can be a time-varying phenomenon. The *venturi meter* and *orifice plate* restrict the flow and use the pressure difference to determine the flow rate. The *pitot tube* pressure probe is another popular method of measuring flow rate. When positioned against the flow, they measure the total and static pressures. The flow velocity and in turn the flow rate can then be determined. The *rotameter* and the *turbine meters* when placed in the flow path, rotate at a speed proportional to the flow rate. The *electromagnetic flow meters* use noncontact method. Magnetic field is applied in the transverse direction of the flow and the fluid acts as the conductor to induce voltage proportional to the flow rate.

Ultrasonic flow meters measure fluid velocity by passing high-frequency sound waves through fluid. A schematic diagram of the ultrasonic flow meter is as shown in Fig. 16.4. The transmitters (T) provide the sound signal source. As the wave travels towards the receivers (R), its velocity is influenced by the velocity of the fluid flow due to the doppler effect. The control circuit compares the time to interpret the flow rate. This can be used for very high flow rates and can also be used for both upstream and downstream flow. The other advantage is that it can be used for corrosive fluids, fluids with abrasive particles, as it is like a noncontact sensor.

Temperature Sensors

A variety of devices are available to measure temperature, the most common of which are thermocouples, thermisters, resistance temperature detectors (RTD), and infrared types.

Thermocouples are the most versatile, inexpensive, and have a wide range (up to 1200∞C typical). A thermocouple simply consists of two dissimilar metal wires joined at the ends to create the sensing junction. When used in conjunction with a reference junction, the temperature difference between the reference junction and the actual temperature shows up as a voltage potential. *Thermisters* are semiconductor devices whose resistance changes as the temperature changes. They are good for very high sensitivity measurements in a limited range of up to 100∞C. The relationship between the temperature and the resistance is nonlinear. The *RTDs* use the phenomenon that the resistance of a metal changes with temperature. They are, however, linear over a wide range and most stable.

Infrared type sensors use the radiation heat to sense the temperature from a distance. These noncontact sensors can also be used to sense a field of vision to generate a thermal map of a surface.

Proximity Sensors

They are used to sense the proximity of an object relative to another object. They usually provide a on or off signal indicating the presence or absence of an object. *Inductance, capacitance, photoelectric*, and *hall effect* types are widely used as proximity sensors. Inductance proximity sensors consist of a coil wound around a soft iron core. The inductance of the sensor changes when a ferrous object is in its proximity. This change is converted to a voltage-triggered switch. Capacitance types are similar to inductance except the proximity of an object changes the gap and affects the capacitance. Photoelectric sensors are normally aligned with an infrared light source. The proximity of a moving object interrupts the light beam causing the voltage level to change. Hall effect voltage is produced when a current-carrying conductor is exposed to a transverse magnetic field. The voltage is proportional to transverse distance between the hall effect sensor and an object in its proximity.

Light Sensors

Light intensity and full field vision are two important measurements used in many control applications. *Phototransistors, photoresistors*, and *photodiodes* are some of the more common type of light intensity sensors. A common photoresistor is made of cadmium sulphide whose resistance is maximum when the sensor is in dark. When the photoresistor is exposed to light, its resistance drops in proportion to the intensity of light. When interfaced with a circuit as shown in Fig. 16.5 and balanced, the change in light intensity will show up as change in voltage. These sensors are simple, reliable, and cheap, used widely for measuring light intensity.

Smart Material Sensors

There are many new smart materials that are gaining more applications as sensors, especially in distributed sensing circumstances. Of these, *optic fibers, piezoelectric,* and *magnetostrictive* materials have found applications. Within these, optic fibers are most used.

Optic fibers can be used to sense strain, liquid level, force, and temperature with very high resolution. Since they are economical for use as *in situ* distributed sensors on large areas, they have found numerous applications in smart structure applications such as damage sensors, vibration sensors, and cure-monitoring sensors. These sensors use the inherent material (glass and silica) property of optical fiber to sense the environment. Figure 16.6 illustrates the basic principle of operation of an embedded optic fiber used to sense displacement, force, or temperature. The relative change in the transmitted intensity or spectrum is proportional to the change in the sensed parameter.

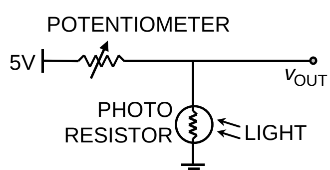

FIGURE 16.5 Light sensing with photoresistors.

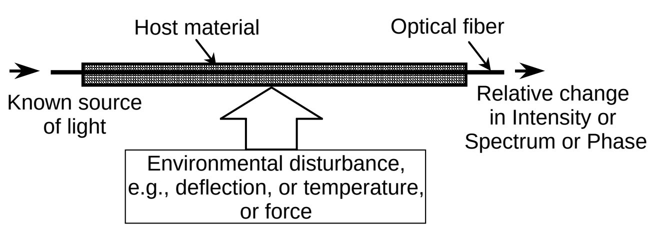

FIGURE 16.6 Principle of operation of optic fiber sensing.

Micro- and Nanosensors

Microsensors (sometimes also called MEMS) are the miniaturized version of the conventional macrosensors with improved performance and reduced cost. Silicon micromachining technology has helped the development of many microsensors and continues to be one of the most active research and development topics in this area.

Vision microsensors have found applications in medical technology. A *fiberscope* of approximately 0.2 mm in diameter has been developed to inspect flaws inside tubes. Another example is a *microtactile sensor*, which uses laser light to detect the contact between a catheter and the inner wall of blood vessels during insertion that has sensitivity in the range of 1 mN. Similarly, the progress made in the area of nanotechnology has fuelled the development of nanosensors. These are relatively new sensors that take one step further in the direction of miniaturization and are expected to open new avenues for sensing applications.

Selection Criteria

A number of static and dynamic factors must be considered in selecting a suitable sensor to measure the desired physical parameter. Following is a list of typical factors:

Range—Difference between the maximum and minimum value of the sensed parameter
Resolution—The smallest change the sensor can differentiate
Accuracy—Difference between the measured value and the true value
Precision—Ability to reproduce repeatedly with a given accuracy
Sensitivity—Ratio of change in output to a unit change of the input
Zero offset—A nonzero value output for no input
Linearity—Percentage of deviation from the best-fit linear calibration curve
Zero Drift—The departure of output from zero value over a period of time for no input
Response time—The time lag between the input and output
Bandwidth—Frequency at which the output magnitude drops by 3 dB
Resonance—The frequency at which the output magnitude peak occurs
Operating temperature—The range in which the sensor performs as specified
Deadband—The range of input for which there is no output
Signal-to-noise ratio—Ratio between the magnitudes of the signal and the noise at the output

Choosing a sensor that satisfies all the above to the desired specification is difficult, at best. For example, finding a position sensor with micrometer resolution over a range of a meter eliminates most of the sensors. Many times the lack of a cost-effective sensor necessitates redesigning the mechatronic system. It is, therefore, advisable to take a system level approach when selecting a sensor and avoid choosing it in isolation.

Once the above-referred functional factors are satisfied, a short list of sensors can be generated. The final selection will then depend upon the size, extent of signal conditioning, reliability, robustness, maintainability, and cost.

Signal Conditioning

Normally, the output from a sensor requires post processing of the signals before they can be fed to the controller. The sensor output may have to be demodulated, amplified, filtered, linearized, range quantized, and isolated so that the signal can be accepted by a typical analog-to-digital converter of the controller. Some sensors are available with integrated signal conditioners, such as the microsensors. All the electronics are integrated into one microcircuit and can be directly interfaced with the controllers.

Calibration

The sensor manufacturer usually provides the calibration curves. If the sensors are stable with no drift, there is no need to recalibrate. However, often the sensor may have to be recalibrated after integrating it with a signal conditioning system. This essentially requires that a known input signal is provided to the sensor and its output recorded to establish a correct output scale. This process proves the ability to measure reliably and enhances the confidence.

If the sensor is used to measure a time-varying input, dynamic calibration becomes necessary. Use of sinusoidal inputs is the most simple and reliable way of dynamic calibration. However, if generating sinusoidal input becomes impractical (for example, temperature signals) then a step input can substitute for the sinusoidal signal. The transient behavior of step response should yield sufficient information about the dynamic response of the sensor.

16.2 Actuators

Actuators are basically the muscle behind a mechatronics system that accepts a control command (mostly in the form of an electrical signal) and produces a change in the physical system by generating force, motion, heat, flow, etc. Normally, the actuators are used in conjunction with the power supply and a coupling mechanism as shown in Fig. 16.7. The power unit provides either AC or DC power at the rated voltage and current. The coupling mechanism acts as the interface between the actuator and the physical system. Typical mechanisms include rack and pinion, gear drive, belt drive, lead screw and nut, piston, and linkages.

Classification

Actuators can be classified based on the type of energy as listed in Table 16.2. The table, although not exhaustive, lists all the basic types. They are essentially of electrical, electromechanical, electromagnetic, hydraulic, or pneumatic type. The new generations of actuators include smart material actuators, micro-actuators, and Nanoactuators.

Actuators can also be classified as *binary* and *continuous* based on the number of stable-state outputs. A relay with two stable states is a good example of a binary actuator. Similarly, a stepper motor is a good example of continuous actuator. When used for a position control, the stepper motor can provide stable outputs with very small incremental motion.

Principle of Operation

Electrical Actuators

Electrical switches are the choice of actuators for most of the on-off type control action. Switching devices such as *diodes, transistors, triacs, MOSFET,* and *relays* accept a low energy level command signal from the controller and switch on or off electrical devices such as motors, valves, and heating elements. For example, a MOSFET switch is shown in Fig. 16.8. The gate terminal receives the low energy control signal from the controller that makes or breaks the connection between the power supply and the actuator load. When switches are used, the designer must make sure that *switch bounce* problem is eliminated either by hardware or software.

Electromechanical Actuators

The most common electromechanical actuator is a motor that converts electrical energy to mechanical motion. Motors are the principal means of converting electrical energy into mechanical energy in industry. Broadly they can be classified as *DC motors, AC motors*, and *stepper motors*. DC motors operate on DC

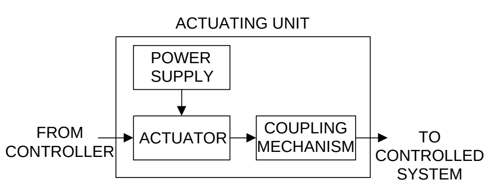

FIGURE 16.7 A typical actuating unit.

TABLE 16.2 Type of Actuators and Their Features

Actuator			Features
			Electrical
Diodes, thyristor, bipolar transistor, triacs, diacs, power MOSFET, solid state relay, etc.			Electronic type Very high frequency response Low power consumption
			Electromechanical
DC motor	Wound field	Separately excited	Speed can be controlled either by the voltage across the armature winding or by varying the field current
		Shunt	Constant-speed application
		Series	High starting torque, high acceleration torque, high speed with light load
		Compound	Low starting torque, good speed regulation Instability at heavy loads
	Permanent magnet	Conventional PM motor	High efficiency, high peak power, and fast response
		Moving-coil PM motor	Higher efficiency and lower inductance than conventional DC motor
		Torque motor	Designed to run for a long periods in a stalled or a low rpm condition
	Electronic commutation (brushless motor)		Fast response High efficiency, often exceeding 75% Long life, high reliability, no maintenance needed Low radio frequency interference and noise production
AC motor	AC induction motor		The most commonly used motor in industry Simple, rugged, and inexpensive
	AC synchronous motor		Rotor rotates at synchronous speed Very high efficiency over a wide range of speeds and loads Need an additional system to start
	Universal motor		Can operate in DC or AC Very high horsepower per pound ratio Relatively short operating life
Stepper motor	Hybrid		Change electrical pulses into mechanical movement Provide accurate positioning without feedback
	Variable reluctance		Low maintenance
			Electromagnetic
Solenoid type devices			Large force, short duration
Electromagnets, relay			On/off control
			Hydraulic and Pneumatic
Cylinder			Suitable for liner movement
Hydraulic motor	Gear type		Wide speed range
	Vane type		High horsepower output
	Piston type		High degree of reliability
Air motor	Rotary type		No electric shock hazard
	Reciprocating		Low maintenance
Valves	Directional control valves		
	Pressure control valves		
	Process control valves		
			Smart Material actuators
Piezoelectric & Electrostrictive			High frequency with small motion High voltage with low current excitation High resolution

(*continued*)

TABLE 16.2 Type of Actuators and Their Features (Continued)

Actuator	Features
Magnetostrictive	High frequency with small motion Low voltage with high current excitation
Shape Memory Alloy	Low voltage with high current excitation Low frequency with large motion
Electrorheological fluids	Very high voltage excitation Good resistance to mechanical shock and vibration Low frequency with large force
Micro- and Nanoactuators	
Micromotors	Suitable for micromechanical system
Microvalves	Can use available silicon processing technology, such as electrostatic motor
Micropumps	Can use any smart material

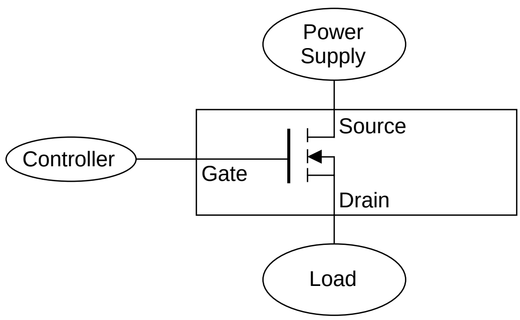

FIGURE 16.8 n-channel power MOSFET.

voltage and varying the voltage can easily control their speed. They are widely used in applications ranging from thousands of horsepower motors used in rolling mills to fractional horsepower motors used in automobiles (starter motors, fan motors, windshield wiper motors, etc.). Although they are costlier, they need DC power supply and require more maintenance compared to AC motors.

The governing equation of motion of a DC motor can be written as:

$$T = J\frac{d\omega}{dt} + T_L + T_{\text{loss}}$$

where T is torque, J is the total inertia, ω is the angular mechanical speed of the rotor, T_L is the torque applied to the motor shaft, and T_{loss} is the internal mechanical losses such as friction.

AC motors are the most popular since they use standard AC power, do not require brushes and commutator, and are therefore less expensive. AC motors can be further classified as the *induction motors, synchronous motors*, and *universal motors* according to their physical construction. The induction motor is simple, rugged, and maintenance free. They are available in many sizes and shapes based on number of phases used. For example, a three-phase induction motor is used in large-horsepower applications, such as pump drives, steel mill drives, hoist drives, and vehicle drives. The two-phase servomotor is used extensively in position control systems. Single-phase induction motors are widely used in many household appliances. The synchronous motor is one of the most efficient electrical motors in industry, so it is used in industry to reduce the cost of electrical power. In addition, synchronous motors rotate at synchronous speed, so they are also used in applications that require synchronous operations. The universal motors operate with either

AC or DC power supply. They are normally used in fractional horsepower application. The DC universal motor has the highest horsepower-per-pound ratio, but has a relatively short operating life.

The *stepper motor* is a discrete (incremental) positioning device that moves one step at a time for each pulse command input. Since they accept direct digital commands and produce a mechanical motion, the stepper motors are used widely in industrial control applications. They are mostly used in fractional horsepower applications. With the rapid progress in low cost and high frequency solid-state drives, they are finding increased applications.

Figure 16.9 shows a simplified unipolar stepper motor. The winding-1 is between the top and bottom stator pole, and the winding-2 is between the left and right motor poles. The rotor is a permanent magnet with six poles resulting in a single step angle of 30∞. With appropriate excitation of winding-1, the top stator pole becomes a north pole and the bottom stator pole becomes a south pole. This attracts the rotor into the position as shown. Now if the winding-1 is de-energized and winding-2 is energized, the rotor will turn 30∞. With appropriate choice of current flow through winding-2, the rotor can be rotated either clockwise or counterclockwise. By exciting the two windings in sequence, the motor can be made to rotate at a desired speed continuously.

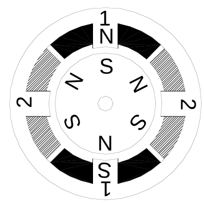

FIGURE 16.9 Unipolar stepper motor.

Electromagnetic Actuators

The *solenoid* is the most common electromagnetic actuator. A DC solenoid actuator consists of a soft iron core enclosed within a current carrying coil. When the coil is energized, a magnetic field is established that provides the force to push or pull the iron core. AC solenoid devices are also encountered, such as AC excitation relay.

A solenoid operated directional control valve is shown in Fig. 16.10. Normally, due to the spring force, the soft iron core is pushed to the extreme left position as shown. When the solenoid is excited, the soft iron core will move to the right extreme position thus providing the electromagnetic actuation.

Another important type is the *electromagnet*. The electromagnets are used extensively in applications that require large forces.

Hydraulic and Pneumatic Actuators

Hydraulic and pneumatic actuators are normally either *rotary motors* or *linear piston/cylinder* or *control valves*. They are ideally suited for generating very large forces coupled with large motion. Pneumatic actuators use air under pressure that is most suitable for low to medium force, short stroke, and high-speed applications. Hydraulic actuators use pressurized oil that is incompressible. They can produce very large forces coupled with large motion in a cost-effective manner. The disadvantage with the hydraulic actuators is that they are more complex and need more maintenance.

The rotary motors are usually used in applications where low speed and high torque are required. The cylinder/piston actuators are suited for application of linear motion such as aircraft flap control. Control valves in the form of directional control valves are used in conjunction with rotary motors and cylinders to control the fluid flow direction as shown in Fig. 16.10. In this solenoid operated directional control valve, the valve position dictates the direction motion of the cylinder/piston arrangement.

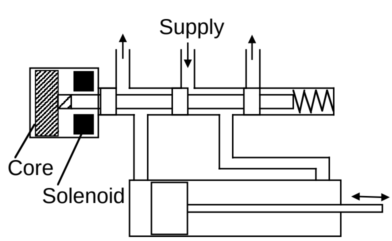

FIGURE 16.10 Solenoid operated directional control valve.

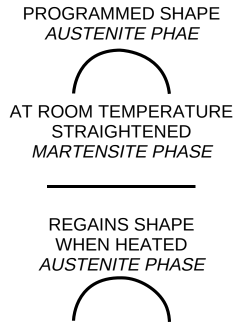

FIGURE 16.11 Phase changes of Shape Memory Alloy.

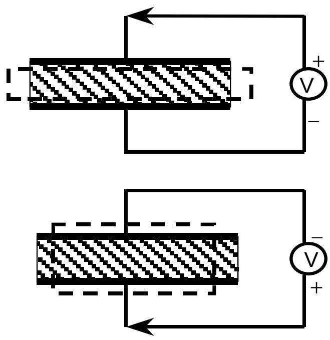

FIGURE 16.12 Piezoelectric actuator.

Smart Material Actuators

Unlike the conventional actuators, the smart material actuators typically become part of the load bearing structures. This is achieved by embedding the actuators in a distributed manner and integrating into the load bearing structure that could be used to suppress vibration, cancel the noise, and change shape. Of the many smart material actuators, *shape memory alloys, piezoelectric* (*PZT*), *magnetostrictive, Electrorheological fluids*, and *ion exchange polymers* are most common.

Shape Memory Alloys (SMA) are alloys of nickel and titanium that undergo phase transformation when subjected to a thermal field. The SMAs are also known as NITINOL for Nickel Titanium Naval Ordnance Laboratory. When cooled below a critical temperature, their crystal structure enters martensitic phase as shown in Fig. 16.11. In this state the alloy is plastic and can easily be manipulated. When the alloy is heated above the critical temperature (in the range of 50–80∞C), the phase changes to austenitic phase. Here the alloy resumes the shape that it formally had at the higher temperature. For example, a straight wire at room temperature can be made to regain its programmed semicircle shape when heated that has found applications in orthodontics and other tensioning devices. The wires are typically heated by passing a current (up to several amperes), 0 at very low voltage (2–10 V typical).

The PZT actuators are essentially piezocrystals with top and bottom conducting films as shown in Fig. 16.12. When an electric voltage is applied across the two conducting films, the crystal expands in the transverse direction as shown by the dotted lines. When the voltage polarity is reversed, the crystal contracts thereby providing bidirectional actuation. The interaction between the mechanical and electrical behavior of the piezoelectric materials can be expressed as:

$$T = c^E S - eE$$

where T is the stress, c^E is the elastic coefficients at constant electric field, S is the strain, e is the dielectric permitivity, and E is the electric field.

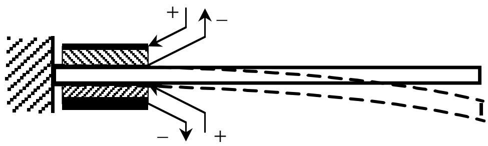

FIGURE 16.13 Vibration of beam using piezoelectric actuators.

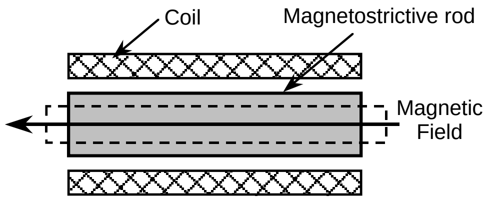

FIGURE 16.14 Magnetostrictive rod actuator.

One application of these actuators is as shown in Fig. 16.13. The two piezoelectric patches are excited with opposite polarity to create transverse vibration in the cantilever beam. These actuators provide high bandwidth (0–10 kHz typical) with small displacement. Since there are no moving parts to the actuator, it is compact and ideally suited for micro and nano actuation. Unlike the bidirectional actuation of piezoelectric actuators, the *electrostriction* effect is a second-order effect, i.e., it responds to an electric field with unidirectional expansion regardless of polarity.

Magnetostrictive material is an alloy of terbium, dysprosium, and iron that generates mechanical strains up to 2000 microstrain in response to applied magnetic fields. They are available in the form of rods, plates, washers, and powder. Figure 16.14 shows a typical magnetostrictive rod actuator that is surrounded by a magnetic coil. When the coil is excited, the rod elongates in proportion to the intensity of the magnetic field established. The magnetomechanical relationship is given as:

$$\varepsilon = S^H \sigma + dH$$

where, ε is the strain, S^H the compliance at constant magnetic filed, σ the stress, d the magnetostriction constant, and H the magnetic field intensity.

Ion exchange polymers exploit the electro-osmosis phenomenon of the natural ionic polymers for purposes of actuation. When a voltage potential is applied across the cross-linked polyelectrolytic network, the ionizable groups attain a net charge generating a mechanical deformation. These types of actuators have been used to develop artificial muscles and artificial limbs. The primary advantage is their capacity to produce large deformation with a relatively low voltage excitation.

Micro- and Nanoactuators

Microactuators, also called micromachines, microelectromechanical system (MEMS), and microsystems are the tiny mobile devices being developed utilizing the standard microelectronics processes with the integration of semiconductors and machined micromechanical elements. Another definition states that any device produced by assembling extremely small functional parts of around 1–15 mm is called a micromachine.

In *electrostatic motors*, electrostatic force is dominant, unlike the conventional motors that are based on magnetic forces. For smaller micromechanical systems the electrostatic forces are well suited as an actuating force. Figure 16.15 shows one type of electrostatic motor. The rotor is an annular disk with uniform permitivity and conductivity. In operation, a voltage is applied to the two conducting parallel

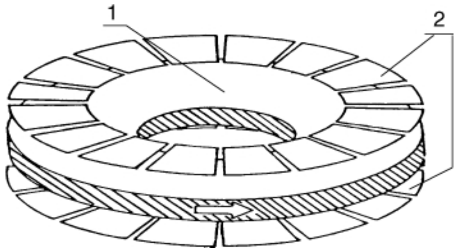

FIGURE 16.15 Electrostatic motor: 1-rotor, 2-stator electrodes.

plates separated by an insulation layer. The rotor rotates with a constant velocity between the two coplanar concentric arrays of stator electrodes.

Selection Criteria

The selection of the proper actuator is more complicated than selection of the sensors, primarily due to their effect on the dynamic behavior of the overall system. Furthermore, the selection of the actuator dominates the power needs and the coupling mechanisms of the entire system. The coupling mechanism can sometimes be completely avoided if the actuator provides the output that can be directly interfaced to the physical system. For example, choosing a linear motor in place of a rotary motor can eliminate the need of a coupling mechanism to convert rotary motion to linear motion.

In general, the following performance parameters must be addressed before choosing an actuator for a specific need:

Continuous power output—The maximum force/torque attainable continuously without exceeding the temperature limits
Range of motion—The range of linear/rotary motion
Resolution—The minimum increment of force/torque attainable
Accuracy—Linearity of the relationship between the input and output
Peak force/torque—The force/torque at which the actuator stalls
Heat dissipation—Maximum wattage of heat dissipation in continuous operation
Speed characteristics—Force/torque versus speed relationship
No load speed—Typical operating speed/velocity with no external load
Frequency response—The range of frequency over which the output follows the input faithfully, applicable to linear actuators
Power requirement—Type of power (AC or DC), number of phases, voltage level, and current capacity

In addition to the above-referred criteria, many other factors become important depending upon the type of power and the coupling mechanism required. For example, if a rack- and-pinion coupling mechanism is chosen, the backlash and friction will affect the resolution of the actuating unit.