LECTURE 1. **INTRODUCTION TO AUTOMATION**

1. AUTOMATION

After the first transistor was invented, then integrated circuits as well as digital computers were developed in the period (1950-1960). In the manufacturing field, the first numerically controlled milling machines were introduced. In 1967, computer numerically controlled (CNC) machines were developed and put into use. Integration of computer and machines greatly improved the flexibility associated with the machines and manufacturing systems. Fixed automation started to evolve into flexible automation. The fast development of computer and information technologies led to information revolution in many fields including manufacturing. In the early 1970s, computer-integrated manufacturing (CIM) was coined to provide a new concept and direction to grow manufacturing enterprises. The CIM concept has changed over time from computerized workcell, flexible manufacturing systems, large scale automation, computer aided design and manufacturing (CAD/CAM), interfacing and communications concepts to the current state: an information system that controls data flow among all the function units in a manufacturing enterprise.

1.1 Automation definition:

Automation is the use of control systems and information technologies to reduce the need for human work in the production of goods and services. In the scope of industrialization, automation is a step beyond mechanization. Whereas mechanization provided human operators with machinery to assist them with the muscular requirements of work, automation greatly decreases the need for human sensory and requirements as well. Automation plays an increasingly important role in the world economy and in daily experience.

Some other simple definitions:

- The automatic operation or control of equipment, a process, or a system.

- The techniques and equipment used to achieve automatic operation or control.
- The use of computers to control a particular process in order to increase reliability and efficiency, often through the replacement of employees. For a manufacturer, this could entail using robotic assembly lines to manufacture a product.

1.2 Automation Types:

There are two basic types of automation are available to today's automation engineer.

1. ***Hard Automation***

The classical type of automation, typical of the 1940s and 1950s, is fixed (hard) equipment, usually custom-made and designed to facilitate the manufacture of a specific product. Hard automation can achieve very high-speed production, but it is usually quite expensive. This expense can become very painful when a product model or design change is introduced. Fixed or hard automation, as the name implies, is not very adjustable or adaptable to product or process change. Therefore, at the very least, a certain amount of product and market stability is prerequisite to a decision to install hard automation equipment, and at the most, hard automation requires huge volumes to justify such a decision.

For example, the production of electric light bulbs. General Electric alone produces approximately two billion light bulbs per year. With this kind of volume, it is easy to justify specialized, high-speed, fixed automation equipment. In addition to their huge volumes, electic light bulbs have achieved a great deal of product stability. It appears unlikely that the incandescent light bulb will become obsolete for several decades. When it does so, millions of dollars of fixed, hard automation equipment will become obsolete with it.

2. ***Flexible Automation***

Contrasted with fixed or hard automation is the newer type of automation available to today's automation engineer: flexible automation. We hesitate to call this type of automation "soft" because it consists of both hardware and software (computer programs and programmed operating systems). However, flexible automation is certainly soft compared to hard or fixed automation.

The salient and identifying feature of flexible automation equipment is that it is programmable, and therefore reprogrammable. Today, this usually means that the equipment has a digital computer as one of its components, but this was not always so. Early numerical control machines could be considered flexible automation, but they were not computer-based. The reprogrammability of flexible automation equipment gives it a key advantage over hard automation. Huge volumes are not necessary to justify flexible automation, because after the production run is complete the flexible automation equipment can be used again to produce something else. The equipment can be either reprogrammed or preprogrammed for a variety of tasks, calling upon its various learned routines by retrieving programmed software from a suitable storage medium such as magnetic tape or disk.

3. BUILDING BLOCKS OF AUTOMATION

The automation components can be classified into four basic categories, depending upon how they are used:

1. Sensors.
2. Analyzers.
3. Actuators.
4. Drives.

The approximate relationship of these four categories is shown in (Figure 1.3). The operator here is a human, not a robot. The industrial robot is a part of the automated system (upper half of the figure). The industrial robot is actually an integrated system made up of all four of the basic automation component categories: sensors, analyzers, actuators, and drives.

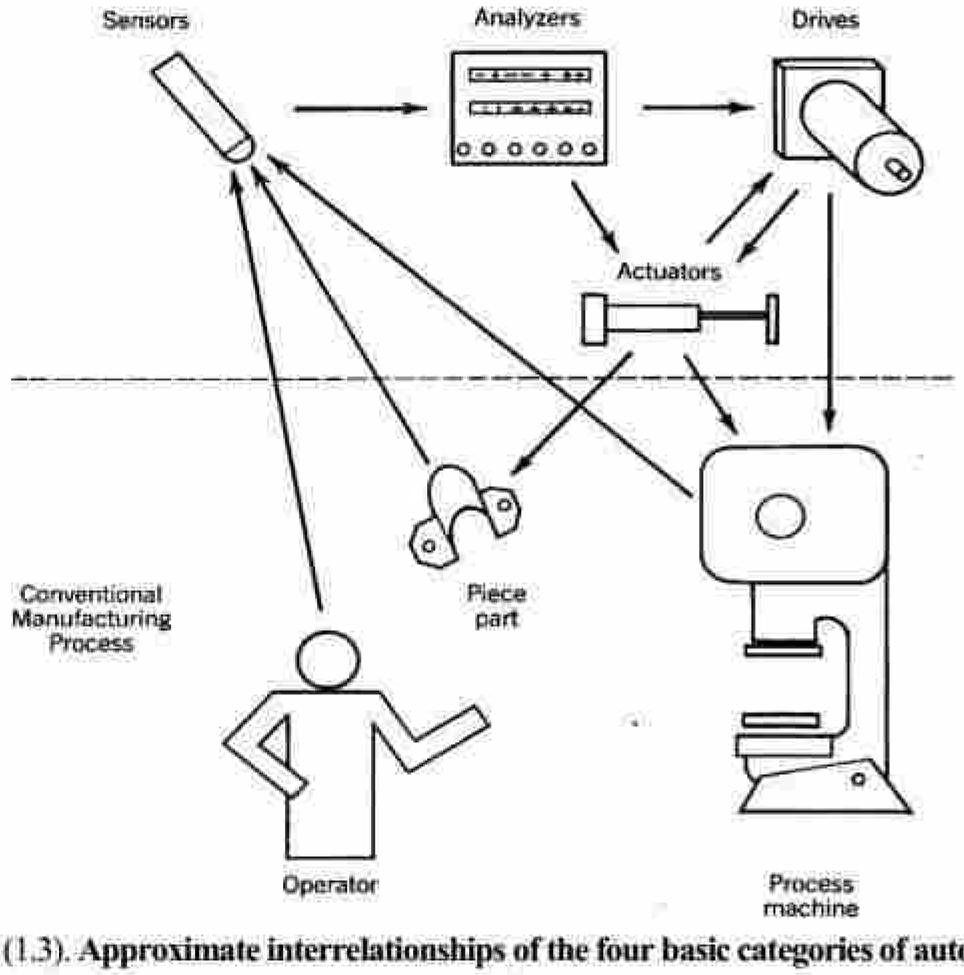


Figure (1.3). **Approximate interrelationships of the four basic categories of automation components.**

1. SENSORS

Sensors are the first link between the typical automated system and the conventional process (*the real world*). Sensors convey information from the manufacturing process equipment, the piece part being manufactured, and from the human operator.

1.1 MANUAL SWITCHES

The automation system is linked to the operator by the manual Switches. The operator may desire to turn the system on or off or make adjustments to the automated cycle.

The manual switch can be *CLOSED* (*ON*) or *OPEN* (*OFF*). Most switches have two stable states: on and off. However, many switches have only a single stable state. Such switches have a spring action that returns them to normal state whenever they are released from an outside force. That normal state can either be in the open position or the closed position, which leads to the terms *NORMALLY OPEN* (*NO*) and *NORMALLY CLOSED* (*NC*) used to describe switches.

Manual switches can be divided into:

- single-pole, single-throw (*SPST*) (Figure (2.1a)).
- single-pole, double-throw (*SPDT*) (Figure (2.1b)).
- double-pole, single-throw (*DPST*) (Figure (2.1c)).
- double-pole, double-throw (*DPDT*) (Figure (2.1d)).
- multiple throws (*rotary switch*) (Figure (2.2)).
- momentary switch (*pushbutton*) (Figure (2.3)).

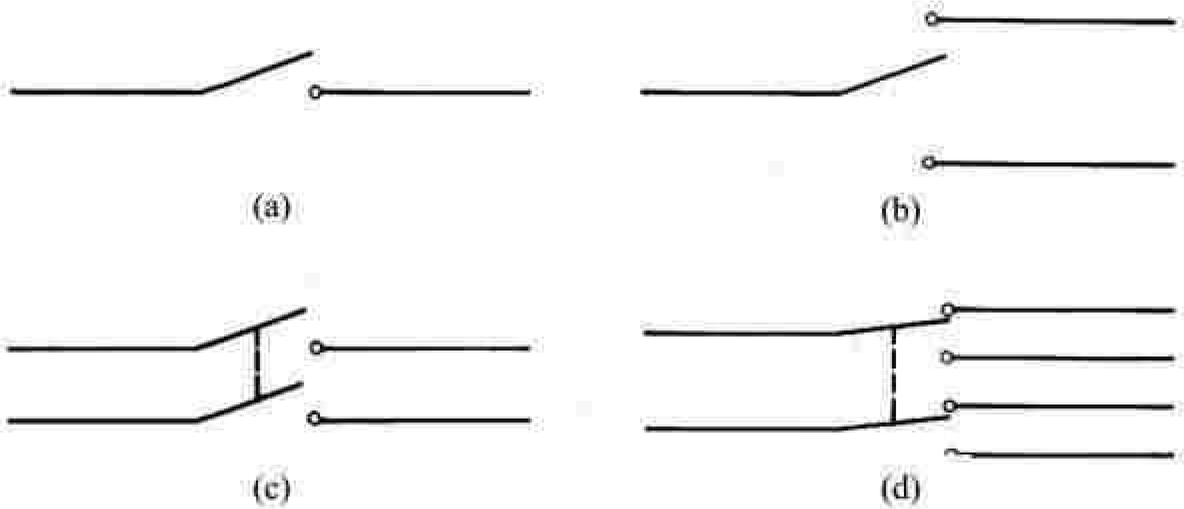


Figure (2.1). **Example electric switch configuration, (a) Simple switch: single-pole; single-throw (*SPST*); (b) Single-pole, double-throw switch (*SPDT*); (c) Double-pole, single-throw switch (*DPST*); (d) Double-pole, double-throw switch (*DPDT*)**

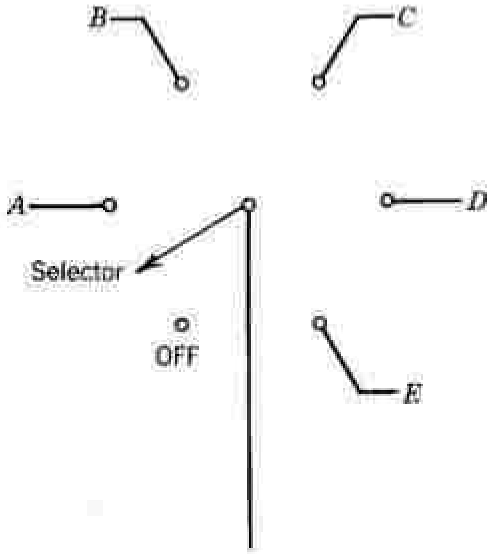


Figure (2.2). **Rotary switch**

Figure (2.3). **Momentary (*spring-return*) pushbutton: (a) Normally open; (b) Normally closed**

1.2 LIMIT SWITCHES

Limit switches are actuated mechanically from the manufacturing process, the material, or the automated system itself, without intervention by the operator, so any limit switch considered as an automatic input.

➢ There are thousands of styles and models of limit switches (Figure (2.4)) (more than manual switches).

Because the limit switches must be designed to be exactly correct in size, lever travel, force of actuation, and ruggedness for the specific automation application. Also manual switches are designed for human operators who have relatively similar physical characteristics. While limit switches are used in very difficult industrial and manufacturing situations.

➢ Robot systems employ limit switches both in the construction of the robot itself and in the peripheral equipment. Limit switches can be used to limit the travel of a robot arm on any of its axes of motion.

➢ When the limit is reached, a circuit is opened (or closed) that removes power from that axis of motion either directly or via the robot controller.

1.3 Proximity Switches

➢ Proximity switches do not require physical contact or light radiation to sense an object because they can sense the presence of a nearby object without touching it. Proximity switches can be used on robots to give the robot certain advantages over human operators. There are three physical bases for proximity switches that can respond to any object-metal or nonmetal (Figure (2.5)).

➢ One type uses an electromagnetic (radio frequency) antenna specially designed and placed to fit the application. The antenna receives a signal transmitted by another strategically placed antenna, but the reception of the signal is disturbed by the intrusion of any object into the field. Unfortunately the sensitivity of the antenna is related to the electrical properties of the material of the object being detected. The size of the object to be detected also plays a role.

- Another type of proximity switch that works for nonmetallic objects is the sonar type. Sonar systems transmit and receive reflections of pressure waves to detect object presence. These pressure waves are commonly called sound waves when their frequencies are within the audible range. Most sonar systems, however, use ultrasonic radiation, which has frequencies higher than audible pressure waves.

- A sophisticated proximity switch system employs *the Hall Effect*, in which a small voltage is generated across a conductor carrying current in an external magnetic field. The amount of Hall voltage is proportional to the flux density of the magnetic field, which is perpendicular to the flow of current. This proportionality enables Hall effect proximity switches to detect not only presence but also relative distance to a sensed object.

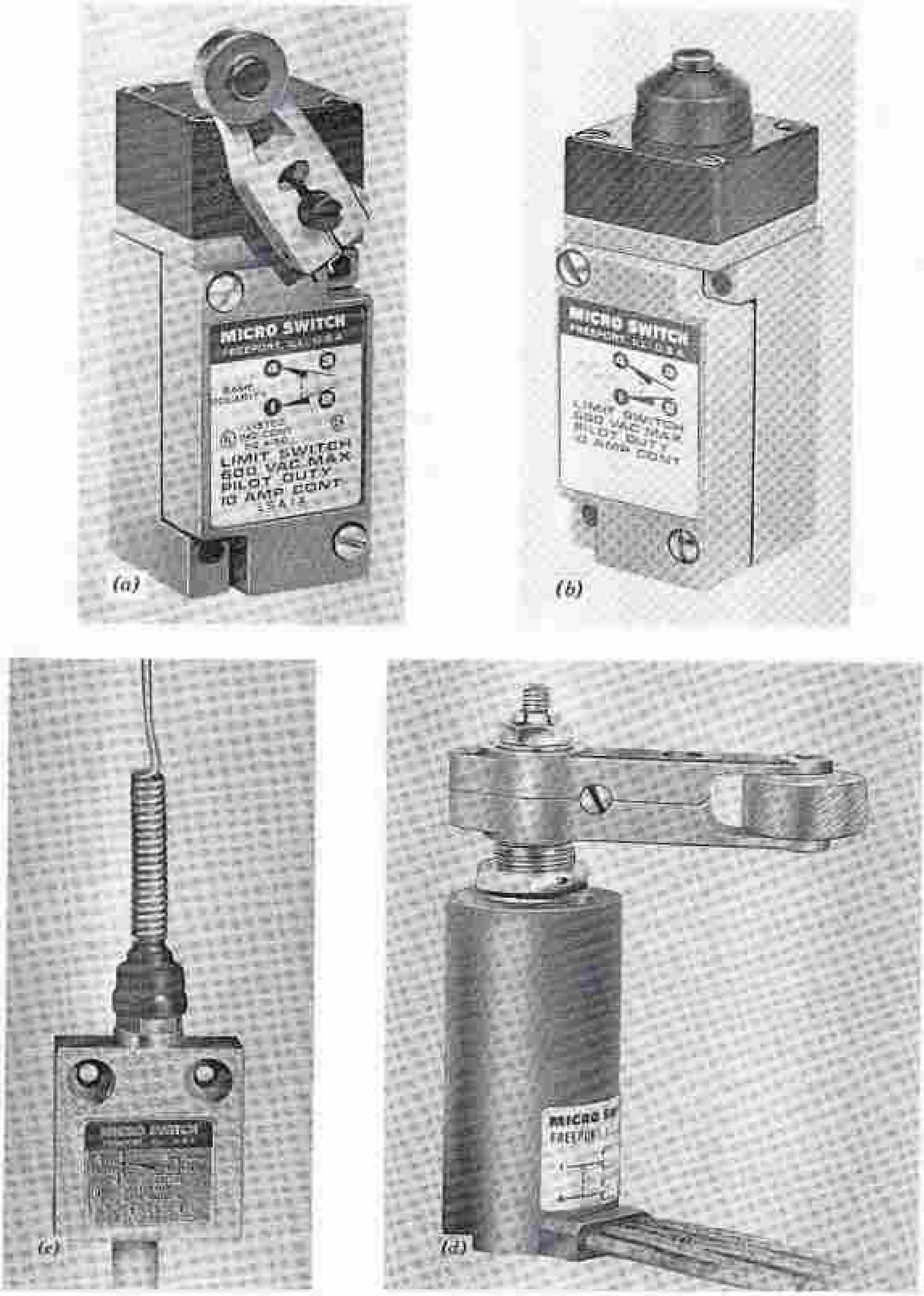


Figure (2.4). **Examples of popular models and some of the more unusual styles of limit switches: *(a)* Standard side rotary limit switch; *(b)* Standard top plunger limit switch; *(c)* Miniature limit switch; *(d)* Aircraft-type limit switch**

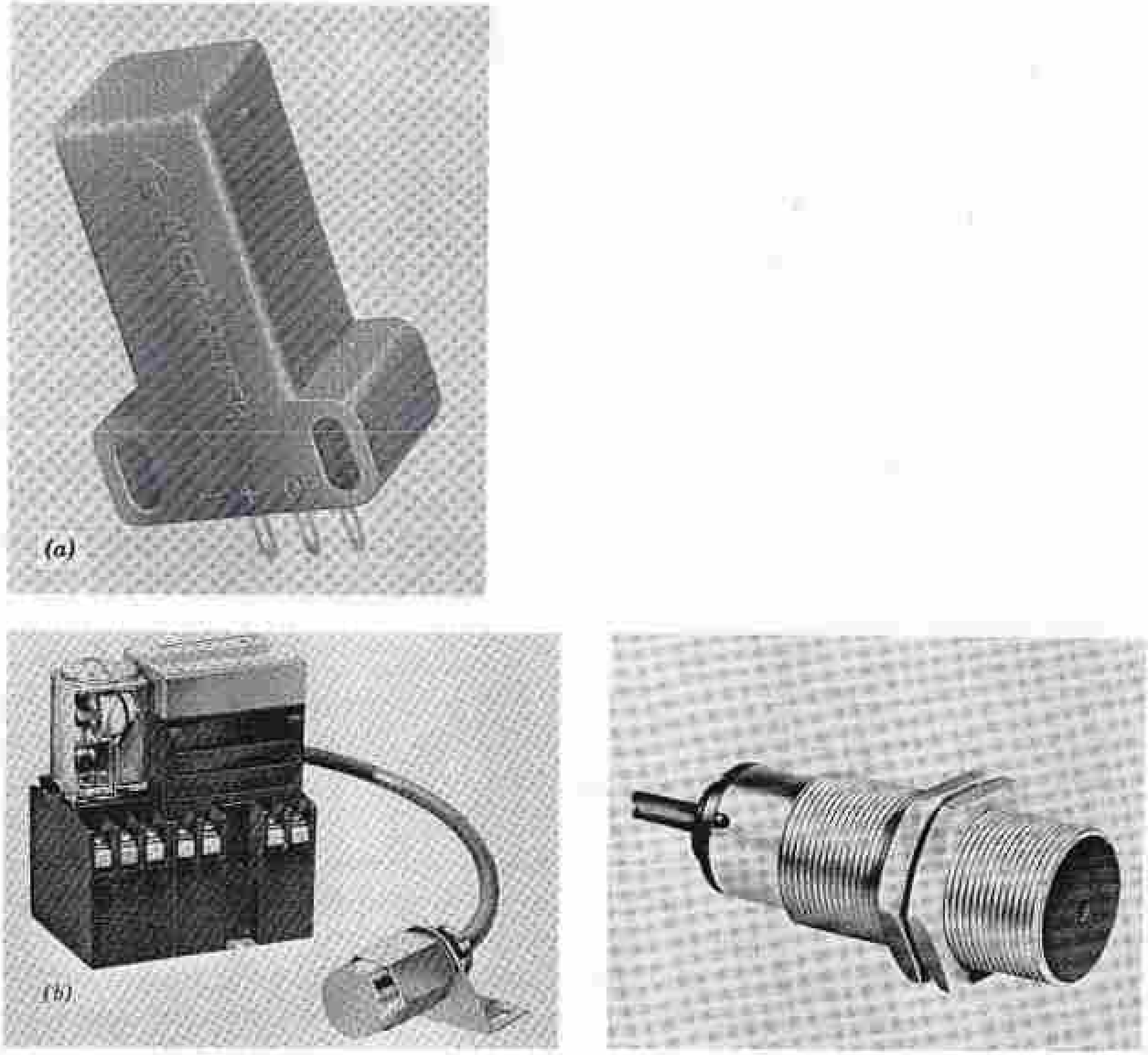


Figure (2.5). **Two types of proximity switches: *(a)* Proximity switch acts only upon presentation of a *ferrous* metal object within its sensing range; *(b)* Proximity switch is capable of sensing both *ferrous* and *nonferrous* metal objects**

1.4 Photoelectric Sensors

Two basic approaches for employing photoelectrics are in use. The first approach uses a photocell to detect the presence of light radiating naturally from some object in the process. The second approach to photoelectrics employs a beam of light emitted by an artificial light source. The principal purpose of the second approach is to detect the presence or absence of objects in the path of the beam. The beam emitter can be a separate unit or can be incorporated into the sensor. The combination variety requires some type of natural or artificial reflector to direct the light beam back to the emitter/sensor.

Reflective surfaces for photoelectric systems are of three types: *diffuse, specular reflective* and *retroreflective* (Figure (2.6)). *The diffuse reflective surface* is the lowest in cost and describes most reflective surfaces. Even an ordinary white object acts as a diffuse reflective surface in that it reflects light but not images. Diffuse reflectors *scatter so much light* that only a small fraction makes its way back to the photoelectric sensor.

Specular reflective surfaces are most often associated with the word *reflective* and include mirrors and very shiny surfaces. Specular reflective surfaces obey the physical law that the angle of incidence equals the angle of reflection. It is obvious that the source and sensor must be more closely aimed for specular reflective surfaces than for diffuse surfaces. For systems in which the emitter and sensor are mounted in the same unit, the plane of the specular reflective surface must be perpendicular to the direction of the incident beam or the reflected beam will be lost. this can be either a disadvantage or an advantage.

Retroreflective surfaces are the most complex and expensive of the three types. Retroreflectors are capable of reflecting back to the source a large percentage of the light beam regardless of the angle of incidence. Basically, the retroreflective surface violates the physical principle that angle of incidence equals angle of reflection, except when the plane of the surface is perpendicular to the incident beam.

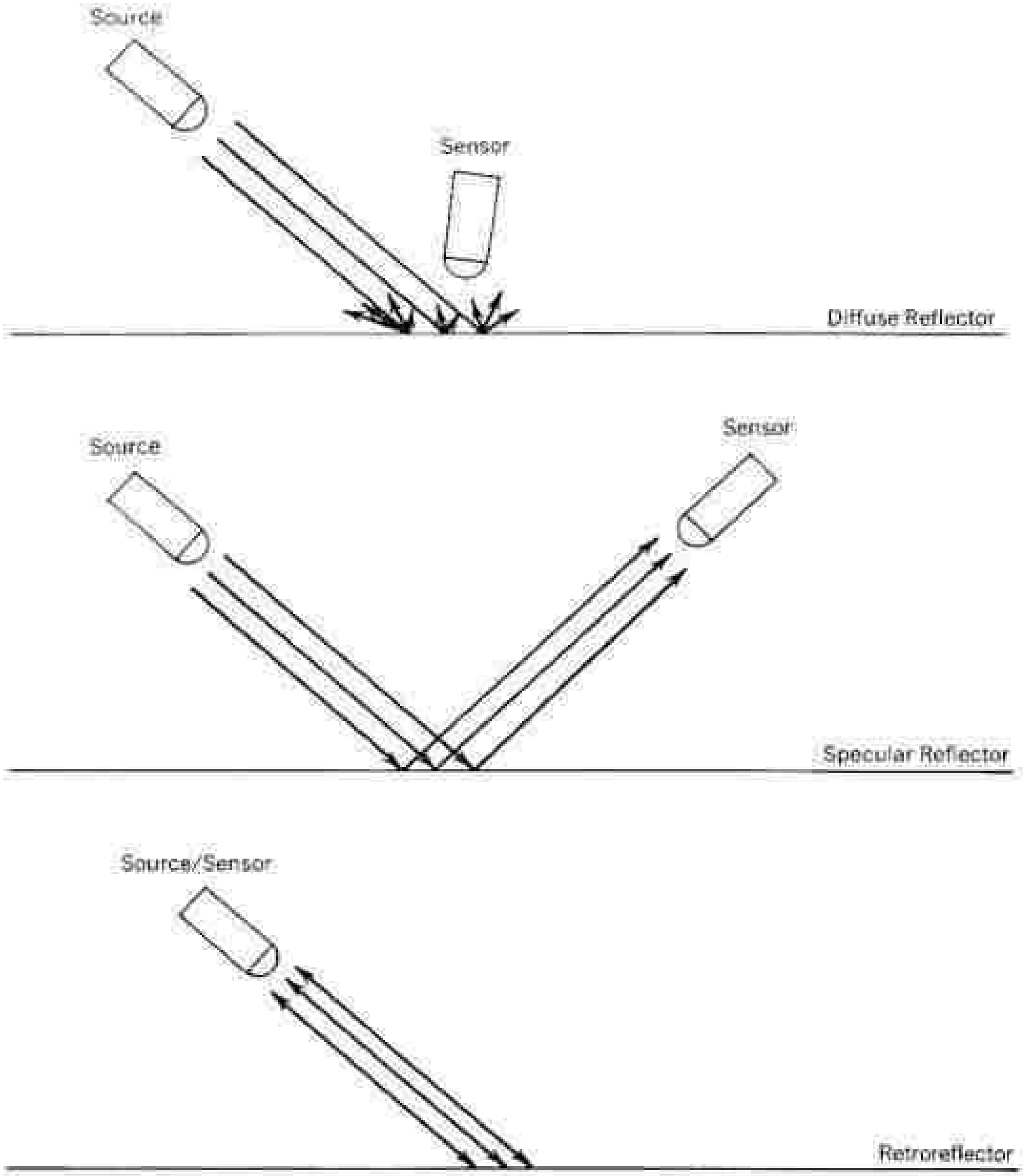
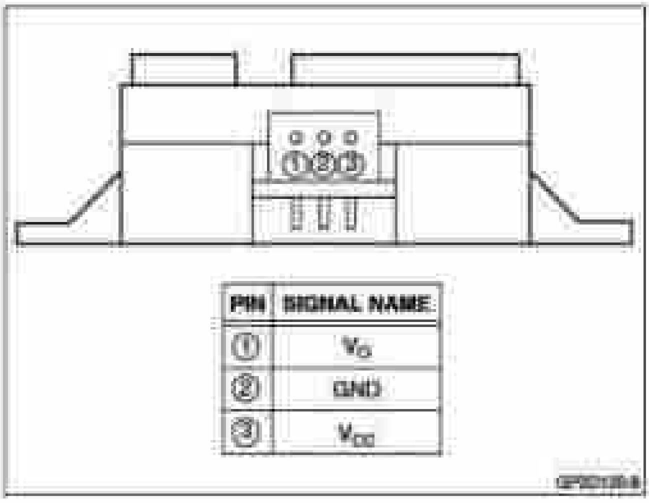


Figure (2.6). **Three types of reflective surfaces for photoelectric systems**

BUILDING BLOCKS OF AUTOMATION

Example of Optoelectronic Sensor (Sharp GP2D120)

The *GP2D120* is a distance measuring sensor with integrated signal processing and analog voltage output.



PIN	SIGNAL NAME
①	V_O
②	GND
③	V_{CC}

Features

- analog output;
- effective range: 4 to 30 cm;
- typical response time: 39 ms;
- typical start up delay: 44 ms
- average Current Consumption: 33 mA

If a prominent boundary line exists in the surface being measured, it should be aligned vertically to avoid measurement error.

When measuring the distance to objects in motion, align the sensor so that the motion is in the horizontal direction instead of vertical (Figure (3.1)).

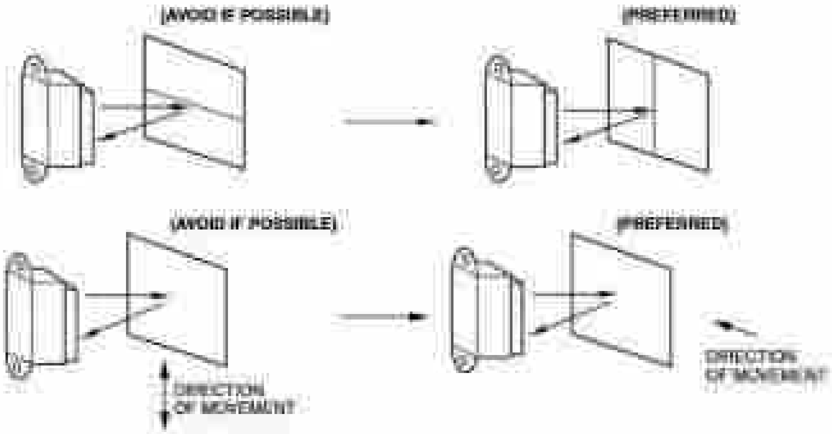


Figure (3.1). **Proper alignment to surface being measured and proper alignment to moving surfaces**

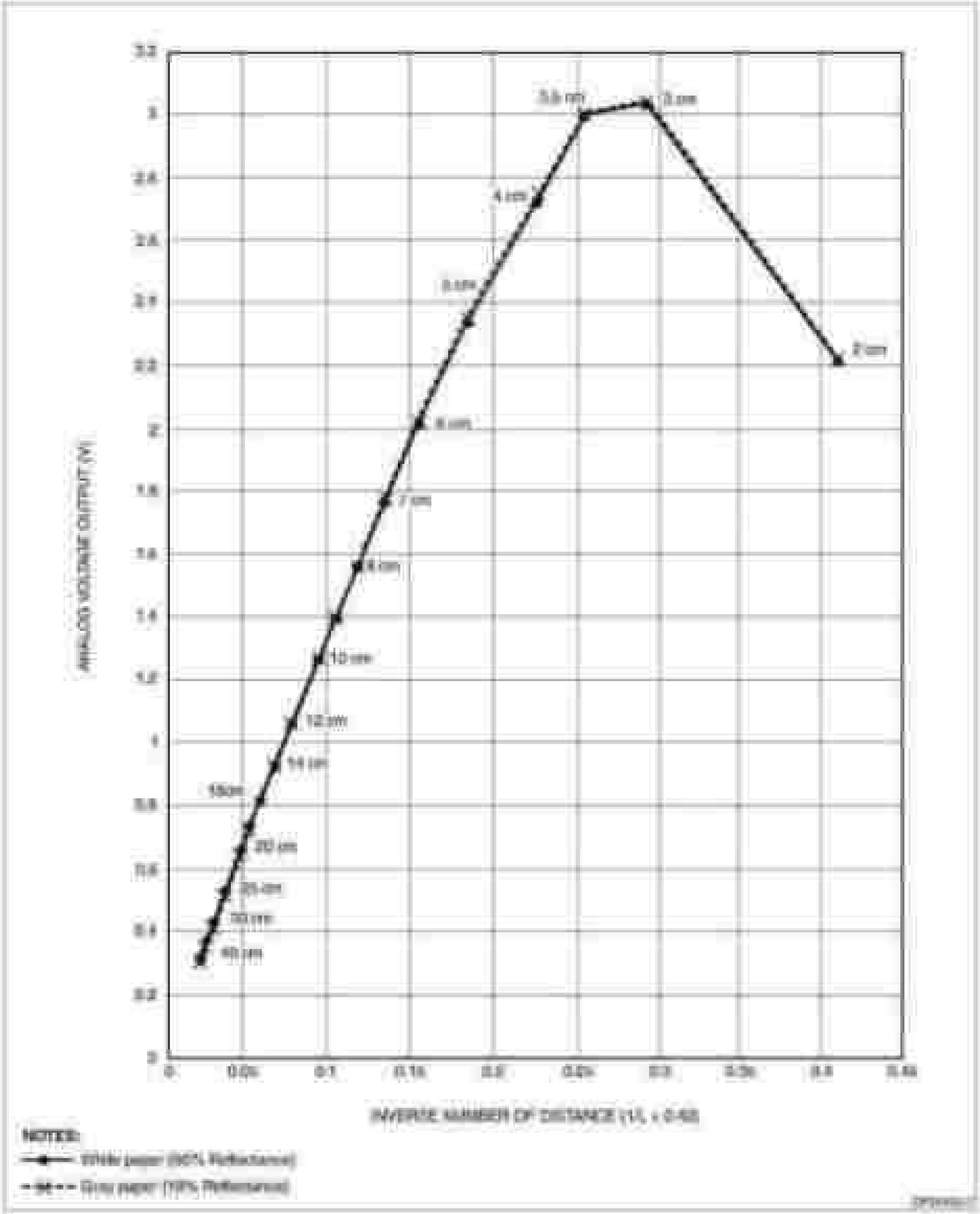


Figure (3.2). ***GP2D120* example of output characteristics with inverse number of distance**

1.5. INFRARED SENSORS

It is useful to detect radiation outside the visible range. Infrared sensors respond to radiation in the range of wavelengths just beyond the visible spectrum at the red end.

- ✓ Infrared sensors are very useful when used with artificial beams to detect the presence or absence of objects, even more so than are photoelectric systems. Since infrared radiation is invisible.
- ✓ There are some advantages of using infrared beams and receivers instead of ordinary photoelectrics. Also, infrared sensors are virtually unaffected by stray ambient light with obvious advantages.
- ✓ A strategy that is gaining popularity is the use of a modulated infrared beam, in which the source is pulsed to provide much greater intensity and the sensor is modulated to receive at the same frequency.

1.6. FIBER OPTICS

- Fiber optics is flexible pipes of glass or plastic that can be used to bend light beams around corners. When bundles of fibers are used together, whole images can be transmitted. However, the typical automation application is to use one fiber to transmit a light beam that is sensed by the system as either present or absent.
- An advantage of fiber optics is their surprising efficiency. Fiber optics are so efficient that it becomes worthwhile for the telephone industry to convert communications circuits from electrical signals to modulated light signals for transmission via fiber optics and subsequent reconversion at the receiving end.

1.7. LASERS

- Lasers are concentrated, amplified beams of collimated light.
- In automated systems, the laser is useful in providing very long, narrow, precise light beams.
- The precision of these beams makes them excellent for detecting tiny objects that are capable of breaking the beam at large and varying distances. The presence or

absence of a continuous beam then can be used as a logic input to an automated control system. Such precision also makes the laser a good tool for dimensional measurement. (Figure (3.3)).

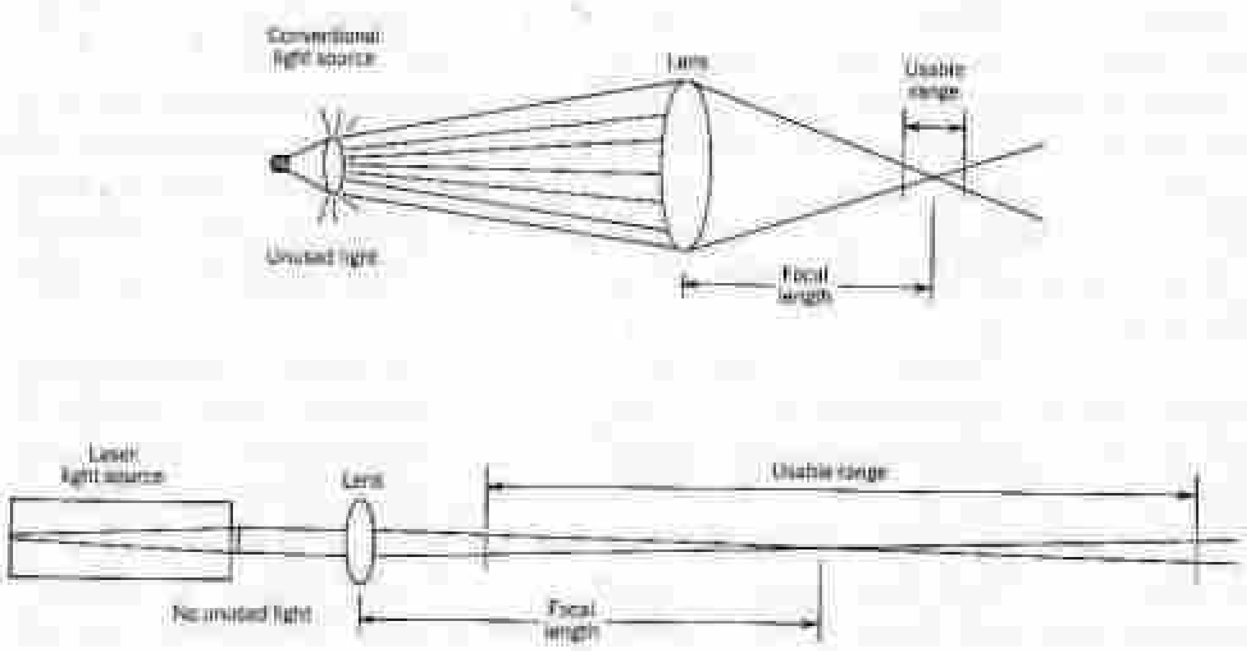


Figure (3.3). **Comparison of usable range of conventional light sources versus laser light sources for the purpose of locating objects at a distance**

2. ANALYZERS

After the information is sensed by an automated system, it must be registered and analyzed for content, and then a decision must be made by the system as to what action should be taken.

2.1. COMPUTERS

- ✓ Computers are so important as analyzers.
- ✓ Digital computers are the primary means of analyzing automation system inputs. Computers are extremely versatile in that the ways they can be programmed to manipulate data are limitless.

- ✓ Increasing in the number of feasible applications of manufacturing automation and rapid growth of industrial robots due to the continuing miniaturization of computer circuits along with decreasing costs.

2.2. COUNTERS

1. In Automation, It is frequently useful to determine how many of various items are present or pass through an automated system. This function can be handled either internally by a computer or programmable controller or externally by a separate device called a *counter*.
2. The counter can be mechanical, but most automatic systems employ solid-state electronic counters. If the counter is a separate unit, it will usually have a display to report current status of the count in progress.
3. The quantity counted is usually a series of voltage pulses that have been generated by a sensor detecting some physical quantity to the automated system
4. Example, glass bottles coming down a conveyor line. The curved glass would be somewhat specular, and at a precise position the angle would be exactly right to reflect a pulse of light from a positioned source upon a photoelectric sensor, as shown in Figure (3.4). The sensor would convert the light pulse to a voltage pulse, which would be transmitted to the counter.

Note in Figure (3.4) that the spacing of the voltage pulses is not uniform. It is also possible for the peaks themselves to be of varying width (time) and amplitude (voltage). This is entirely satisfactory within limits, of course because most industrial counters are capable of detecting peaks and peak intervals of less than 100 μs duration. There is also some tolerance in the voltage required to generate the count.

In Figure (3.4), the counter shown has two display registers. The top register is an electronic display and represents the current count in progress. The bottom register is mechanical and represents a preset number that acts as a target to trigger an output signal when the current count register reaches the target value. This feature enables the counter to cause something to happen in the manufacturing process.

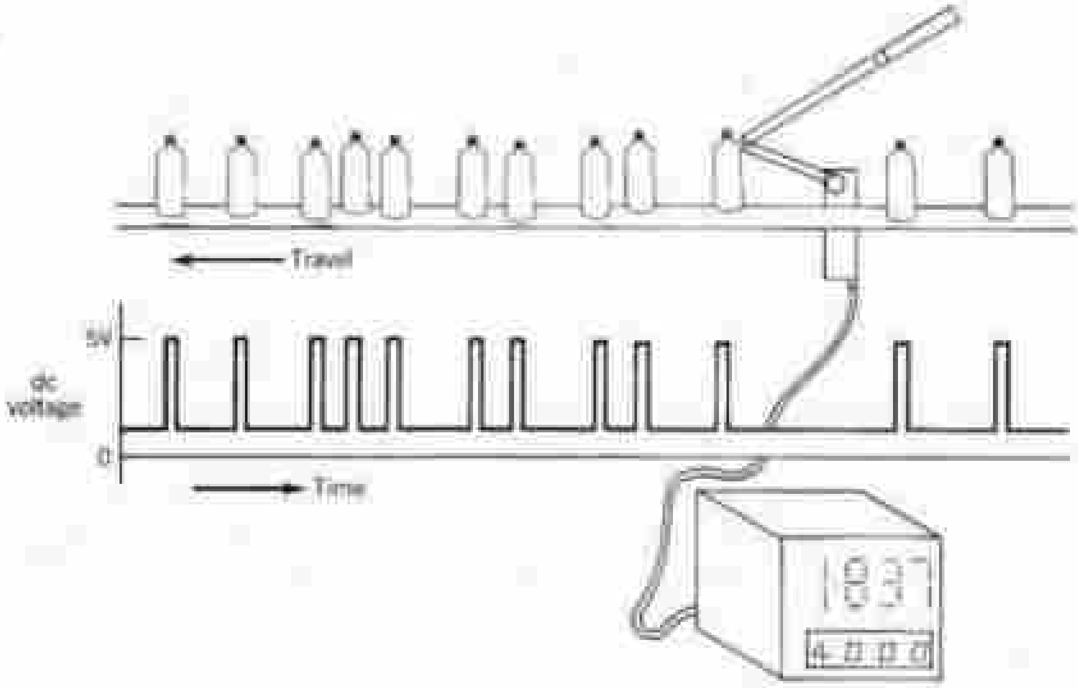


Figure (3.4). **Automatic counting system using photoelectrics to count bottles coming down a conveyor line**

2.3. TIMERS

- If precise clock pulses are available, a counter that counts these pulses becomes a *timer*.
- An industrial timer is more similar to an alarm clock than an ordinary clock. When elapsed time becomes equal to a preset value, an output signal is generated.
- Like counters, industrial timers can be bidirectional that is, time up and time down.
- Timers are very useful devices in industrial logic control systems.
- Timers often have the additional feature of being interruptible that is, they can be cumulative in summing the various periods of voltage up time interrupted by various periods of voltage down time.
- The applications of industrial timers to robots and manufacturing automation is even greater than that of the industrial counters.
- Industrial timers available as external separate units or can be internal to programmable controllers and on-line process control computers.

2.4. BAR CODE READERS

- Bar code reader is an analyzing system that incorporates laser scanner along with timers and counters.
- Successive bars of varying width, as seen in Figure 3.5, are scanned and counted. The scan is orthogonal to the bars, and thus voltage pulses from the photoelectric sensor can be compared to determine individual bar widths. The sequence and width of bars is then analyzed to decode the bars and translate them to an alphanumeric data string for processing by the automated system, as shown in Figure 3.6.

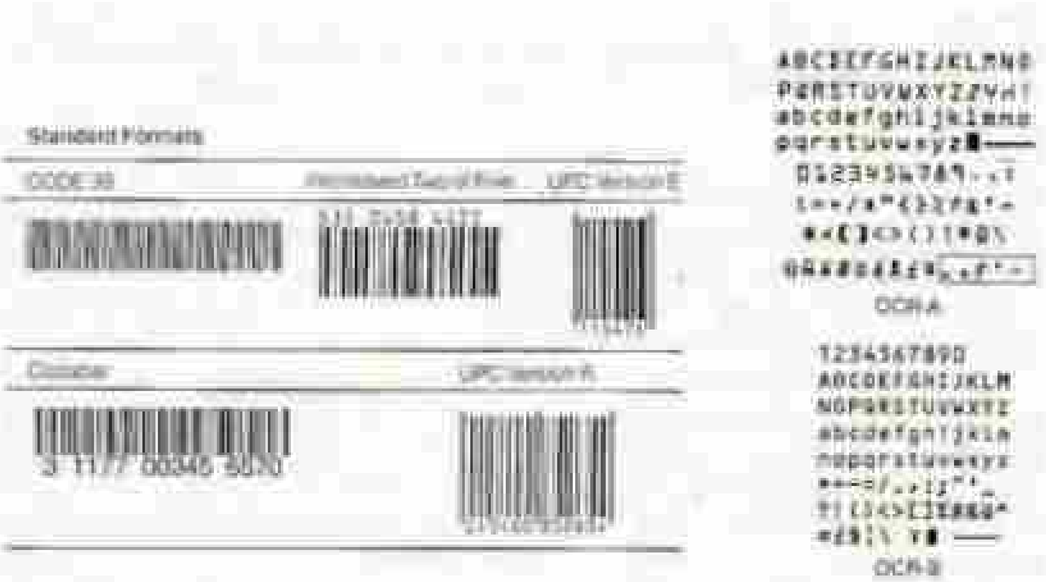


Figure (3.5). **Examples of standard bar code and optical character recognition formats**

Alternatives to bar code readers can be easier for humans to read but present more problems in manufacturing automation systems. Figure (3.5) shows two optical character recognition formats that are used in some automated systems.

Unfortunately, the automatic recognition of these characters is a much more accurate operation than is needed for bar codes. Alignment is important, and some of the characters have tiny differences. Consider the problem in designing a scan procedure to distinguish between the letters *E* and *F*, *O* and *Q*, or *P* and *R*. Multiple scans are essential, and defective type or smudges on the labels can easily result in a misread. Scanning programs contain checks for inconsistencies that can prompt a rescan if necessary to assure a valid read. After repeated attempts with no success, the scanner can be programmed to report "*INVALID READ*". Some label deficiencies, however, can trick the scanner into an *erroneous read*, a problem that is usually worse than an *invalid read*.

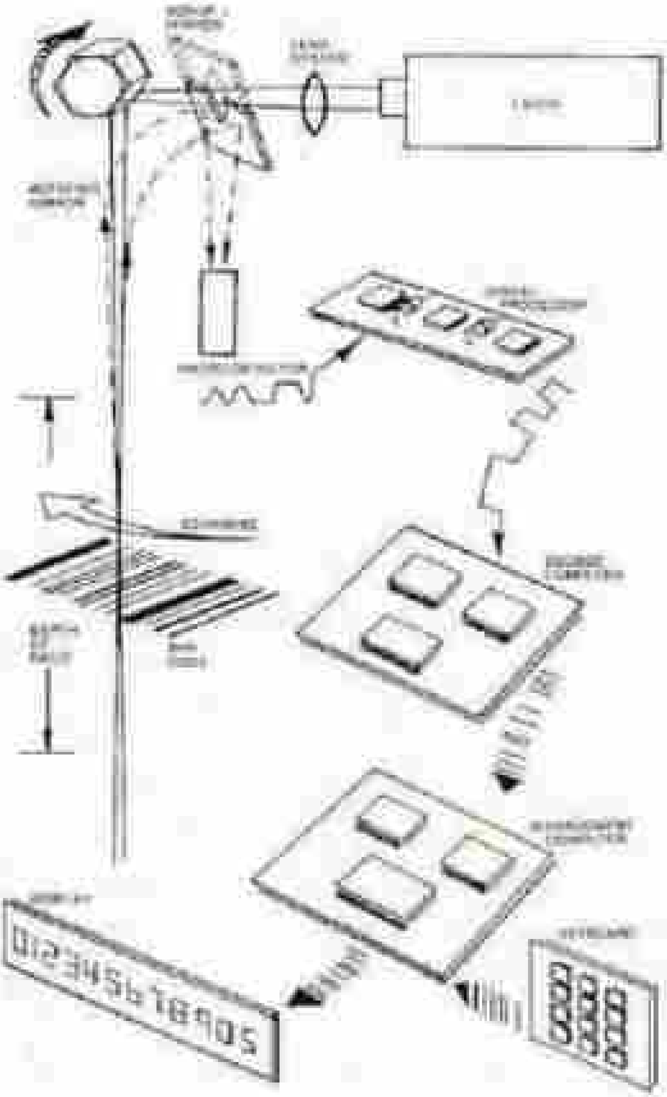


Figure 3.6. **Laser bar code reader scans a label and processes the code to produce a numeric string for use by an automated data system**

Bar code scanners usually employ lasers because the concentrated coherent laser light can retain its focus over a larger depth of field which explains why the bar code label does not have to be precisely positioned at a fixed distance from the scanner.

BUILDING BLOCKS OF AUTOMATION

2.5. OPTICAL ENCODERS

✓ Optical encoder useful for automatically detecting shaft rotation. The shaft rotation information can be fed back into a computer or control mechanism for controlling velocity or position of the shaft. Such a device has application for robots and numerical control machine tools.

✓ Optical encoders can be either incremental or absolute.

✓ An encoder is a simple device that can output a digital signal for each small portion of a movement. The encoder wheel or strip is divided into small sections, (Figure (3.1)). Each section is either opaque or clear. (Also it can be either reflective or nonreflective.) A light source, such as an *LED*, on one side provides a beam of light to the other side of the encoder wheel or strip, where it is seen by another light-sensitive sensor, such as a phototransistor. If the wheel's angular position (or in the case of a strip, the linear position) is such that the light can go through, the sensor on the opposite side will be turned on and will have a high signal. If the angular position of the wheel is such that the light is stopped, the sensor will be off, and its output will be low (thus, a digital output). As the wheel rotates, it can continuously send signals. If the signals are counted, the approximate total angular displacement of the wheel can be measured at any time.

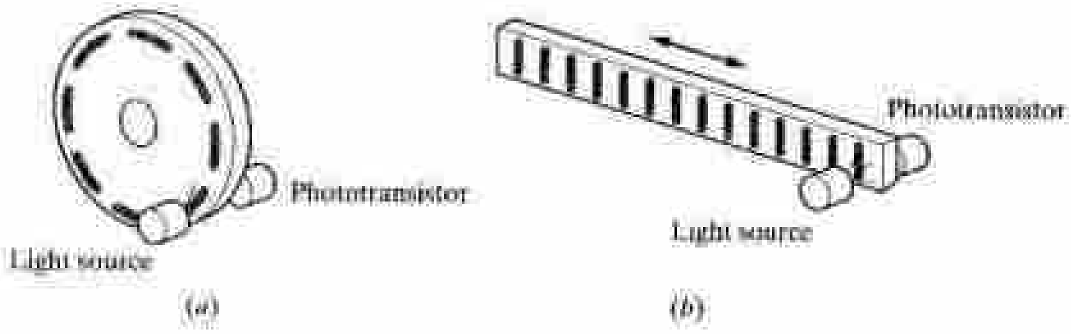


Figure (3.1). **a) A simple rotary incremental encoder wheel. This encoder measures angular rotations; b) A linear incremental encoder, which can measure linear movements**

✓ The incremental types transmit a series of voltage pulses proportional to the angle of rotation of the shaft. The control computer must know the previous position of the shaft in order to calculate the new position.

✓ Absolute encoders transmit a pattern of voltages that describes the position of the shaft at any given time. The innermost ring switches from dark to light every 180°, the next ring every 90°, the next 45°, and so on, dependent upon the number of rings on the disk. The resulting bit pattern output by the encoder reveals the exact angular position of the shaft.

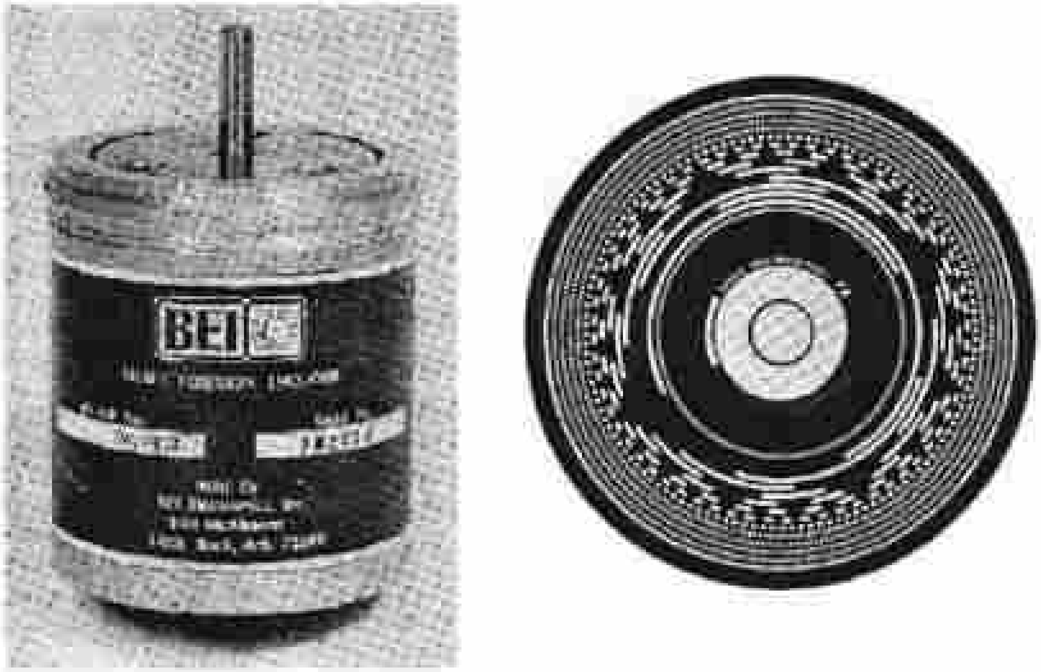


Figure (3.2). **Absolute optical encoder for monitoring shaft rotation on robots or other automation devices and the Sample portion of optical encoder disk**

Example

An absolute optical encoder disk has eight rings and eight LED sensors, and in turn provides 8-bit outputs. Suppose the output pattern is 10010110. What is the angular position of the shaft?

Solution

	Encoder Ring	Angular Value (degrees)	Observed Pattern	Computed Value (degrees)
(innermost)	1	180	1	180
	2	90	0	
	3	45	0	
	4	22.5	1	22.5
	5	11.25	0	
	6	5.625	1	5.625
	7	2.8125	1	2.8125
(outermost)	8	1.40625	0	
			Total	**210.94**

$$A = \sum_{i=1}^{n} m_i \cdot A_i ,$$

where i = ring number;

$m_i = 0$ if i is white (clear);

$m_i = 1$ if i is black (opaque);

$A_i =$ angular value for ring i;

$n =$ total number of rings.

3. ACTUATORS

After a real-world condition is sensed and analyzed, and then the actuation may be a direct physical action upon the process, such as a sweep bar that sweeps items off a conveyer belt at the command of a computer or other analyzer. In other cases, an actuator is simply a physical making of an electrical circuit, which in turn has a direct effect upon the process. An example would be an actuator (relay) that turns on power to an electric furnace heating circuit.

In Robotics, actuators are the muscles of robots. If you imagine that the links and the joints are the skeleton (Mechanical Structure) of the robot, the actuators act as muscles, which move or rotate the links to change the configuration of robots. The actuator must have enough power to accelerate and decelerate the links and to carry the loads, yet be light, economical, accurate, responsive, reliable, and easy to maintain.

3.1. CYLINDERS

In an automation application the Cylinder is usually used when a linear movement is required. The most popular are the pneumatic types because of the convenience of piping compressed air throughout a manufacturing plant. Shop air is generally regulated to the range 80 to 100 psi (***pound-force per square inch*** lb/in^2), which is adequate for most grippers, movers, positioners, and tool-stroking devices. Figure (3.3) shows the use of pneumatic cylinders in an automatic work station. The control of air cylinders is accomplished by valves that may be driven by electrical impulses or by air logic devices.

When the manufacturing process requires forces to be applied automatically in excess of 200 pounds, the more powerful hydraulic cylinder is usually selected over the pneumatic cylinder. Hydraulic pressures in excess of 2000 psi are readily available; compare these pressures with the 80 to 100 psi commonly used in pneumatic systems. Given the mechanical advantage of a large enough cylinder, pneumatics can deliver as large a force as the hydraulics, but space and convenience tend to favor hydraulics for the large forces. The most powerful industrial robots are driven by hydraulic actuators.

Besides being powerful, hydraulic cylinders have the advantage of being well controlled throughout the stroke. In addition, they are quiet, although the pump and reservoir (to store hydraulic) can be quite noisy. Disadvantages are high initial cost, maintenance, and problems from leaking cylinders.

In the design of either pneumatic or hydraulic actuators both pressure and volume requirements must be met. A system may have sufficient pressure to actuate cylinders or other actuators, but may not be able to maintain that pressure during high-speed operations. This mistake has been observed especially in partially automated factories in which pneumatic systems are used to power mechanized screwdrivers, staplers, and handling equipment. System design that anticipates the demands which will be placed upon the pneumatic or hydraulic equipment and actuators during peak periods will avoid this drawback.

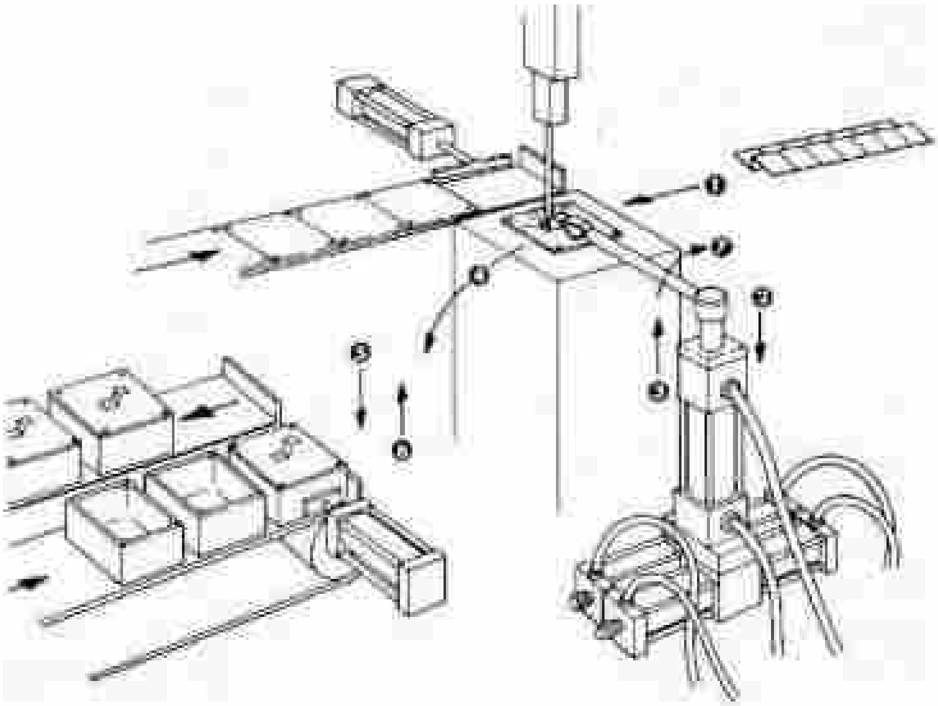


Figure (3.3). **Use of pneumatic cylinders to achieve robotic motions in an automatic work station**

3.2. SOLENOIDS

An electrical solenoid is needed, when a small, light, quick linear motion is desired in an automated system. In basic physics, we learned that the principle of the solenoid operation is the creation of a magnetic field set up by passing an electrical current through a coil. Thus, the core of the solenoid can be selectively drawn into the coil in response to an electrical current. In the absence of the coil current, the core can be automatically returned by spring action. The stroke motion of a solenoid is not very controlled in comparison, for example, with a hydraulic cylinder, but many automation applications require only a short, quick, discrete action, not a smooth, controlled stroke.

3.3. RELAYS

✓ Basically a Relay is used to switch an electrical circuit. Switching-type circuits usually operate at lower voltages and especially at lower amperage than power circuits. The output of the switching logic network then can be used to trip one or more relays to close or open a power circuit. There are many ways in which relays can be combined in switching networks form the basis for the classical approach to automating manufacturing systems.

✓ Figure (3.4) shows the use of relays to close electrical circuits under the automatic control of process sensors. Compare the logic of the two circuits shown. In Figure (3.4 *a*), relays from *both* sensors must be energized to make the power circuit. In the arrangement in Figure (3.4 *b*), the action of either relay *A* or *B* is sufficient to make the circuit.

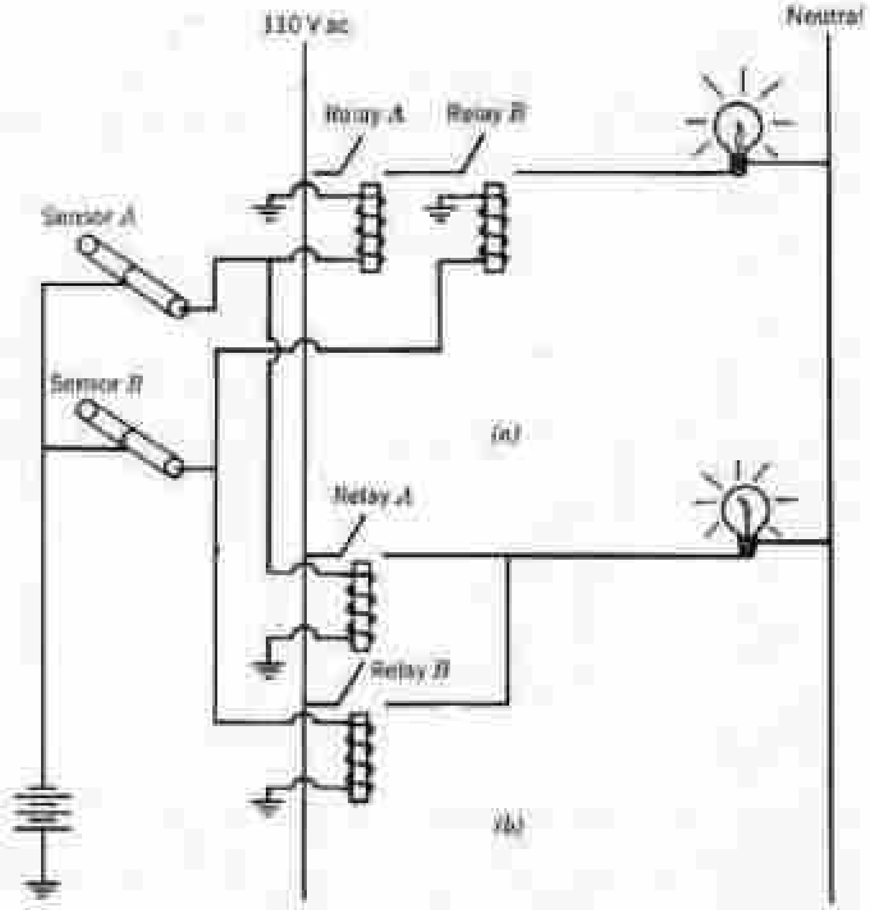


Figure (3.4). **Using relays to automatically switch power circuits. In circuit *(a)*, *both* sensors A and B must supply voltage to their respective relays to close the power circuit. In circuit (*b*), a voltage at *either* sensor is sufficient to close the power circuit**

✓ A relay can be described as either "*latching*" or "*nonlatching*" (Figure (3.5)). A latching relay needs only an electrical *impulse* to pull and hold the power circuit closed. Another impulse is needed on a different switching circuit to release the latch. Nonlatching relays hold only while the switching relay is energized and thus require a *continuous* electrical signal. The discontinuation of that signal permits the relay to release the switch immediately.

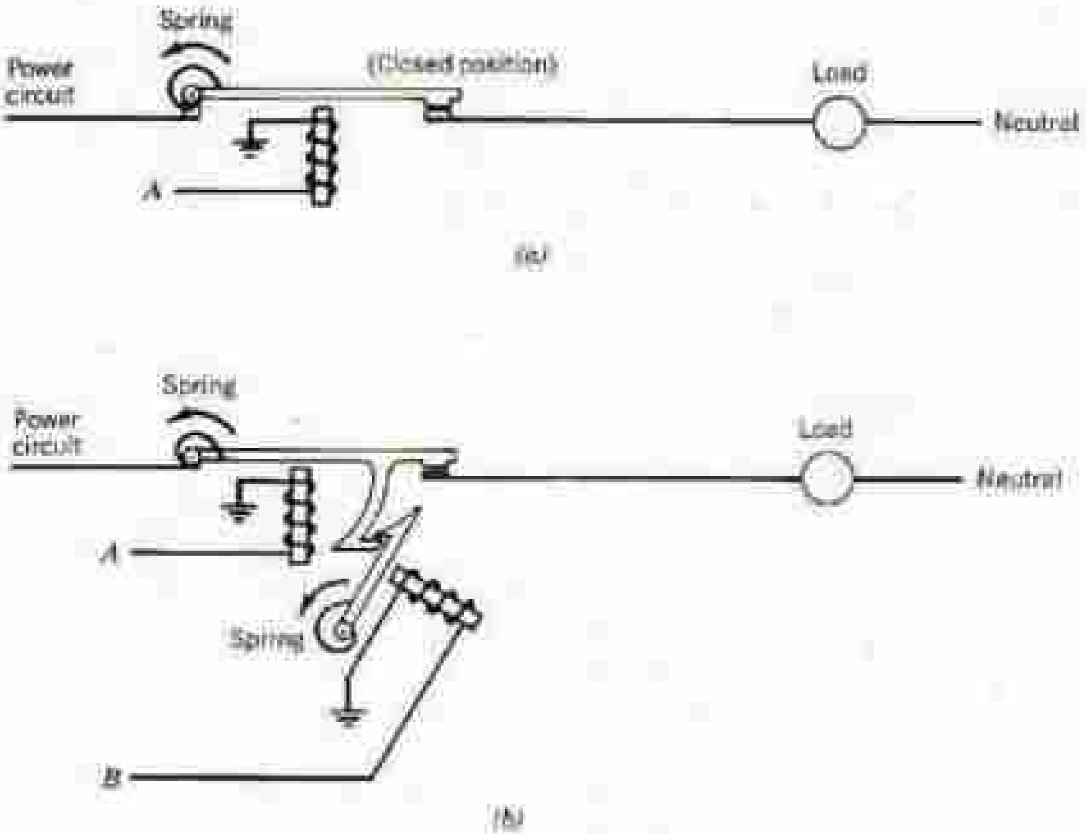


Figure (3.5). **Comparison of ordinary versus latching relays. (*a*) Ordinary, nonlatching relay is closed only when current is applied to the coil via control input A. (*b*) Latching relay stays closed by a mechanical latch after an impulse at Apulls it in. An impulse at B releases the latch.**

✓ When the energization of a relay coil makes a circuit closed, the relay is designated "***normally open***" Conversely, the relay that breaks a circuit when energized is designated "***normally closed***" It follows, then, that the normal state of an electric relay is the deenergized state. Figure (3.6) compares a normally open relay with a normally closed relay in a single power circuit. In Figure (3.6 *a*), the sensor must provide an energized control input in order to make the power circuit. In Figure (3.6 *b*), the control input must be *de-energized* to make the power circuit.

- ✓ The typical relay and solenoids in general operate on low-voltage direct current. But the convenience and availability of 110-volt alternating current (ac) have given rise to the ac relay and ac solenoid. Another advantage to the higher voltage ac solenoids is their relative immunity to induced voltages from power conductors in the manufacturing environment.

- ✓ Small motors, handling devices, and automated tool actuators usually are served by power circuits of less than 10 A, and the relays that trip them are indeed called "*relays*". However, as the amperage ranges upward between 10 and 30 A, the *power relay* may be called a ***contactor***. Still, the basic principle of the simple relay is being employed, and the automation engineer should not be confused by these terms.

- ✓ A special need for a relay is in the tripping of power circuits for electric motors. The automation engineer will hear reference to "***motor starters***"; these devices are either contactors or relays that in addition provide ***overload protection*** to open the motor circuit if a heavy mechanical load begins to cause the motor to carry too much current.

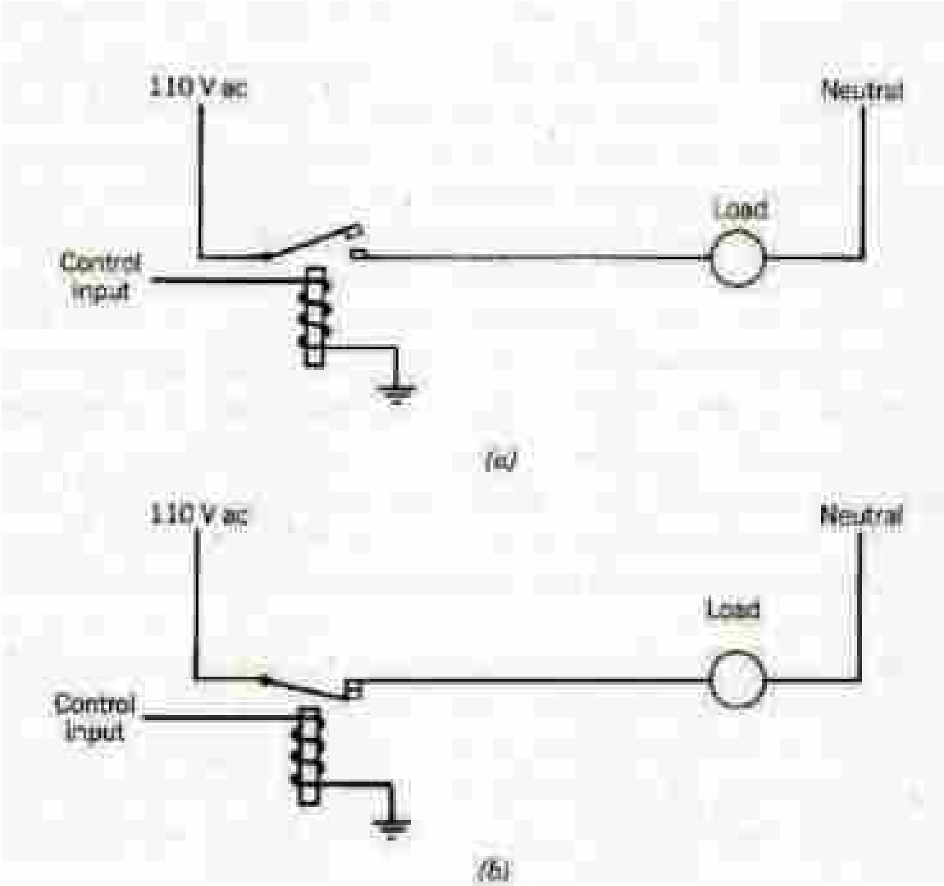


Figure (3.6). **Normally open relay (a) versus normally closed relay *(b).***

BUILDING BLOCKS OF AUTOMATION

3.4. HYDRAULIC ACTUATORS

The hydraulic actuators receive pressurized hydraulic oil with controlled direction and pressure through a system known as "power packs". The speed and volume flow rates are also controlled by the elements of the power pack. To produce linear motion the hydraulic cylinders are used and hydraulic motors are used to produce rotational movements.

- *Elements of Power pack and functions*

#	Elements	Functions
1.	Reservoir or tank	Stores and supply hydraulic oil to the system, in a closed circuit.
2.	Hydraulic pump	Receives oil from the reservoir and pressurizes the oil in accordance with its capacity.
3.	Electric motor	Receives electric current from mains and provides rotational movement to the pump.
4.	Valves	Control the direction of flow, regulate the pressure and provide safety to the system.
5.	Hoses and pipes	Provide connection between the various elements transporting the high pressure oil.

- *Hydraulic System*

The hydraulic circuit shown in Figures (4.1(a) and 4.1(b)) shows symbolically the hydraulic system of linear actuator in a simplest arrangement. On the forward stroke of the piston of the cylinder the high pressure relief valve is effective and in the return stroke the low pressure relief valve acts to regulate the system pressure. The load handling capacity is determined by the system pressure in the forward stroke. The directional control valve controls the direction of motion of the piston in case of the linear actuators.

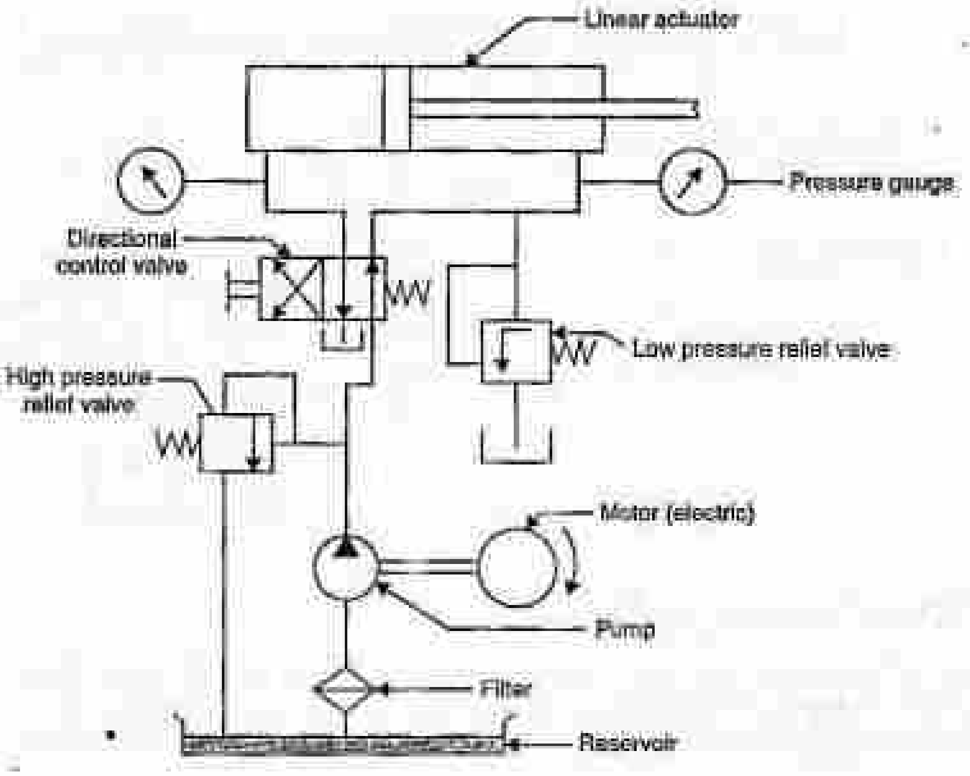


Figure (4.1(a)). **Typical hydraulic circuit**

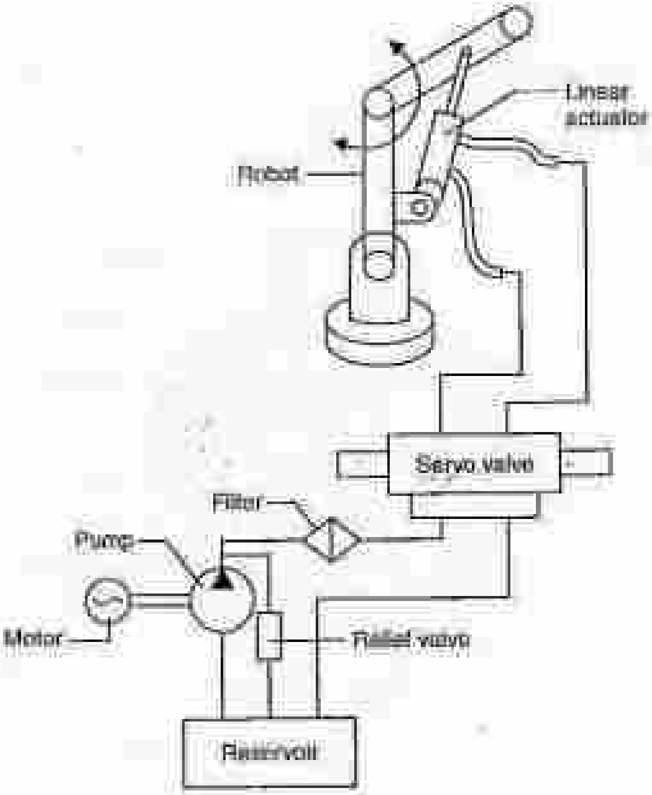


Figure (4.1(b)). **Hydraulic system for Robot**

- *Hydraulic Motors*

These are a type of power utilizing elements which convert hydraulic energy into mechanical rotational work useful in driving the links with revolute joints, in this context. One of the types of hydraulic motors; the vane motor is most commonly used type. The motor consists of a circular rotor mounted eccentrically inside a circular stator ring. The rotor has got suitable slots for accommodating radially moving vanes. The rotational output of the motor depends on the eccentricity *"e"* of the rotor with respect to the stator.

The power output:

$$P = \frac{D_r \cdot e \cdot V_r \cdot p}{1000}, \text{kW}$$

where D_r – outermost diameter of the vane, m;

e – eccentricity, m;

V_r – linear speed of rotation, m/sec,

$$V_r = \frac{2\pi NR}{60},$$

where N – revolution per minute;

$$R = \frac{D_r}{2},$$

p – pressure of the oil supplied to the motor.

And the torque developed:

$$T = \frac{60{,}000\ P}{2\pi N}, \text{kN} \cdot \text{m}.$$

- *Linear Actuators*

The actuators that provide linear reciprocating motion to the prismatic joints, by utilizing hydraulic power are known as linear actuators or cylinders, the constructional details are as shown in Figure (4.2).

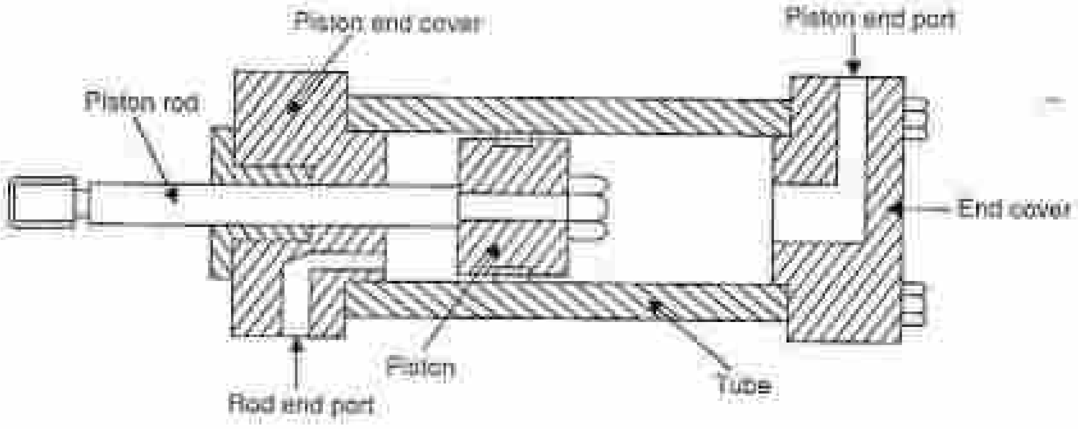


Figure (4.2): **Construction of Cylinder**

A cylinder essentially consists of a piston located in the tubular housing and a piston rod passing through one of the end covers. The ports provided in the end covers permit entry and return of the hydraulic oil. If the hydraulic oil is supplied to the cylinder is at a pressure p (N/m^2) with a volume flow rate of Q (m^3/sec), the power delivered is given by

$$\mathrm{P} = \frac{p \cdot \mathrm{Q}}{1000}, \mathrm{kW}$$

The force developed in the rod is given by

$$\mathrm{F} = p \cdot \frac{\pi}{4} \cdot \mathrm{D}_p^2$$

where $\mathrm{D_p}$ – diameter of the piston in meter.

The speed of motion:

$$\mathrm{V}_e = \frac{\mathrm{Q}}{4} = \frac{4\mathrm{Q}}{\pi \mathrm{D}_p^2}$$

This is the speed in extension of the rod.

The speed of retraction:

$$V_r = \frac{4Q}{\pi(D_p^2 - D_r^2)}$$

- *Features of Hydraulic Actuators*

✓ Provide high power in small light components.
✓ Have flat load-speed or torque speed characteristics.
✓ Can operate safely and continuously under stall conditions.
✓ Provide stepless variation in speed.
✓ Have longer life and reliability due to the lubricating properties of the oil.
✓ Can be easily built using readily available standard elements.
✓ Have contaminant sensitive elements.
✓ The operation is noisy.
✓ Higher inertia on the robot joints.
✓ Power loss and unclean work area due to possibility of leak.
✓ Less deflection due to low compliance of the elements.

- *Applications of Hydraulic Actuators*

✓ Used to drive the spray coating robots.
✓ Used in heavy part loading robots.
✓ Useful in material handling robot system.
✓ Used to drive the joints of assembly (heavy) robots.
✓ Useful in producing translatory motion in cartesian robot.
✓ Useful in robots operating in hazardous, sparking environments.
✓ Useful in gripper mechanisms.

3.5. PNEUMATIC ACTUATORS

The principles of pneumatic actuators match with that of hydraulic actuator. The working fluid in case of this is the compressed air. The pressure of air used in this varies from 6-10 MPa. Because of low air pressure the components are light and the force/torque transmitted is also less, Pneumatic cylinders are used to actuate the linear joints and pneumatic motors are used to drive the revolute joints. The main problem with the pneumatic devices is that the working fluid (air) is compressible; hence the actuator drifts under loads.

The pneumatic actuators are characterized by the following features:

- lowest power to weight ratio;
- highly compliant system;
- drift under load constantly;
- low, inaccurate response due to low stiffness;
- less leakage of air and not susceptible to sparks;
- uses low pressure compressed air, hence less actuation force or torque;
- useful in on-off applications like pick and place robot;
- simple and low cost components;
- reliable and easily available components;
- the exact positions of the actuators can be controlled by servo control valves differential movements.

4. DRIVES

Like actuators, drives take some action upon the process at the command of a computer or other analyzer. For purposes of classification, the distinction being made here between actuators and drives is that actuators are used to effect a short, complete, discrete motion usually linear and drives execute more continuous movements typified by, but not limited to, rotation. Actuators may turn drives on and off, and drives may provide the energy for the movement of actuators. Some automation devices, such as genevas and walking beams, seem to belong to both categories.

4.1. ELECTRIC DRIVES

Principle

A rotational movement is produced in a rotor when an electric current flows through the windings of the armature setting up a magnetic field opposing the field set up by the magnets.

The Main Components

Rotor, stator, brush and commutator assembly. The rotor has got windings of armature and the stator has got the magnet. The brush and the commutator assemblies switch the current to the armature maintaining an opposed field in the magnets.

Performance

The torque on the rotor of the electric motor is given as:

$$\mathrm{T}_m = \mathrm{K}_m \cdot \mathrm{I}_a,$$

where K_m – motor torque constant;

I_a – armature current.

$$\mathrm{I}_a = \frac{\mathrm{V}_{in} - e_b}{\mathrm{R}_a}$$

where V_{in} – input voltage to the motor;

e_b – back e.m.f.;

R_a – armature resistance,

but e_b is back e.m.f., the opposing voltage produced in the winding due to the rotation of the rotor e_b is given as

$$e_b = \mathrm{K}_b \cdot \omega$$

where K_b – voltage constant, ω is the angular velocity.

Selection

The selection of the electric drive is based on the torque rating and the current rating of the motor. The torque rating of an electric motor is derived from the power rating of the motor. If P_m is the power rating the torque rating:

$$\mathrm{T}_r = \frac{60\mathrm{P}_m}{2\pi \cdot \mathrm{N}_m}$$

where N_m – speed specification of the motor.

Types

The most commonly used electric drives in robotics are:

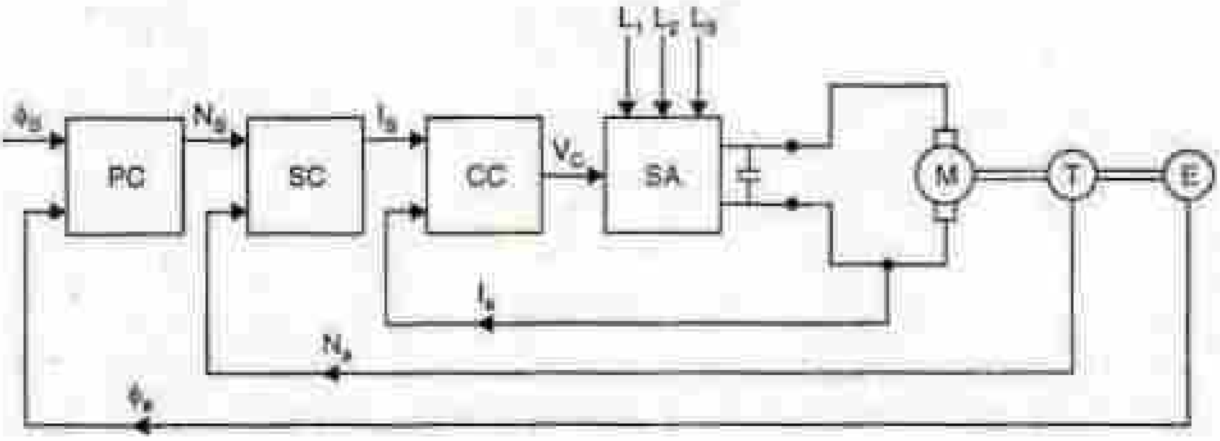
1. *DC* Servo Motor.
2. *AC* Servo Motor.
3. Stepper Motor.

Features

DC Servo Motor	*AC Servo Motor*	*Stepper Motors*
• ***Higher power to weight ratio.***	• ***Rotor is a permanent magnet and stator is housing the winding..***	• ***Moves in known angle of rotation.***
• ***High acceleration.***	• ***No commutators and brushes.***	• ***Position feed back is not necessary.***
• ***Uniform torque.***	• ***Switch is due to AC but not by commutation.***	• ***Rotation of the shaft by rotation of the magnetic field.***
• ***Good response for better control.***	• ***Fixed nominal speed.***	• ***Needs microprocessor circuit to start.***
• ***Reliable, sturdy and powerful.***	• ***Favourable heat dissipation.***	• ***Used in table top robot.***
• ***Produces sparks in operation, not suitable for certain environments.***	• ***More powerful.***	• ***Finds less use in industrial robotic.***
	• ***Reversibility of rotation possible.***	• ***Extensive use is robotic devices.***

Servo Motors

The *desired position* (ϕ_s) is compared with the *actual position* (ϕ_a) feedback from, the *encoder* (E). This gives the *desired speed (N_s)*, which is compared with the *actual speed* (N_a) obtained as feedback from the tacho-generator (T). This gives the desired current (I_s) which is adjusted by the inner loop giving a feedback of actual current (I_a). A *control signal* (V_c) is generated which along with *supply voltage(V_s)* from a 3-phase system is given to the motor as input. In a servo-motor the position and speed of motor is controlled by the feedback control. The block diagram of servo motor is shown below (Figure (4.3)).



PC – position controller
SC – speed controller
CC – current controller
SA – servo amplifier
M – DC/AC motor
T – tacho-generator
E – encoder

N_a – actual speed
ϕ_a – actual position
I_a – actual current
L_1, L_2, L_3 – 3-phase supply
ϕ_s, N_s, I_s – desired position, speed and current
V_c –control voltage

Figure (4.3). **Servo motor**

Stepper Motors

The stepper motors are unique type of motors that produce rotational movement in the form of finite angular steps. The intermittent electrical pulses make the stepper motor shaft to rotate in steps.

The schematic arrangement of the principle stepper motor is shown in Figure (4.4(a)). The stator in this case is made up of four-electromagnetic poles. The rotor is a permanent magnet with two poles N and S. When the excitation of pole 2 (P2) is changed to P3 pole the magnetic north rotates by 90° clockwise. By continuous change in excitation in the order P2-P3-P4-P1-P2 the clockwise rotation is produced in the shaft of the rotor, which results in continuous movement.

The multiple pole stepper Motor shown in Figure (4.4(b)). The stator has a winding made of concentrated coils on distinct poles. The rotor is permanent magnet cylinder. Single-phase stepper motor with two poles is shown in Figure (4.4(c)). By reversal of the current in the coil the polarity changes continuously by change in flow of flux in the poles. The rotor which is the permanent magnet makes rotation.

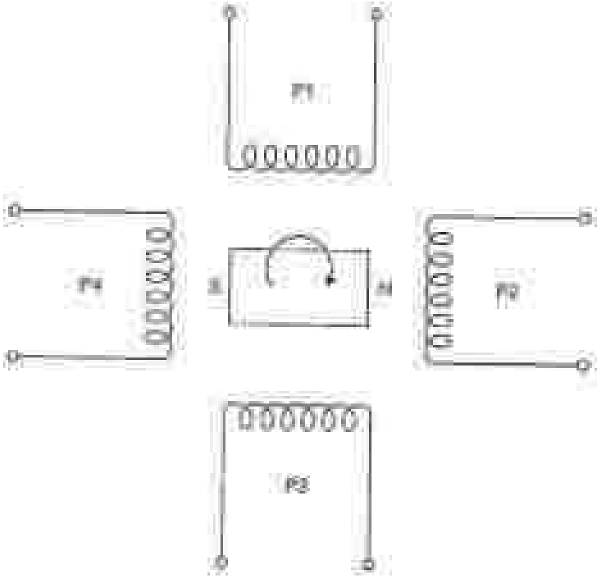


Figure (4.4(a)). **Schematic of Stepper Motor**

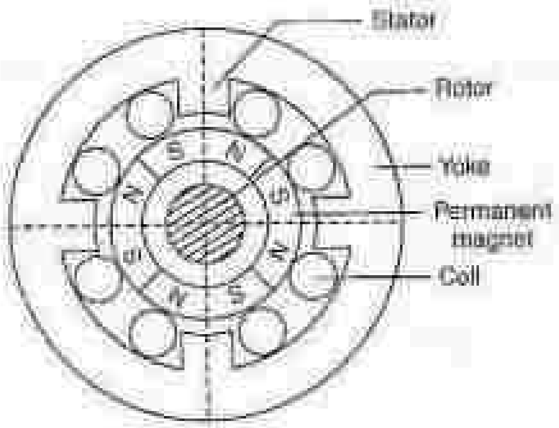


Figure (4.4(b)). **Permanent magnet stepper motor**

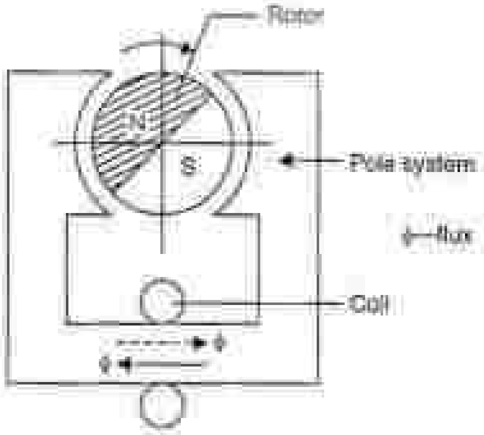


Figure (4.4(c)). **Single phase stepper motor**

- ### *Resolution of Stepper Motor*

Resolution is determined by the number of stator poles in the stepper motor.

Step angle,

$$A_s = \frac{360^\circ}{n_s}$$

where n_s is number of poles

or

$$n_s = \frac{360^\circ}{A_s}$$

The resolution is given by the inverse of the number of steps or the poles.

$$R_s = \frac{A_s}{360^\circ}$$

Puls:

Single pules of electrical signal is necessary for the robot to rotate by one step. For one rotation number of pulse,

$$n_p = n_s = \frac{360^\circ}{A_s}$$

The pulse count for N_R revolutions of the rotor:

$$n = N_R \cdot n_p$$

$$n = \left(\frac{360^\circ}{A_s}\right) \cdot N_R$$

or

$$n = \frac{N_R}{R_s}$$

as

$$R_s = \frac{A_s}{360^\circ}$$

Hence the pulse count is the ration of number of revolutions and the resolution of the stepper motor.

If the rotor is rotating with a speed of N_m revolutions per minute. The pulse rate,

$$n_r = \frac{\mathrm{N_m}}{\mathrm{R_s}} = \frac{\text{number of revolution/min}}{\text{resolution}}$$

BUILDING BLOCKS OF AUTOMATION

Stepper motors operation (continued)

Stepper motors are either bipolar, requiring two power sources or a switchable polarity power source, or unipolar, requiring only one power source. They are powered by DC sources and require digital circuitry to produce coil energizing sequences for rotation of the motor. Feedback is not always required for control, but the use of an encoder or other position sensor can ensure accuracy when exact position control is critical. The advantage of operating without feedback (in open-loop mode) is that a closed-loop control system is not required. Generally, stepper motors produce less than 1 hp (746 W) and are therefore used only in low-power position control applications.

A commercial stepper motor has a large number of poles that define a large number of equilibrium positions of the rotor. In the case of a permanent magnet stepper motor, the stator consists of wound poles, and the rotor poles are permanent magnets. Exciting different stator winding combinations moves and holds the rotor in different positions. The permanent magnet stepper motor has the advantage of a small residual holding torque, called the detent torque, even when the stator is not energized.

To understand how the rotor moves in an incremental fashion, consider a simple design consisting of four stator poles and a permanent magnet rotor as shown in Figure (5.1).In step 0, the rotor is in equilibrium, because opposite poles on the stator and rotor are adjacent to and attract each other. Unless the magnet polarities of the stator poles are changed, the rotor remains in this position and can withstand an opposing torque up to a value called the holding torque. When the stator polarities are changed as shown (step 0 to step 1), a torque is applied to the rotor, causing it to move 90° in the clockwise direction to a new equilibrium position shown as step 1. When the stator polarities are again changed as shown (step 1 to step 2).The rotor experiences a torque driving it to step 2. By successively changing the stator polarities in this manner, the rotor can move to successive equilibrium positions in the clockwise direction. The sequencing of the pole excitations is the means by which the direction of rotation occurs. Counterclockwise motion can be achieved by applying the polarity sequence in the opposite direction. The motor torque is directly related to the magnetic field strength of the poles and the rotor.

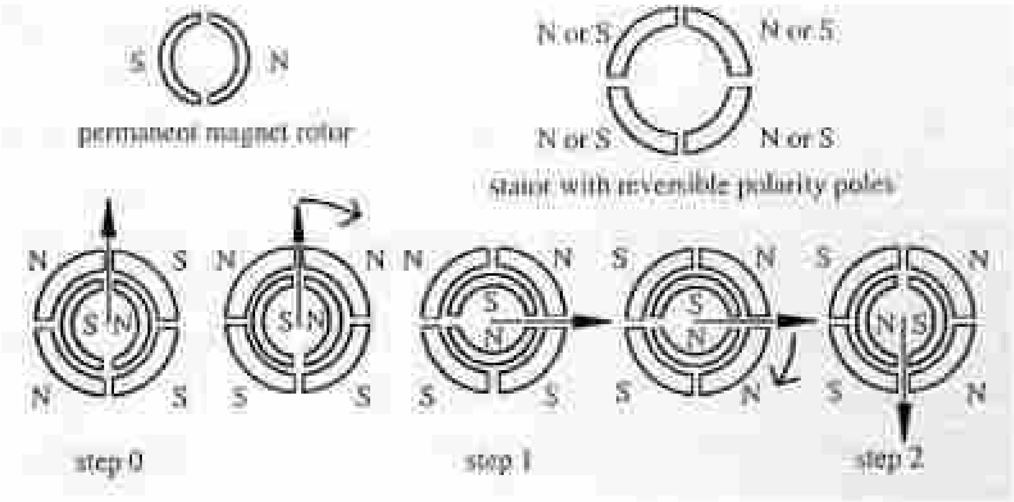


Figure 5.1.**Stepper motor step sequence**

The dynamic response of the rotor and attached load must be carefully considered in applications that involve starting or stopping quickly, changing or ramping speeds quickly, or driving large or changing loads. Due to the inertia of the rotor and attached load, rotation can exceed the desired number of steps. Also, as illustrated in Figure (5.2), a stepper motor driving a typical mechanical system through one step will exhibit an underdamped response. If damping is increased in the system, for example, with mechanical, frictional, or viscous damping, the response can be modified to reduce oscillation, as shown in the Figure (5.2). Note, however, that even with an ideal choice for damping, the motor requires time to totally settle into a given position, and this settling time varies with the step size and the amount of damping. It is also important to note that the torque required from the motor increases with added damping.

Figure (5.3) shows a unipolar stepper motor field coil schematic with external power transistors that must be switched on and off to produce the controlled sequence of stator polarities to cause rotation. This Figure shows six wires connected to the motor. Because the second and fifth wires are usually connected externally as shown, manufacturers sometimes connect them inside the motor, in which case the motor only has five external wires. The wires are usually color coded by the manufacturers to help the user make a correspondence to the schematic. Figure (5.3) includes a common color scheme used for a six-wire unipolar stepper motor: yellow (coil 1), red (1/2 common), orange (coil 2), black (coil 3), green (3/4 common), brown (coil 4). Another common six-wire color scheme is green (coil 1), white (1/2 common), blue (coil 2), red (coil 3), white (3/4 common), black (coil 4). A common color scheme for a five-wire unipolar stepper is red (coil 1), green (coil 2), black (common), brown (coil 3), white (coil 4).

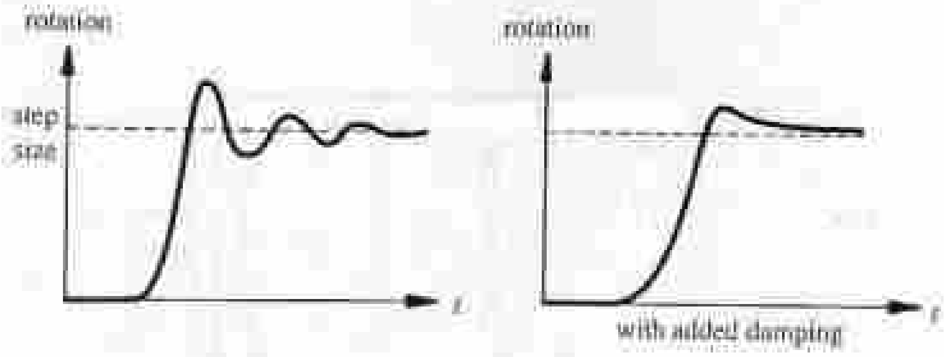


Figure (5.2).**Dynamic response of a single step**

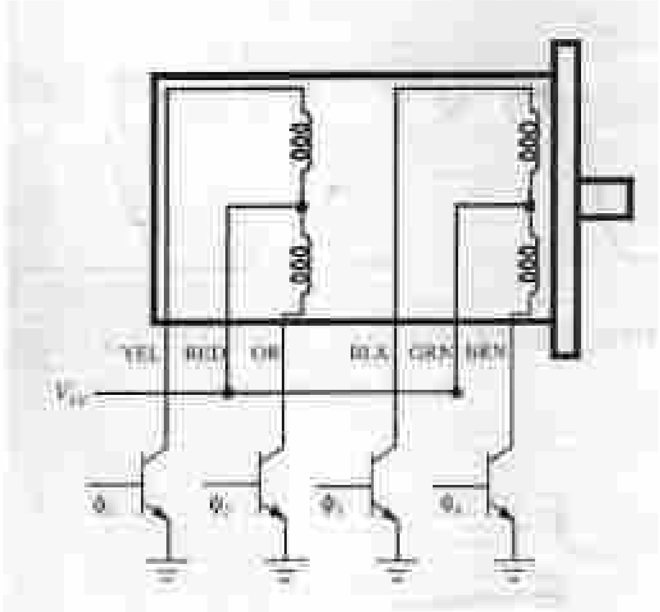


Figure (5.3).**Standard unipolar stepper motor field**

Figure (5.4) shows the construction of and stepping sequence for a four-phase unipolar stepper motor. It consists of a two-pole permanent magnet rotor and a four-pole stator, with each pole wound by two complementary windings (ϕ_1, ϕ_2 wound in opposite directions on the top left pole). Table (5.1) lists the phase sequence required to step the motor in full steps, where two of the four phases are energized (ON) and each stator pole is polarized. Table (5.2) lists the phase sequence for half-stepping, where between each full step only one phase is energized (ON) and only two stator poles are polarized. Another technique for increasing the number of steps is called micro stepping, where the phase currents are controlled by fractional amounts, rather than just ON and OFF, resulting in more magnetic equilibrium positions between the poles. In effect, discretized sine waves are applied to the phases instead of square waves. The most common commercially available stepper motors have 200 steps/rev in full-step mode and are sometimes referred to as 1.8° (3607200) steppers. In micro-stepping mode, 10,000 or more steps per revolution can be achieved.

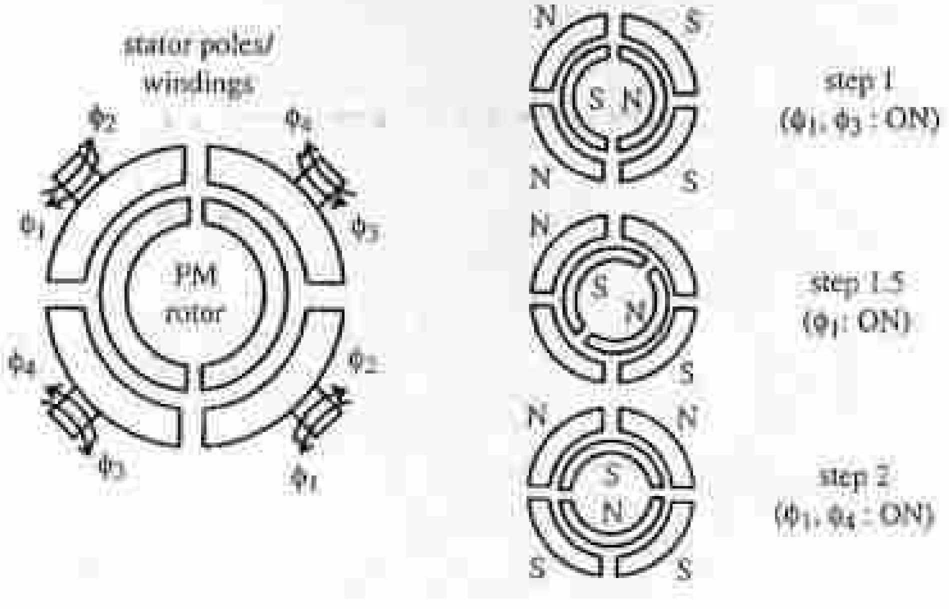


Figure (5.4).**Example of unipolar stepper motor**

Table 5.1.**Unipolar full-step phase sequence**

	Step	ϕ_1	ϕ_2	ϕ_3	ϕ_4
CW	1	ON	OFF	ON	OFF
↓	2	ON	OFF	OFF	ON
CCW	3	OFF	ON	OFF	ON
↑	4	OFF	ON	ON	OFF

Table 5.2.**Unipolar half-step phase sequence**

	Step	ϕ_1	ϕ_2	ϕ_3	ϕ_4
	1	ON	OFF	ON	OFF
	1.5	ON	OFF	OFF	OFF
↑	2	ON	OFF	OFF	ON
CW	2.5	OFF	OFF	OFF	ON
↓	3	OFF	ON	OFF	ON
CCW	3.5	OFF	ON	OFF	OFF
	4	OFF	ON	ON	OFF
	4.5	OFF	OFF	ON	OFF

Stepper Motor Drive Circuits

A drive circuit for properly phasing the signals applied to the poles of the unipolar stepper motor for rotation in full-step mode is easily and economically produced using the components shown in Figure (5.5). The discrete circuit includes **7414** Schmitt trigger buffers, a **74191** up-down counter, and **7486** Exclusive OR gates. The Schmitt triggers produce well-defined control signals with sharp rise and fall times in the presence of noise or fluctuations. The hysteresis of the Schmitt triggers provides sharp square-wave signals for the direction (CW/ CCW), initialization (RESET), and single step (STEP) inputs. The up-down counter and the XOR gates in turn create four properly phased motor drive signals. These four digital signals (ϕ_1, ϕ_2,ϕ_3, ϕ_4) are coupled to the bases of power transistors that sequentially energize the respective motor coils connected to the DC motor supply, resulting in shaft rotation.

Each square-wave pulse received at the STEP input causes the motor to rotate a full step in the direction determined by the CW/CCW input.

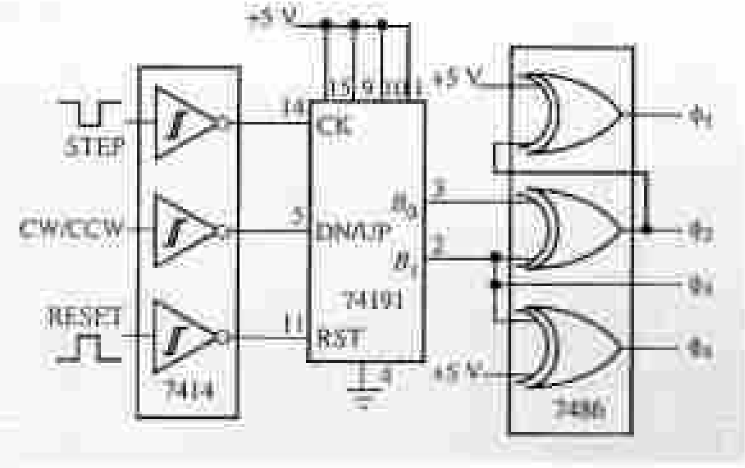


Figure (5.5).**Unipolar stepper motor full step drive circuit**

The timing diagram for the two least significant output bits B_0 and B_1, of the counter and the phase control signals is shown in Figure (5.6). Compare the signals to the sequence in Table (5.1). They are in agreement. Boolean expressions that produce the four desired phased outputs from the two counter bits can be represented in both AND-OR-NOT and XOR forms:

$$\phi_1 = \overline{\phi_2} = \phi_2 \oplus 1$$
$$\phi_2 = \left(B_0 \cdot \overline{B}_1\right) + \left(\overline{B}_0 \cdot B_1\right) = B_0 \oplus B_1$$
$$\phi_3 = B_1$$
$$\phi_4 = \overline{B}_1 = B_1 \oplus 1$$

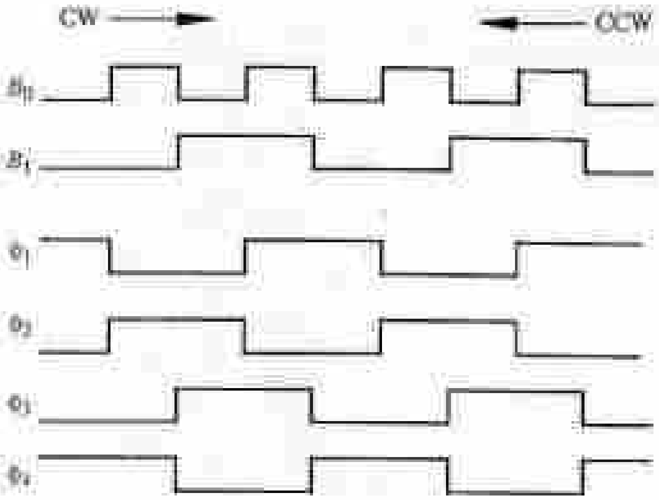


Figure (5.6).**Timing diagram of full step unipolar stepper motor**

Pulse Width Modulation (PWM)

Most interesting problems require some sort of automatic control, where the voltage is automatically varied to produce a desired motion. This is called closed-loop or feedback control, and it requires an output speed and/or torque sensor to feedback output values to continuously compare the actual output to a desired value, called the set point. The controller then actively changes the motor output to move closer to the set point. Electronic speed controllers are of two types: linear amplifiers and pulse width modulators. Pulse width modulation controllers have the advantage that they either drive bipolar power transistors rapidly between cutoff and saturation or they turn FETs on and off. In either case, power dissipation is small. Because of the lower power requirements, ease of design, smaller size, and lower cost, we focus on the pulse-width modulation (PWM) amplifiers.

The principle of a PWM amplifier is shown in Figure (5.7). A DC power supply voltage is rapidly switched at a fixed frequency f between two values (ON and OFF). This frequency is often in excess of 1 kHz. The high value is held during a variable pulse width t within the fixed period T where

$$T = \frac{1}{f}$$

The resulting asymmetric waveform has a duty cycle defined as the ratio between the ON time and the period of the waveform, usually specified as a percentage:

$$\text{Duty cycle} = \frac{t}{T} 100\%$$

As the duty cycle is changed (by the controller), the average current through the motor changes, causing changes in speed and torque at the output. It is primarily the duty cycle, and not the value of the power supply voltage, that is used to control the speed of the motor.

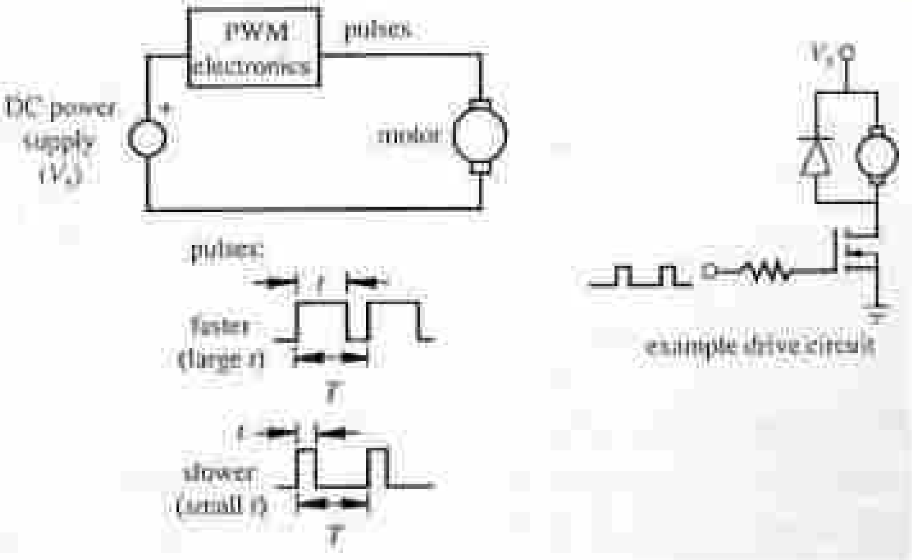


Figure (5.7).**Pulse width modulation of a DC motor**

The block diagram of a PWM speed feedback control system for a DC motor is shown in Figure (5.8). A voltage tachometer produces an output linearly related to the motor speed. This is compared to the desired speed set point (another voltage that can be manually set or computer controlled). The error and the motor current are sensed by a pulse width modulation regulator that produces a width modulated square wave as an output. This signal is amplified to a level appropriate to drive the motor.

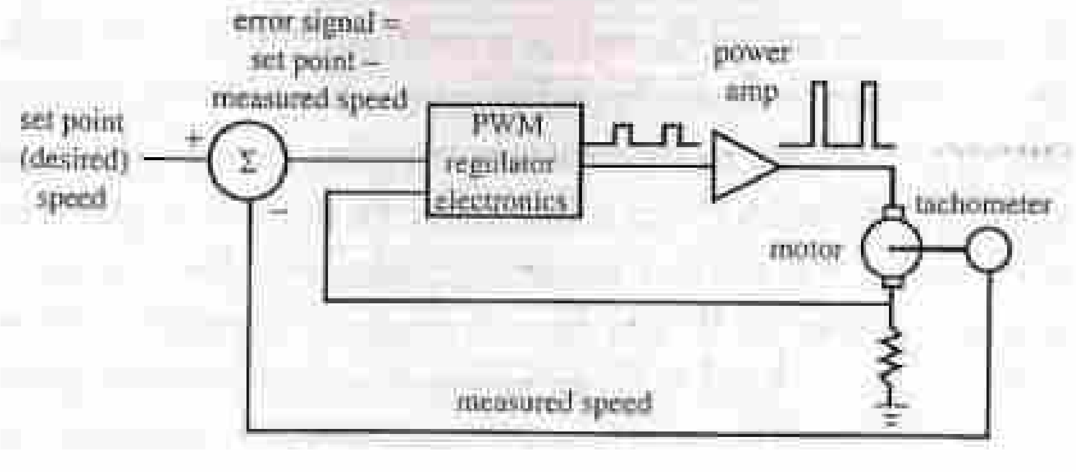


Figure 5.8.**PWM velocity feedback control**

In a PWM motor controller, the armature voltage switches rapidly, and the current through the motor is affected by the motor inductance and resistance. Since the switching speed is high, the resulting current through the motor has a small fluctuation around an average value, as shown in Figure 5.9. As the duty cycle grows larger, the average current grows larger and the motor speed increases.

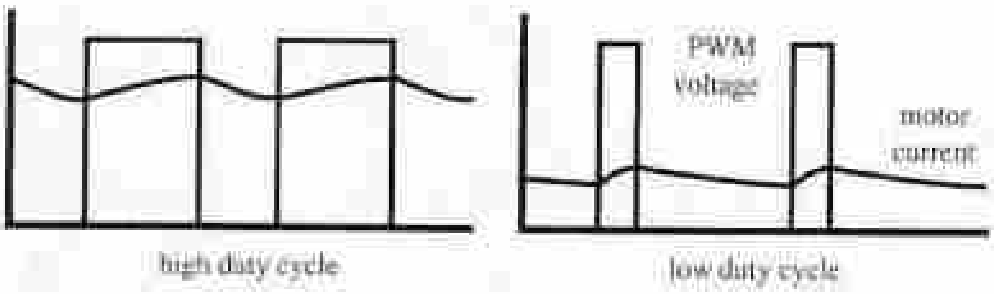


Figure 5.9 **PWM voltage and motor current**

4.2. SELECTING A MOTOR

When selecting a motor for a specific mechatronics application, the designer must consider many factors and specifications, including speed range, torque-speed variations, reversibility, operating duty cycle, starting torque, and power required. These and other factors are described here in a list of questions that a designer must consider when selecting and sizing a motor in consultation with a motor manufacturer. The torque-speed curve provides important information, helping to answer many questions about a motor's performance. Recall that the torque-speed curve displays the torques the motor can deliver at different speeds at rated voltage. Figure (5.10)shows an example of a torque-speed curve for a stepper motor, and Figure (5.11)shows an example of a torque-speed curve for a servomotor. These figures are examples from motor manufacturer specification sheets.