Chapter Six – Manufacturing Systems

Automation Technologies For Manufacturing Systems:

- A manufacturing system can be defined as a collection of integrated equipment and human resources that performs one or more processing and/or assembly operations on a starting work material, part, or set of parts.
- The integrated equipment consists of: production machines, material handling and positioning devices, and computer systems.
- Human resources are required either full-time or part-time to keep the equipment operating.
- The position of the manufacturing systems in the larger production system is shown in figure (6-1).

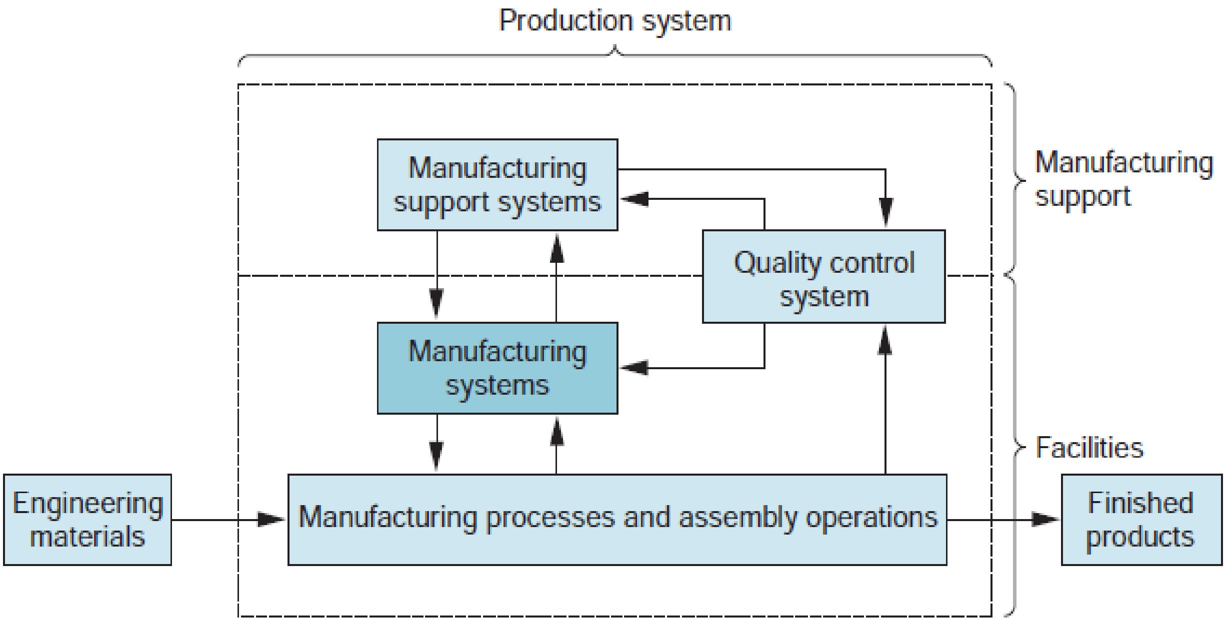

Figure (6-1) The position of the manufacturing systems in the larger production system.

Automation Fundamentals:

- Automation can be defined as the technology by which a process or procedure is performed without human assistance.
- Humans may be present as observers or even participants, but the process itself operates under its own self-direction.
- Automation is implemented by means of a control system that executes a program of instructions.
- To automate a process, power is required to operate the control system and to drive the process itself.

Three Components of an Automated System:

- The automated system consists of three basic components, see Fig.(6-2):
  1- power,
  2- program of instructions,
  3- control system to carry out the instructions.

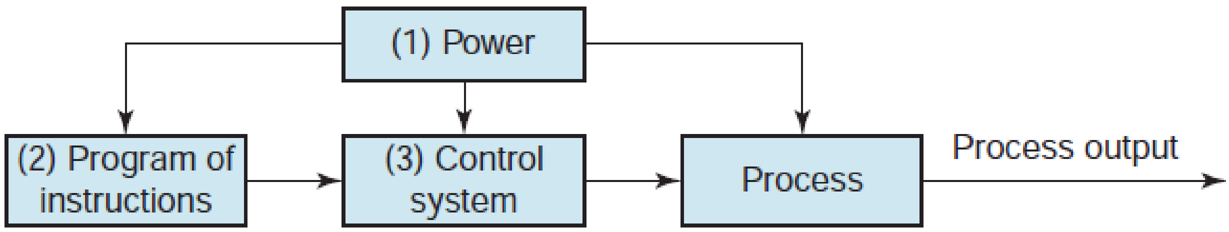

Figure (6-2) Elements of an automated system.

- The form of power used in most automated systems is electrical.
- The advantages of electrical power include:
  1- it is widely available,
  2- it can be readily converted to other forms of power such as mechanical, thermal, or hydraulic,
  3- it can be used at very low power levels for functions such as signal processing, communication, data storage, and data processing,
  4- it can be stored in long-life batteries.

- In a manufacturing process, power is required to accomplish the activities associated like: melting a metal, material handling (loading and unloading), and operate control system.
- The activities in an automated process are determined by a program of instructions.

- In simple automation (like maintain a certain controlled variable at a specified level, such as regulating the temperature in a heat treatment furnace).
- In complex automation, a sequence of activities is required during the work cycle. Each activity involves changes in one or more process parameters, such as changing the x-coordinate position of a machine tool worktable, opening or closing a valve in a fluid flow system, or turning a motor on or off.
- Process parameters are inputs to the process. They may be continuous (continuously variable over a given range, such as the x-position of a worktable) or discrete (On or Off). Their values affect the outputs of the process, which are called process variables.
- Like process parameters, process variables can be continuous or discrete. Examples include the actual position of the machine worktable, the rotational speed of a motor shaft, or whether a warning light is on or off.
- The program of instructions specifies the changes in process parameters and when they should occur during the work cycle, and these changes determine the resulting values of the process variables.
- For example, in computer numerical control, the program of instructions is called a part program. The numerical control (NC) part program specifies the individual sequence of steps required to machine a given part, including worktable and cutter positions, cutting speeds, feeds, and other details of the operation.
- In some automated processes, the work cycle program must contain instructions for making decisions or reacting to unexpected events during the work cycle. Examples of situations requiring this kind of capability include (1) variations in raw materials that require adjusting certain process parameters to compensate, (2) interactions and communications with human such as responding to requests for system status information, (3) safety monitoring requirements, and (4) equipment malfunctions.
- The program of instructions is executed by a control system.
- Two types of control system can be distinguished: closed loop and open loop.
- A closed loop system (feedback control system), is one in which the process variable (output of the process) is compared with the corresponding process parameter (input to the process), and any difference between them is used to drive the output value into agreement with the input.
- Figure (6-3a) shows the six elements of a closed loop system: (1) input parameter, (2) process, (3) output variable, (4) feedback sensor, (5) controller, and (6) actuator.

(1) Input parameter: is the desired value of the output variable.

(2) Process: is the operation or activity being controlled; (output variable).

(3) Feedback sensor: is used to measure the output variable and feedback its value to the controller.

(4) Controller: it compares output with input and makes the required adjustment to reduce any difference by using the actuator.

(5) Actuator: it makes the adjustment by one or more actuators, which is hardware device that physically accomplishes the control actions.

- The other type of control system is an open loop system, presented in Figure (6-3b).
- As shown in the diagram, there is no comparison between output and input in an open loop system.
- In open loop, the controller relies on the expectation that the actuator will have the intended effect on the output variable.
- There is always a risk in an open loop system that the actuator will not function properly or that its actuation will not have the expected effect on the output.
- The cost of open loop system is less than a closed loop system.

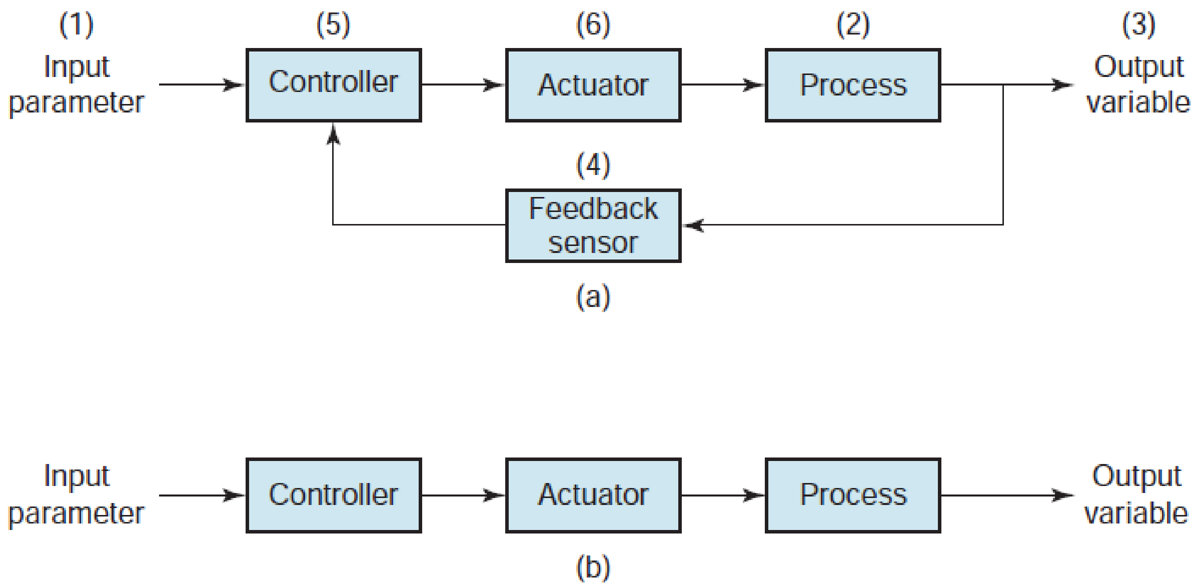

Figure (6-3): (a) closed loop, and (b) open loop

Types of Automation:

(1) Fixed automation
(2) Programmable automation
(3) Flexible automation

(1) Fixed Automation:

- In fixed automation, the processing or assembly steps and their sequence are fixed by the equipment configuration.
- The program of instructions is determined by the equipment design and cannot be easily changed.
- Each step in the sequence usually involves a simple action, such as feeding a rotating spindle along a linear trajectory.
- Typical features of fixed automation include:

(1) high initial investment for specialized equipment,
(2) high production rates, and
(3) little or no flexibility to accommodate product variety.
(4) It is justified for parts and products that are produced in very large quantities.

(2) Programmable Automation:

- In which, the equipment is designed with the capability to change the program of instructions to allow production of different parts or products.
- The features that characterize programmable automation are:
  (1) high investment in general purpose equipment that can be reprogrammed,
  (2) lower production rates than fixed automation,
  (3) ability to cope with product variety by reprogramming the equipment, and
  (4) suitability for batch production of various part or product styles.

(3) Flexible Automation:

- Flexible automation is an extension of programmable automation in which there is virtually no lost production time for setup changes and/or reprogramming.
- A flexible system is therefore capable of producing a mixture of different parts or products one right after the other instead of in batches.
- Features usually associated with flexible automation include:

(1) high investment cost for custom engineered equipment,
(2) medium production rates, and
(3) continuous production of different part or product styles.

- It is might say that fixed automation is applicable in situations of hard product variety, programmable automation is applicable to medium product variety, and flexible automation can be used for soft product variety.

Hardware Components for Automation:

- **Sensors**
- **Actuators**
- **Interface Devices**
- **Process Controllers**

1-Sensors:

- A sensor is a device that converts a physical stimulus or variable of interest (e.g., temperature, force, pressure, or other characteristic of the process) into a more convenient physical form (e.g., electrical voltage) for the purpose of measuring the variable.
- The conversion allows the variable to be interpreted as a quantitative value.
- Sensors of various types are available to collect data for feedback control in manufacturing automation.
- They are often classified according to type of stimulus; thus, we have mechanical (position, velocity, force, torque, etc), electrical (voltage, current, and resistance, etc), thermal, radiation, magnetic, and chemical variables.
- In addition to type of stimulus, sensors are also classified as analog or discrete.
- An analog sensor measures a continuous analog variable and converts it into a continuous signal such as electrical voltage (thermocouples, strain gages, and ammeters are examples of analog sensors).
- A discrete sensor produces a signal that can have only a limited number of values (binary and digital sensors).
- A binary sensor can take on only two possible values, such as Off and On, or 0 and 1. Limit switches operate this way.
- A digital sensor produces a digital output signal, either in the form of parallel status bits, such as a photoelectric sensor array) or a series of pulses that can be counted, such as an optical encoder.
- Digital sensors have an advantage that they can be readily interfaced to a digital computer.
- The signals from analog sensors must be converted to digital in order to be read by the computer.

- The relationship between the value of the physical stimulus and the value of the signal produced by the sensor (input/output relationship) is called the sensor's transfer function:

$$S = f(s)$$

S: output signal of the sensor (typically voltage),
s: stimulus or input,
f(s): functional relationship between them.

- The ideal form for an analog sensor is a proportional relationship:

$$S = C + ms$$

C: value of the sensor output when the stimulus value is zero,
m: constant of proportionality between s and S.

- The constant ***m*** indicates how much the output S is affected by the input s. This is referred to as the ***sensitivity*** of the measuring device.
- For example, a standard thermocouple produces 40.6 microvolts per ºC change in temperature.

- A binary sensor (e.g., limit switch, photoelectric switch) exhibits a binary relationship between stimulus and sensor output:

$$S = 1 \;\; if\; s > 0 \quad and \quad S = 0 \;\; if\; s \leq 0$$

2-Actuators

- In automated systems, an actuator is a device that converts a control signal into a physical action (change in position of a worktable or rotational speed of a motor), which refers to a change in a process input parameter.
- The control signal is a low level signal, and an amplifier may be required to increase the power of the signal to drive the actuator.
- Actuators can be classified according to type of amplifier as:
  (1) electrical, (2) hydraulic, or (3) pneumatic. (They are linear or rotational devices)
- Electrical actuators include AC and DC electric motors, stepper motors, and solenoids.
- Hydraulic actuators utilize hydraulic fluid to amplify the control signal and are often specified when large forces are required in the application.
- Pneumatic actuators are driven by compressed air, which is commonly used in factories.
- This designation distinguishes whether the output action is a linear motion or a rotational motion. Electric motors and stepper motors are rotational actuators, whereas most hydraulic and pneumatic actuators provide a linear output.

3-Interface Devices

- Interface devices allow the process to be connected to the computer controller and vice versa.
- Sensor signals from the manufacturing process are fed into the computer, and command signals are sent to actuators that operate the process.
- The interface devices include analog-to-digital converters, digital-to-analog converters, contact input/output interfaces, and pulse counters and generators.

- Continuous analog signals from sensors attached to the process must be transformed into digital values that can be used by the control computer, a function that is accomplished by an analog-to-digital converter (ADC), figure (6-4).

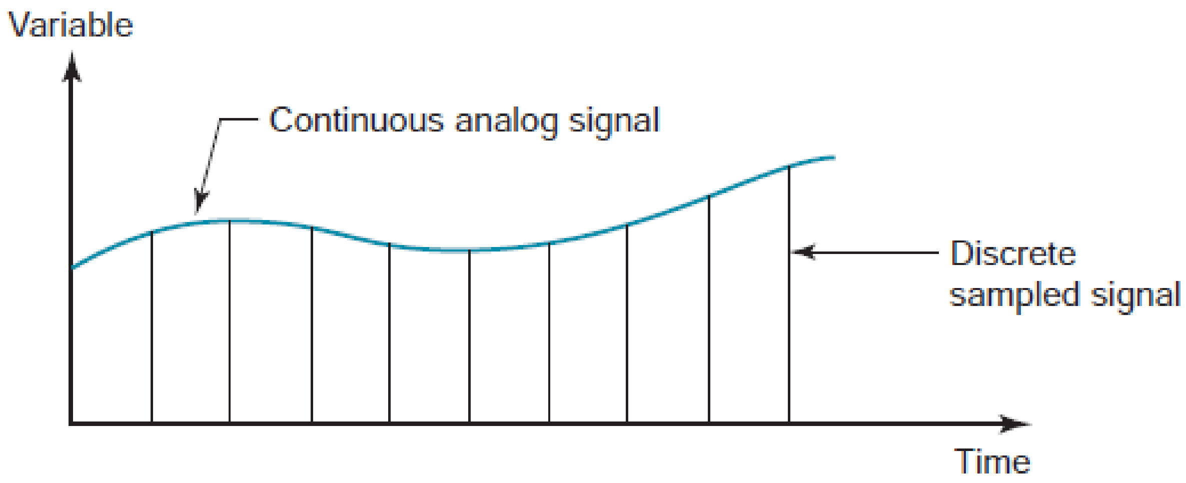

Figure (6-4): An ADC works by converting a continuous analog signal into a series of discrete sampled data. Encodes each discrete amplitude level into a sequence of binary digits that can be interpreted by the control computer.

- Important characteristics of ADC include sampling rate and resolution.
- Sampling rate is the frequency with which the continuous signal is sampled.
- Resolution refers to the precision with which the analog value can be converted into binary code. The more bits, the higher the resolution.
- A digital-to-analog converter (DAC) converts the digital output of the control computer into a quasi-continuous signal capable of driving an analog actuator or other analog device (reverse of ADC.).
- The DAC performs its function in two steps:

(1) decoding, in which the sequence of digital output values is transformed into a corresponding series of analog values at discrete time intervals, and

(2) data holding, in which each analog value is changed into a continuous signal during the duration of the time interval.

- In the simplest case, the continuous signal consists of a series of step functions, as in figure (6-5), which are used to drive the analog actuator.

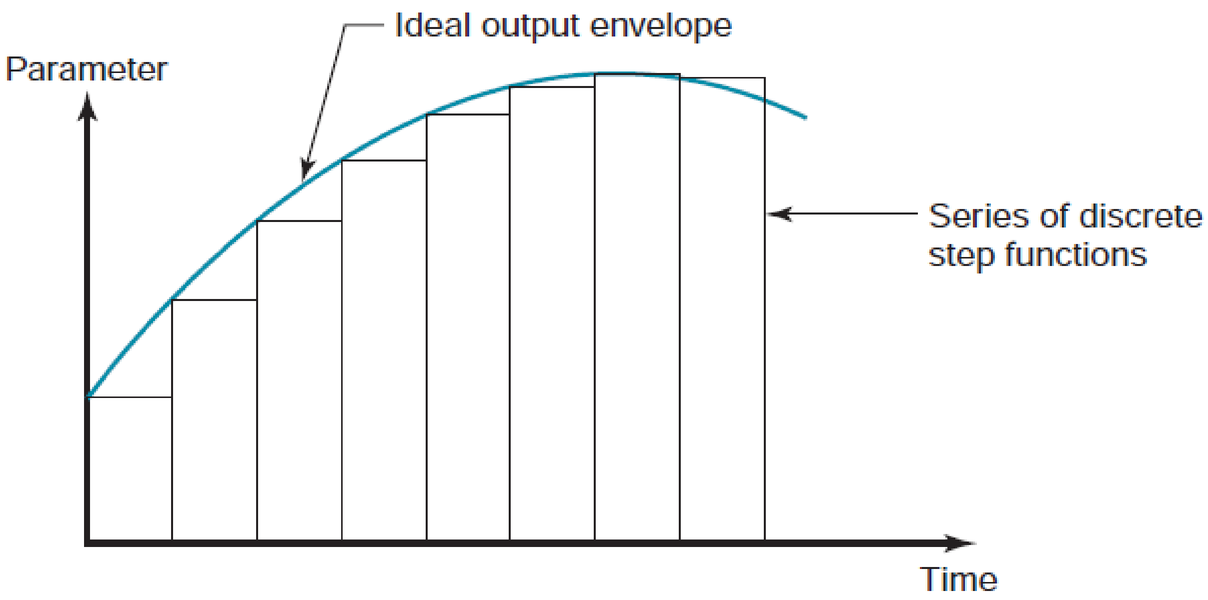

Figure (6-5): An ADC works by converting a continuous analog signal into a series of discrete sampled data. Encodes each discrete amplitude level into a sequence of binary digits that can be interpreted by the control computer.

- Many automated systems operate by turning (1 or 0) on and off motors, switches, etc, to respond to conditions and as a function of time.
- Binary sensors commonly used in process control systems include limit switches and photocells.
- Common binary actuators solenoids, valves, clutches, lights, control relays, and certain motors.
- Contact input/output interfaces are components used to communicate binary data back and forth between the process and the control computer.
- A contact output interface is a device used to communicate on/off signals from the computer to external binary components such as solenoids, alarms, and indicator lights. It can also be used to turn on and off constant speed motors.
- Discrete data sometimes exist in the form of a series of pulses as in the optical encoder to measure the position and velocity.
- A pulse counter is a device that converts a series of pulses from an external source into a digital value, which is entered into the control computer.
- The opposite of a pulse counter is a pulse generator, a device that produces a series of electrical pulses based on digital values generated by a control computer.
- An important pulse generator application is to drive stepper motors, which respond to each step by rotating through a small incremental angle, called a step angle.

4-Process Controllers

- Most process control systems use some type of digital computer as the controller.
- Requirements generally associated with real-time computer control include the following:
  - The capability of the computer to respond to incoming signals from the process and to interrupt execution of the program if necessary.
  - The capability to transmit commands to the process that are implemented by means of actuators connected to the process.
  - The capability to execute certain actions at specific points in time during process operation.
  - The capability to communicate and interact with other computers that may be connected to the process.
  - The capability to accept input from operating personnel for purposes such as entering new programs or data, editing existing programs, and stopping the process in an emergency.

- A widely used process controller that satisfies these requirements is a programmable logic controller (PLC).
- A programmable logic controller (PLC) is a microcomputer based controller that uses stored instructions in programmable memory to implement logic, sequencing, timing, counting, and arithmetic control functions, through digital or analog input/output modules, for controlling various machines and processes.
- The major components of a PLC, shown in Figure (6-6), are:

(1) input and output modules: which connect the PLC to the industrial equipment.
(2) processor: the central processing unit (CPU), which executes the logic and sequencing functions to control the process by operating on the input signals.
(3) PLC memory: which is connected to the processor and contains the logic and sequencing instructions.
(4) power supply: 115 VAC is typically used to drive the PLC.
(5) a programming device (usually detachable) is used to enter the program into the PLC.

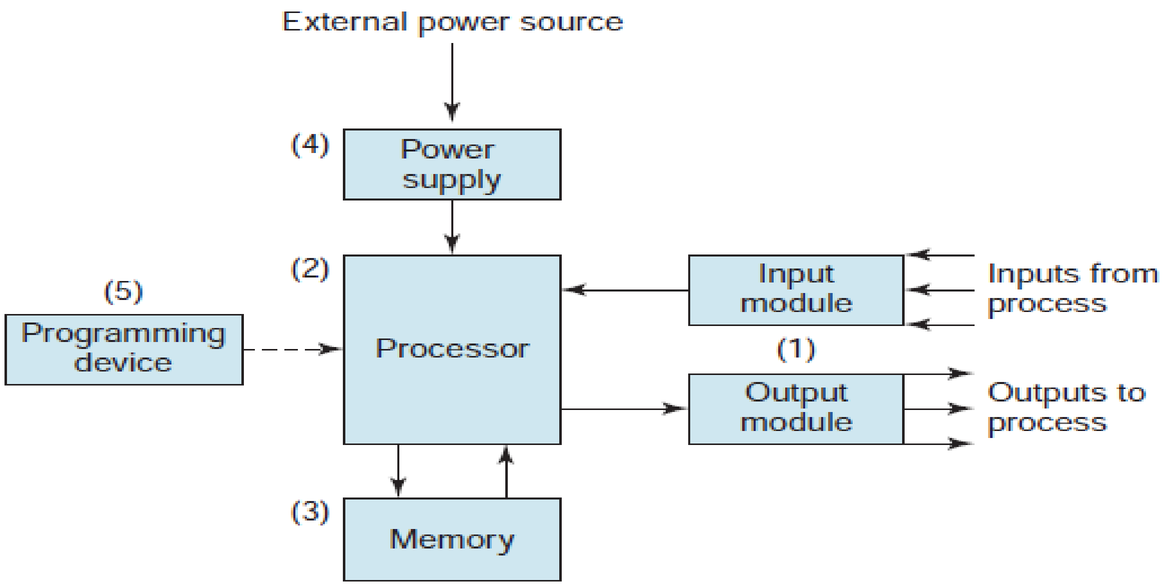

Figure (6-6): Major Components of a PLC.

- Advantages associated with PLC include:

(1) programming a PLC is easier than wiring a relay control panel.

(2) PLCs can be reprogrammed, whereas conventional hard-wired controls must be rewired and are often scrapped instead because of the difficulty in rewiring.

(3) a PLC can be interfaced with the plant computer system more readily than conventional controls.

(4) PLCs require less floor space than relay controls.

(5) PLCs offer greater reliability and easier maintenance.

Computer Numerical Control:

- Numerical control (NC) is a form of programmable automation in which the mechanical actions of a piece of equipment are controlled by a program containing coded alphanumeric data.
- The data represent relative positions between a workhead (tool or other processing element) and a w.p.
- The operating principle of NC is to control the motion of the workhead relative to w.p. and to control the sequence in which the motions are carried out.
- The first application of numerical control was in machining.

The Technology of Numerical Control:

Components of an NC System:

- A NC system consists of three basic components: (1) part program, (2) machine control unit, and (3) processing equipment.
- The part program is the detailed set of commands to be followed by the processing equipment. It is the program of instructions (position or motion of workhead relative to W.P.) in the NC control system.
- A position is defined by its x-y-z coordinates in NC system.
- Also additional details like spindle rotation speed, spindle direction, feed rate, tool change instructions, etc., may be included in the NC program.
- The part program is prepared by a part programmer.
- The machine control unit MCU (hardware and software) is a microcomputer that stores and executes the program by converting each command into actions by the processing equipment.
- The hardware in MCU includes the microcomputer, components to interface with the processing equipment, and feedback control elements.
- The software in MCU includes control system software, calculation algorithms, and translation software to convert the NC part program into a usable format for MCU.
- Because the MCU is a computer, the term computer numerical control (CNC) is often used to distinguish this type of NC from its technological predecessors that were based entirely on hard-wired electronics.
- The processing equipment accomplishes the sequence of processing steps to transform the starting workpart into a completed part.

Coordinate System and Motion Control in NC:

- The coordinate system used in NC consists of (x, y, z) of the Cartesian coordinate system, plus three rotational axes (a, b, c), as shown in Figure (6-7a).

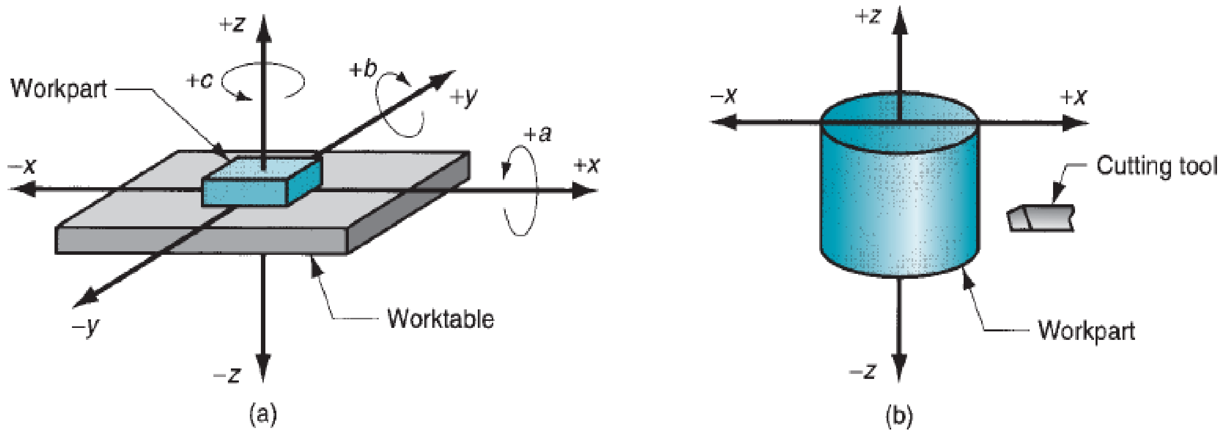

Figure (6-7): coordinate system used in NC: (a) for flat and prismatic work, and (b) for rotational work

- The rotational axes are used to rotate w.p. to present different surfaces for machining, or to orient the tool or workhead at some angle relative to the part.
- The simplest NC systems (e.g., plotters, press working machines for flat sheet-metal stock, and component insertion machines) are defined in an x-y plane.
- Some machine tools have five-axis control to shape complex w.p. geometries.
- These systems typically include three linear axes plus two rotational axes.
- The coordinates for a rotational NC system are illustrated in Figure (6-7b). These systems are associated with turning operations on NC lathes.
- Although the w.p. rotates, this is not one of the controlled axes in a conventional NC turning system. The cutting path of the tool relative to the rotating w.p. is defined in the x-z plane.
- In many NC systems, the relative movements between the processing tool and w.p. are accomplished by fixing the part to a worktable and then controlling the positions and motions of the table relative to a stationary or semi-stationary workhead.
- In other systems, the w.p. is held stationary and the workhead is moved along two or three axes. Flame cutters, x-y plotters, and coordinate measuring machines operate in this mode.
- Motion control systems based on NC can be divided into two types: (1) point-to-point and (2) continuous path (contouring).
- Point-to-point systems (positioning systems), move the workhead (or w.p.) to a programmed location with no regard for the path taken to get to that location. Once the move is completed, some processing action is accomplished by the workhead at the location, such as drilling or punching a hole.
- Continuous path systems (certain milling, turning, and flame cutting operations) provide continuous simultaneous control of more than one axis, thus controlling the path followed by the tool relative to w.p.
- This permits the tool to perform a process while the axes are moving, generate angular surfaces, two-dimensional curves, or three-dimensional in the w.p.

- Continuous path includes an interpolation (linear & circular), which means calculating the intermediate points along a path to be followed by the workhead relative to w.p.
- Linear interpolation (used for straight line), in which the part programmer specifies the coordinates of the beginning and end points of straight line and feed rate. The interpolator then computes the travel speeds of the two or three axes that will accomplish the specified trajectory.
- Circular interpolation allows the workhead to follow a circular arc by specifying the coordinates of its beginning and end points together with either the center or radius of the arc.
- The interpolator computes a series of small straight line segments that will approximate the arc within a defined tolerance.
- Another aspect of motion control is (positions are defined absolutely or incrementally).
- In absolute positioning, the workhead locations are always defined with respect to the origin of the axis system.
- In incremental positioning, the next workhead position is defined relative to the present location. The difference is illustrated in figure (6-8).

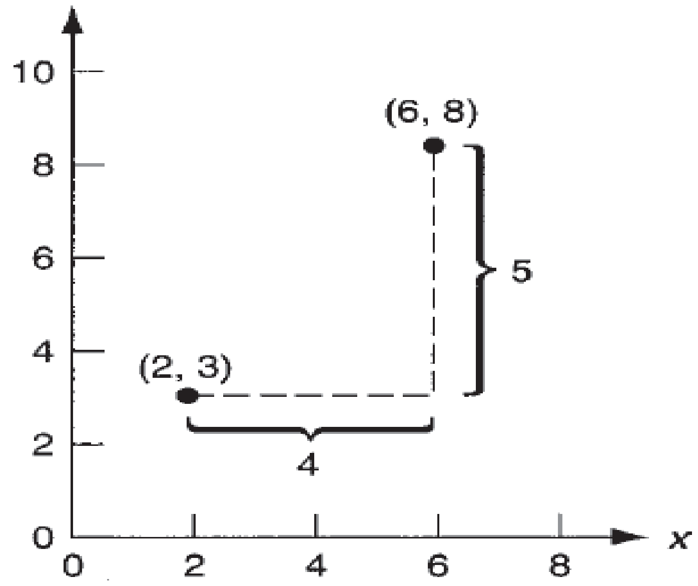

Figure (6-8): Absolute vs incremental positioning. The workhead is at point (2,3) and is to be moved to point (6,8). In absolute positioning, the move is specified by x=6, and y=8; while in incremental positioning, the move is specified by x=4, and y=5.

Analysis of NC Positioning Systems:

- The function of the positioning system is to convert the coordinates specified in the NC part program into relative positions between the tool and w.p. during processing.
- Figure (6-9) shows a simple positioning system, only one axis is used.

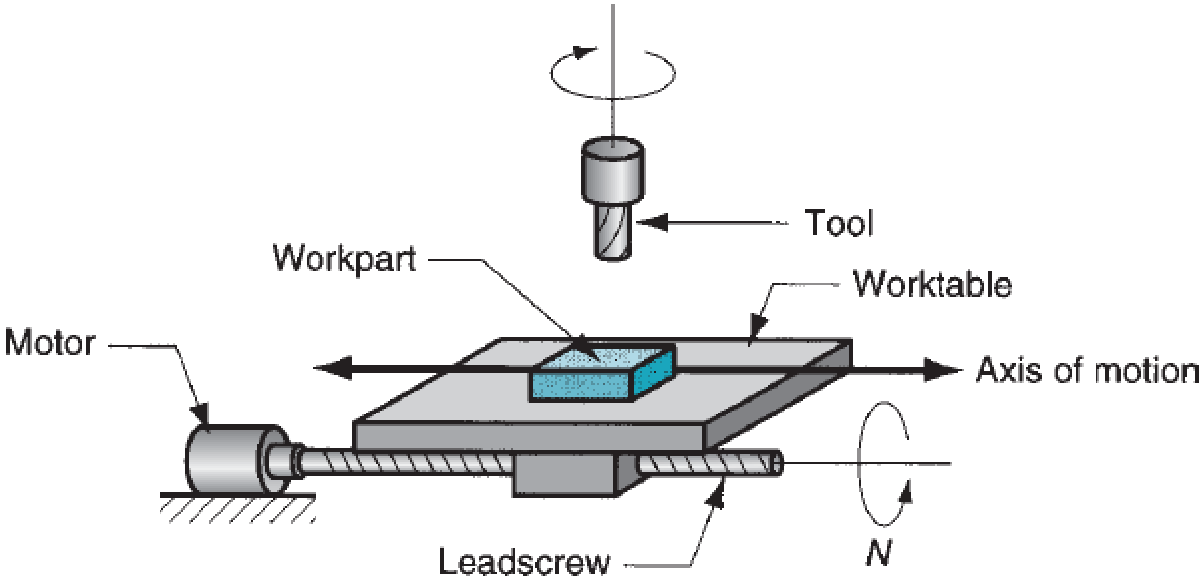

Figure (6-9): Motor and leadscrew arrangement in an NC positioning system.

- The table is moved a distance equal to the leadscrew pitch [mm/thread (in/thread) or mm/rev (in/rev)] for each revolution. The velocity of table is determined by the rotational speed of the leadscrew.
- Two basic types of motion control are used in NC:
  (a) open loop (b) closed loop, as shown in Figure (6-10).

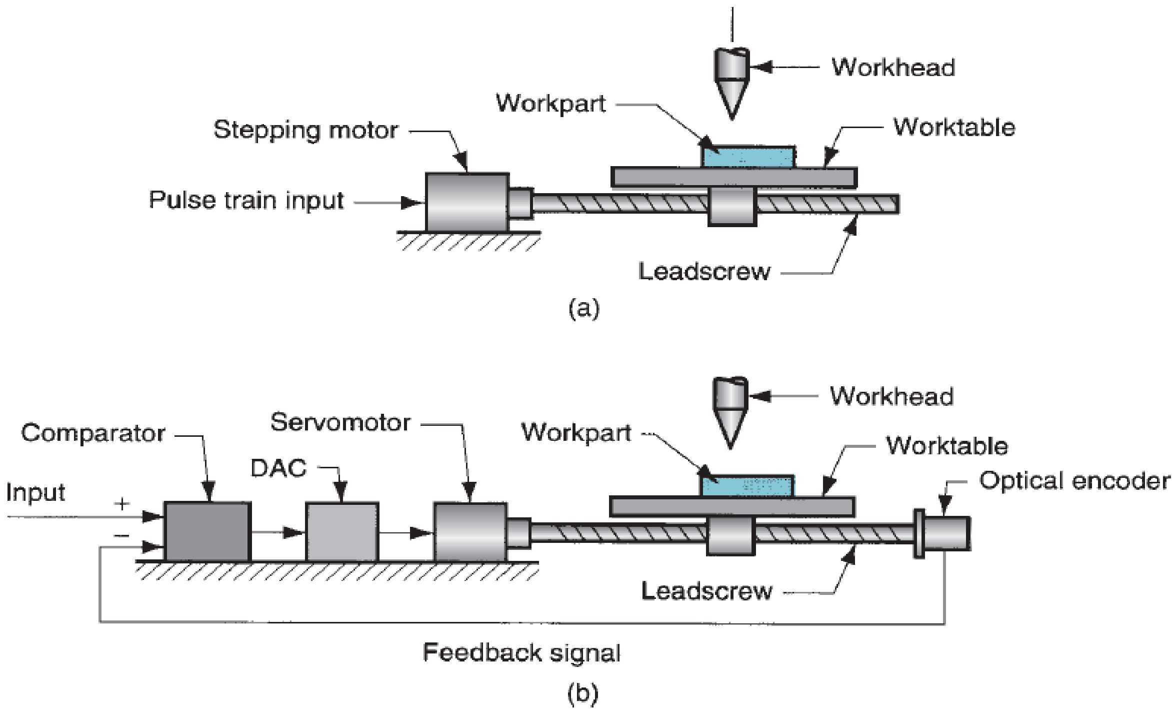

Figure (6-10): Two types of motion control in NC: (a) open loop (b) closed loop.

- The open-loop system operates without verifying that the desired position of the worktable has been achieved. Usually, it is suitable when the force resisting the actuating motion is minimal (e.g. point-to-point drilling).
- The closed loop system uses feedback measurement to verify that the position of the worktable is indeed the location specified in the program. Normally, it is used in continuous path operations (e.g. milling, turning) in which the resisting forces can be high.

Open-Loop Positioning Systems:
- To turn the leadscrew, an open-loop system uses a stepping motor (a.k.a. stepper motor).
- In NC, the stepping motor is driven by a series of electrical pulses generated by the machine control unit.
- Each pulse causes the motor to rotate a fraction of one revolution, called the step angle. The allowable step angle is as follows:

$$\alpha = \frac{360}{n_s}$$

α: step angle (^{o}).
n_s: number of step angles for the motor (integer number).

- The angle through which the motor shaft rotates is given by:

$$A_m = \alpha n_p$$

A_m: angle of motor shaft rotation (^{o}).
n_p: number of pulses received by the motor.
α: step angle (^{o} / pulse).

- The rotational speed of motor shaft is determined by the frequency of pulses sent to the motor as follows:

$$N_m = \frac{60\alpha f_p}{360}$$

N_m: speed of motor shaft rotation (rev/min).
f_p: frequency of pulses driving the stepper motor H_z (pulses/sec).
constant 60: converts (pulses/sec) to (pulses/min).

constant 360: converts degrees of rotation to full revolutions.

α: step angle of motor (^{o} / pulse).

- The motor shaft drives the leadscrew that determines the position and velocity of worktable.
- The connection is often designed using a gear reduction to increase the precision of table movement. The angle of rotation and rotational speed of the leadscrew are reduced by this gear ratio as follows:

$$A_m = r_g\, A_{ls}$$

$$N_m = r_g\, N_{ls}$$

A_m: angle of rotation of the motor (^{o}).

N_m: rotational speed of the motor (rev/min).

A_{ls}: angle of rotation of the leadscrew (^{o}).

N_{ls}: rotational speed of the leadscrew (rev/min).

r_g: gear reduction between the motor shaft and the leadscrew.

For example: r_g=2 : N_m=2 and N_{ls}=1

- The linear position of the table in response to the rotation of the leadscrew depends on the leadscrew pitch p, as follows:

$$x = \frac{pA_{ls}}{360}$$

x: x-axis position relative to the starting position, mm (in).

p: pitch of the leadscrew, mm/rev (in/rev).

$A_{ls}/360$: the number of revolutions (and partial revolutions) of the leadscrew.

- From the following equations:

$$A_m = \alpha n_p \quad \& \quad A_m = r_g\, A_{ls} \quad \& \quad x = \frac{pA_{ls}}{360} \quad \& \quad \alpha = \frac{360}{n_s}$$

Then the number of pulses required to achieve a specified x-position increment in a point-to-point system is as follows:

$$n_p = \frac{360\, r_g\, x}{p\, \alpha} = \frac{r_g\, n_s\, A_{ls}}{360}$$

- The velocity of the worktable in the direction of the leadscrew axis is as follows:

$$v_t = f_r = N_{ls}\, p$$

v_t: table speed, mm/min (in/min).
f_r: table feed rate, mm/min (in/min).
N_{ls}: rotational speed of the leadscrew, (rev/min).
p: leadscrew pitch, mm/rev (in/rev).

- The rotational speed of the leadscrew depends on f_p:

$$N_{ls} = \frac{60 f_p}{n_s r_g}$$

N_{ls}: leadscrew rotational speed, (rev/min).
f_p: pulse train frequency, Hz (pulses/sec).
n_s: steps/rev, or pulses/rev.
r_g: gear reduction between the motor and the leadscrew.

- From the following equations:

$$v_t = f_r = N_{ls}\, p \qquad \& \qquad N_{ls} = \frac{60 f_p}{n_s r_g}$$

Then the required pulse frequency (f_p) to drive the table at a specified feed rate:

$$f_p = \frac{v_t n_s r_g}{60p} = \frac{f_r n_s r_g}{60p} = \frac{N_{ls} n_s r_g}{60} = \frac{N_m n_s}{60}$$

Example (1):

A stepping motor has 48 step angles. Its output shaft is coupled to a leadscrew with a 4:1 gear reduction. The leadscrew pitch = 5 mm. The worktable of a positioning system is driven by the leadscrew. The table must move a distance of 75 mm from its current position at a travel speed of 400 mm/min. Determine (a) how many pulses are required to move the table the specified distance and (b) the motor speed and (c) pulse frequency required to achieve the desired table speed.

Solution:

(a) From equation:

$$n_p = \frac{360\, r_g\, x}{p\, \alpha}$$

$$\alpha = \frac{360}{n_s} = \frac{360}{48} = 7.5° \ (step\ angle)$$

$$\therefore n_p = \frac{360\, r_g\, x}{p\, \alpha} = \frac{360(4)(75)}{5(7.5)} = 2880\ pulses$$ **Answer**

(b) From equation:

$$N_m = r_g\, N_{ls}$$

$$v_t = N_{ls}\, p \quad \rightarrow \quad N_{ls} = \frac{v_t}{p} = \frac{400}{5} = 80\ rev/min$$

$$\therefore N_m = r_g\, N_{ls} = 4(80) = 320\ rev/min$$ **Answer**

(c) From equation:

$$f_p = \frac{v_t n_s r_g}{60p} = \frac{400(48)(4)}{60(5)} = 256\ Hz$$ **Answer**

Closed-Loop Positioning Systems:

- Closed-loop NC systems, Figure (6-11b), use servomotors and feedback measurements to ensure that the desired position is achieved.

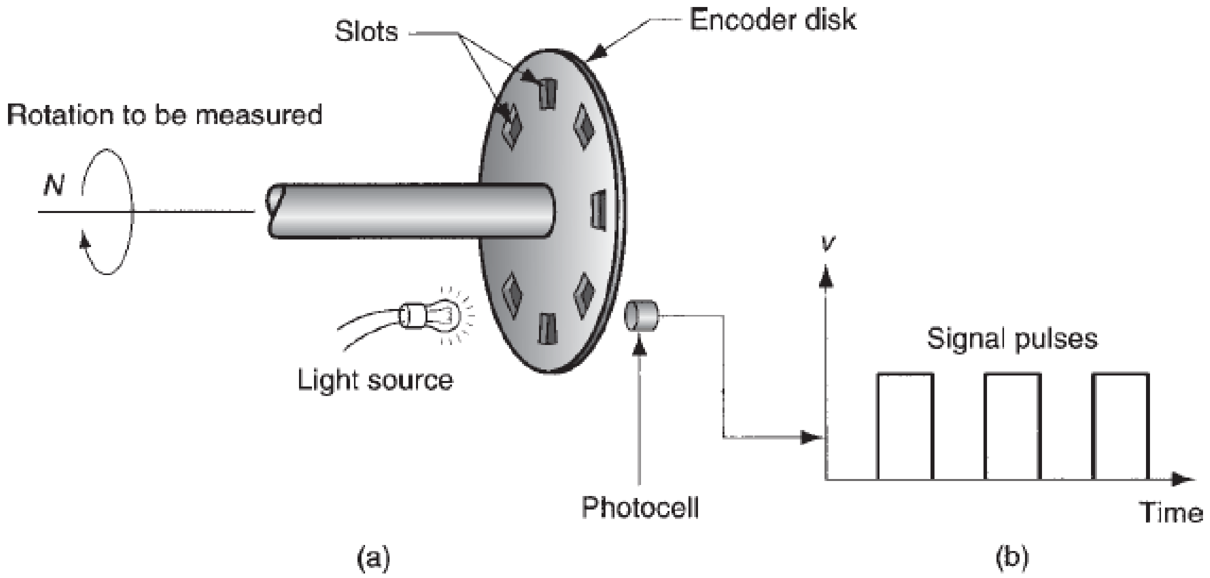

Figure (6-11): optical encoder: (a) apparatus, and (b) series of pulses emitted to measure rotation of disk.

- A common feedback sensor used in NC (industrial robots) is the optical rotary encoder, illustrated in Figure (6-11).
- It consists of a light source, a photocell, and a disk containing a series of slots through which the light source can shine to energize the photocell.
- The disk is connected to a rotating shaft (it is connected directly to leadscrew).
- At rotation, the slots cause the light source to be seen by the photocell as a series of flashes (converted into an equivalent series of electrical pulses).
- By counting the pulses and computing the frequency of the pulse train, the leadscrew angle and rotational speed can be determined, and thus worktable position and speed can be calculated also.
- In the basic optical encoder, the angle between slots is as follows:

$$\alpha = \frac{360}{n_s}$$

α: angle between slots (°/slot).
n_s: number of slots in the disk slots/rev.
360: degrees/rev.

- The number of pulses which generated by the encoder:

$$n_p = \frac{A_{ls}}{\alpha} = \frac{A_{ls} n_s}{360}$$

n_p: pulse count.
A_{ls}: angle of rotation of the leadscrew, degrees.
α: angle between slots in the encoder (^{o}/pulse).

- The linear x-axis position of the worktable is determined by factoring in the leadscrew pitch:

$$x = \frac{p n_p}{n_s} = \frac{p A_{ls}}{360}$$

- The feed rate at which the worktable moves is obtained from the frequency of the pulse train:

$$v_t = f_r = \frac{60 p f_p}{n_s}$$

v_t: table travel speed, mm/min (in/min).
f_r: feed rate, mm/min (in/min).
p: pitch, mm/rev (in/rev).
f_p: frequency of the pulse train, Hz (pulses/sec).
n_s: number of slots in the encoder disk, pulses/rev.
60: converts seconds to minutes.

- The series of pulses generated by the encoder is compared with the coordinate position and feed rate specified in the part program, and the difference is used by the machine control unit to drive a servomotor that in turn drives the leadscrew and worktable.
- The relations of gear reduction can be used here as in open-loop.

Example (2):
An NC worktable is driven by a closed-loop positioning system consisting of a servomotor, leadscrew, and optical encoder. The leadscrew has a pitch = 5 mm and is coupled to the motor shaft with a gear ratio of 4:1. The optical encoder generates 100 pulses/rev of the leadscrew. The table has been programmed to move a distance of 75 mm at a feed rate = 400 mm/min. Determine (a) how many pulses are received by the control system to verify that the table has moved exactly 75

mm; and (b) the pulse rate and (c) motor speed that correspond to the specified feed rate.

Solution:

(a) From equation:

$$x = \frac{pn_p}{n_s} \rightarrow n_p = \frac{xn_s}{p} = \frac{75(100)}{5} = 1500\,pulses$$ **Answer**

(b) From equation:

$$f_r = \frac{60pf_p}{n_s} \rightarrow f_p = \frac{f_r n_s}{60p} = \frac{400(100)}{60(5)} = 133.33\,pulses/sec$$ **Answer**

(c) From equation:

$$v_t = f_r = N_{ls}\,p \rightarrow N_{ls} = \frac{f_r}{p} = \frac{400}{5} = 80\,rev/min$$

$$\therefore N_m = r_g\,N_{ls} = 4(80) = 320\,rev/min$$ **Answer**

Precision in Positioning:

- Three critical measures of precision in positioning are **control resolution**, **accuracy**, and **repeatability**.

- **Control Resolution**: the system's ability to divide the total range of the axis movement into closely spaced points that can be distinguished by the control unit.
- The distance separating two adjacent control -or addressable- points (locations along the axis can the table goes them) in the axis movement.
- The electromechanical factors that limit resolution include:
  (1) leadscrew pitch,
  (2) gear ratio,
  (3) the step angle in a stepping motor (for an open-loop system),
  (4) the angle between slots in an encoder disk (for a closed-loop system).

- These factors determine a control resolution, or minimum distance that worktable can be moved.
- For example, the control resolution for an open-loop system driven by a stepper motor with a gear reduction between the motor shaft and the leadscrew is given by:

$$CR_1 = \frac{p}{n_s r_g}$$

CR_1: control resolution of the electromechanical components, mm (in).
p: leadscrew pitch, mm/rev (in/rev).
n_s: number of steps/rev.
r_g: gear reduction.

- The corresponding expression for a closed-loop positioning system is similar but does not include the gear reduction because the encoder is connected directly to the leadscrew. Thus the control resolution:

$$CR_1 = \frac{p}{n_s}$$

n_s: refers to the number of slots in the optical encoder.

- Although unusual in modern computer technology, the second possible factor is the number of bits (B) in the storage register for the axis.
- The number of control points into which the axis range can be divided = 2^B. Thus:

$$CR_2 = \frac{L}{2^B - 1}$$

CR_2: control resolution of the computer control system, mm (in).
L: axis range, mm (in).

- The control resolution of the positioning system is the maximum of the two values; that is:

$$CR = Max\{CR_1, CR_2\}$$

- It is desirable [$CR_2 \leq CR_1$], meaning that the electromechanical system is the limiting factor in control resolution.

- When the worktable is moved to a given control point, the capability of the system to move to that point will be limited by mechanical errors.
- These errors are due to a variety of inaccuracies and imperfections in the mechanical system, such as play between the leadscrew and the worktable, backlash in the gears, and deflection of machine components.

- **Accuracy:** of any given axis of a positioning system is the maximum possible error that can occur between the desired target point and the actual position taken by the system as follows:

$$\boldsymbol{Accuracy = 0.5CR + 3\sigma}$$

CR: control resolution, mm (in).

σ: standard deviation of the error distribution, mm (in).

- **Repeatability:** the capability of a positioning system to return to a given control point that has been previously programmed.
- This capability can be measured in terms of the location errors (e.g., mechanical errors) encountered when the system attempts to position itself at the control point.
- Thus, **Repeatability** can be defined as the range of mechanical errors associated with the axis of positioning system:

$$\boldsymbol{Repeatability = \pm 3\sigma}$$

- The definition of control resolution, accuracy and repeatability is explained in figure (6-12).

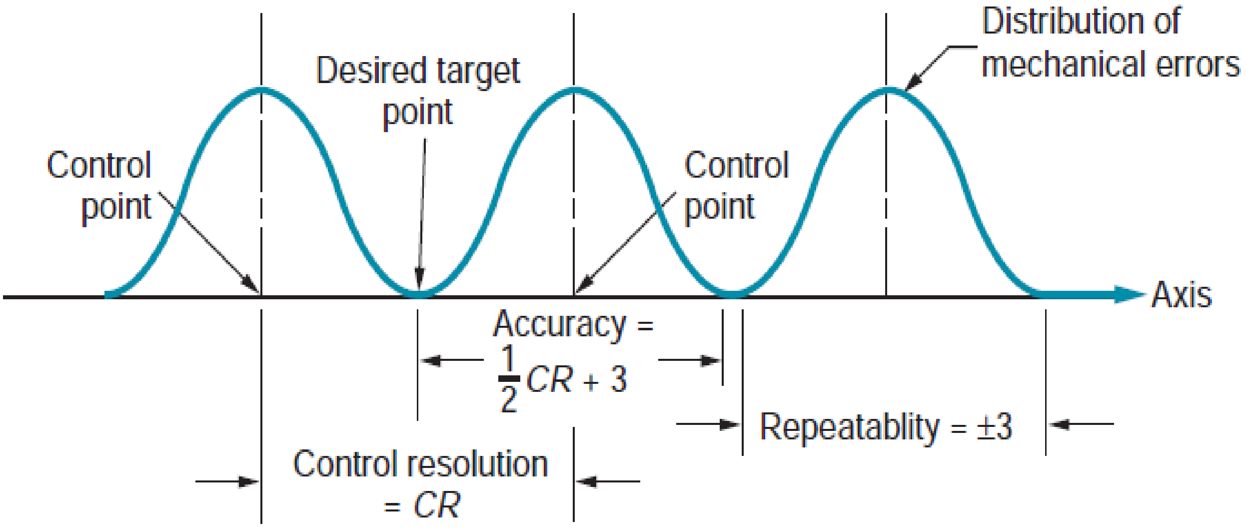

Figure (6-12): A portion of a linear positioning system axis, with definition of control resolution, accuracy, and repeatability.

Example (3):

Referring back to Example (1), the mechanical inaccuracies in the open-loop positioning system can be described by a normal distribution whose standard deviation = 0.005 mm. The range of the worktable axis is 550mm, and there are 16 bits in the binary register used by the digital controller to store the programmed position. Determine (a) control resolution, (b) accuracy, and (c) repeatability for the positioning system.

Solution:

(a) From equation:

$$CR_1 = \frac{p}{n_s r_g} = \frac{5}{48(4)} = 0.026\ mm$$

$$CR_2 = \frac{L}{2^B - 1} = \frac{550}{2^{16} - 1} = 0.0084\ mm$$

$$CR = Max\{CR_1, CR_2\} = Max\{0.026, 0.0084\} = 0.026\ mm$$ **Answer**

(b) From equation:

$Accuracy = 0.5CR + 3\sigma = 0.5(0.026) + 3(0.005) = 0.028\ mm$ **Answer**

(c) From equation:

$Repeatability = \pm 3\sigma = \pm 3(0.005) = \pm 0.015\ mm$ **Answer**