Part X Manufacturing Systems

37 Automation Technologies for Manufacturing systems

Chapter Contents

This part of the book describes the manufacturing systems that are commonly used to implement the production and assembly processes discussed in preceding chapters. 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 37.1. As the diagram indicates, the manufacturing systems are located in the factory. They accomplish the value-added work on the part or product.

Manufacturing systems include both automated and manually operated systems. The distinction between the two categories is not always clear, because many manufacturing systems consist of both automated and manual work elements (e.g., a machine tool that operates on a semiautomatic processing cycle but must be loaded and unloaded each cycle by a human worker). The coverage includes both categories and is organized into

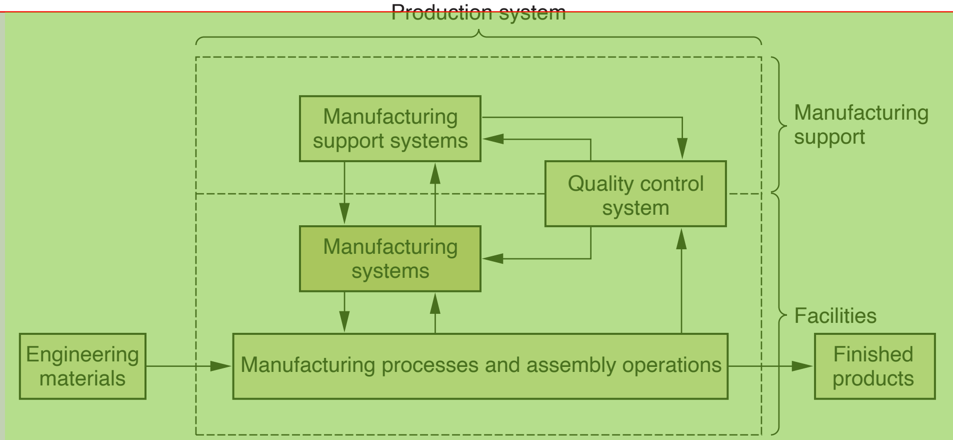


FIGURE 37.1 The position of the manufacturing systems in the larger production system.

two chapters: Chapter 37 on automation technologies and Chapter 38 on integrated manufacturing systems. Chapter 37 provides an introductory treatment of automation technology and the components that make up an automated system. Also, two important automation technologies used in manufacturing are described: numerical control and industrial robotics. Chapter 38 examines how these automation technologies are integrated into more sophisticated manufacturing systems. Topics include production lines, cellular manufacturing, flexible manufacturing systems, and computer integrated manufacturing. A more detailed discussion of the topics in these two chapters can be found in [5].

37.1 Automation Fundamentals

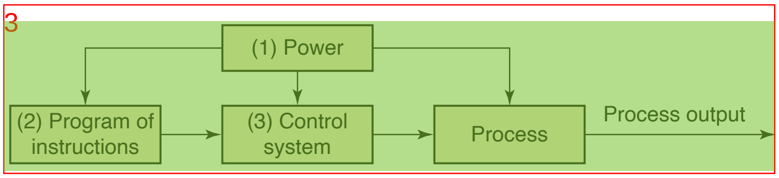
Automation can be defined as the technology by which a process or procedure is performed without human assistance. Humans may be present as observers or even participants, but the process itself operates under its own self-direction. Automation is implemented by means of a control system that executes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

37.1.1 THREE COMPONENTS OF AN AUTOMATED SYSTEM

As indicated above, an automated system consists of three basic components: (1) power, (2) a program of instructions, and (3) a control system to carry out the instructions. The relationship among these components is shown in Figure 37.2.

The form of power used in most automated systems is electrical. The advantages of electrical power include that it (1) is widely available, (2) can be readily converted

FIGURE 37.2 Elements of an automated system: (1) power, (2) program of instructions, and (3) control system.



to other forms of power such as mechanical, thermal, or hydraulic, (3) can be used at very low power levels for functions such as signal processing, communication, data storage, and data processing, and (4) can be stored in long-life batteries [5].

In a manufacturing process, power is required to accomplish the activities associated with the particular process. Examples of these activities include (1) melting a metal in a casting operation, (2) driving the motions of a cutting tool relative to a workpiece in a machining operation, and (3) pressing and sintering parts in a powder metallurgy process. Power is also used to accomplish any material handling activities needed in the process, such as loading and unloading parts, if these activities are not performed manually. Finally, power is used to operate the control system.

The activities in an automated process are determined by a program of instructions. In the simplest automated processes, the only instruction may be to maintain a certain controlled variable at a specified level, such as regulating the temperature in a heat treatment furnace. In more complex processes, a sequence of activities is required during the work cycle, and the order and details of each activity are defined by the program of instructions. 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 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 humans 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, the third basic component of an automated system. Two types of control system can be distinguished: closed loop and open loop. A ***closed-loop system***, also known as a ***feedback control system***, is one in which the process variable of interest (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 37.3(a) 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. The input parameter represents the desired value of the output variable. The process is the operation or activity being controlled; more specifically, the output variable is being controlled by the system. A sensor is used to measure the output variable and feed back its value to the controller, which compares output with input and makes the required adjustment to reduce any difference. The adjustment

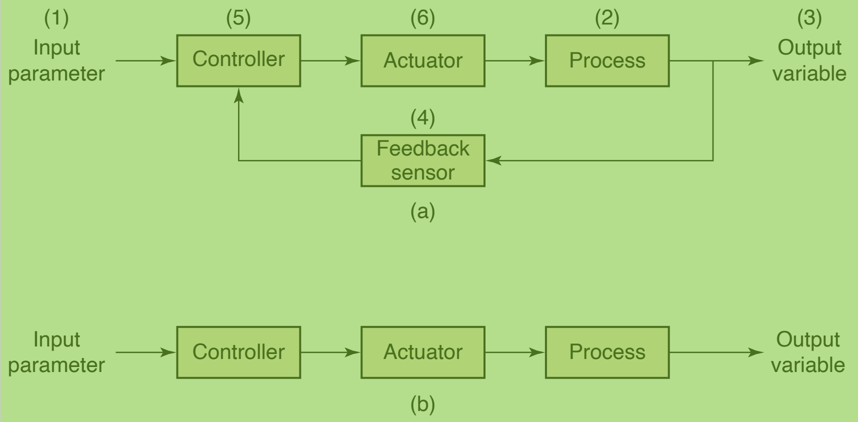


FIGURE 37.3 Two basic types of control systems: (a) closed loop and (b) open loop.

is made by means of one or more actuators, which are hardware devices that physically accomplish the control actions.

The other type of control system is an open-loop system, presented in Figure 37.3(b). As shown in the diagram, an ***open-loop system*** executes the program of instructions without a feedback loop. No measurement of the output variable is made, so there is no comparison between output and input in an open loop system. In effect, the controller relies on the expectation that the actuator will have the intended effect on the output variable. Thus, 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. On the other hand, the advantage of an open-loop system is that its cost is less than a comparable closed-loop system.

37.1.2 TYPES OF AUTOMATION

Automated systems used in manufacturing can be classified into three basic types: (1) fixed automation, (2) programmable automation, and (3) flexible automation.

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. Although the work cycle consists of simple operations, integrating and coordinating the actions can result in the need for a rather sophisticated control system, and computer control is often required.

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. Automated systems with these features can be justified for parts and products that are produced in very large quantities. The high investment cost can be spread over many units, thus making the cost per unit relatively low compared to alternative production methods. The automated production lines discussed in the following chapter are examples of fixed automation.

Programmable Automation As its name suggests, the equipment in programmable automation is designed with the capability to change the program of instructions to allow production of different parts or products. New programs can be prepared for new parts, and the equipment can read each program and execute the encoded instructions. Thus 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. Examples of programmable automation include computer numerical control and industrial robotics, discussed in Sections 37.3 and 37.4, respectively.

Flexible Automation Suitability for batch production is mentioned as one of the features of programmable automation. As discussed in Chapter 1, the disadvantage of batch production is that lost production time occurs between batches due to equipment and/or tooling changeovers that are required to accommodate the next batch. Thus, programmable automation usually suffers from this disadvantage. Flexible automation is an extension of programmable automation in which there is virtually no lost production time for setup changes and/or reprogramming. Any required changes in the program of instructions and/or setup can be accomplished quickly; that is, within the time needed to move the next work unit into position at the machine. 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.

Using terminology developed in Chapter 1, one 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.

37.2 Hardware for Automation

Automation and process control are implemented using various hardware devices that interact with the production operation and associated processing equipment. Sensors are required to measure the process variables. Actuators are used to drive the process parameters. And various additional devices are needed to interface the sensors and actuators with the process controller, which is usually a digital computer.

37.2.1 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, there are mechanical, electrical, thermal, radiation, magnetic, and chemical variables. Within each category, multiple variables can be measured. For example, within the mechanical category, the physical variables include position, velocity, force, torque, and many others. Electrical variables include voltage, current, and resistance. And so on for the other major categories.

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. Within this category, there are binary sensors 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, whereas the signals from analog sensors must be converted to digital to be read by the computer.

For a given sensor, there is a relationship between the value of the physical stimulus and the value of the signal produced by the sensor. This input/output relationship is called the sensor's ***transfer function***, which can be expressed as:

$$S = f(s) \tag{37.1}$$

where S = the output signal of the sensor (typically voltage), s = the stimulus or input, and $f(s)$ is the functional relationship between them. The ideal form for an analog sensor is a proportional relationship:

$$S = C + ms \tag{37.2}$$

where C = the value of the sensor output when the stimulus value is zero, and m = the 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 Chromel/Alumel thermocouple produces 40.6 microvolts per degree °C change in temperature.

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

$$S = 1 \text{ if } s > 0 \text{ and } S = 0 \text{ if } s \leq 0 \tag{37.3}$$

Before a measuring device can be used, it must be calibrated, which basically means determining the transfer function of the sensor; specifically, how is the value of the stimulus s determined from the value of the output signal S? Ease of calibration is one criterion by which a measuring device can be selected. Other criteria include accuracy, precision, operating range, speed of response, reliability and cost.

37.2.2 ACTUATORS

In automated systems, an actuator is a device that converts a control signal into a physical action, which usually refers to a change in a process input parameter. The action is typically mechanical, such as a change in position of a worktable or rotational speed of a motor. The control signal is generally 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. Electrical actuators include AC and DC electric motors, stepper motors, and solenoids. The operations of two types of electric motors (servomotors and stepper motors) are described in Section 37.3.2, which deals with the analysis of positioning systems. 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. All three actuator types are available as linear or rotational devices. This designation distinguishes whether the output action is a linear motion or a rotational motion. Electric motors and stepper motors are more common as rotational actuators, whereas most hydraulic and pneumatic actuators provide a linear output.

37.2.3 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. This section describes the hardware devices that enable this communication between the process and the controller. The 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). As illustrated in Figure 37.4, an ADC (1) samples the continuous signal at periodic intervals, (2) converts the sampled data into one of a finite number of defined amplitude levels, and (3) encodes each amplitude level into a sequence of binary digits that can be interpreted by the control computer. Important characteristics of an analog-to-digital converter include sampling rate and resolution. Sampling rate is the frequency with which the continuous signal is sampled. A faster sampling rate means that the actual form of the continuous signal can be more closely approximated. Resolution refers to the precision with which the analog value can be converted into binary code. This depends on the number of bits used in the encoding procedure, the more bits, the higher the resolution. Unfortunately, using more bits requires more time to make the conversion, which can impose a practical limit on the sampling rate.

A ***digital-to-analog converter*** (DAC) accomplishes the reverse process of the ADC. It converts the digital output of the control computer into a quasi-continuous signal capable of driving an analog actuator or other analog device. 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

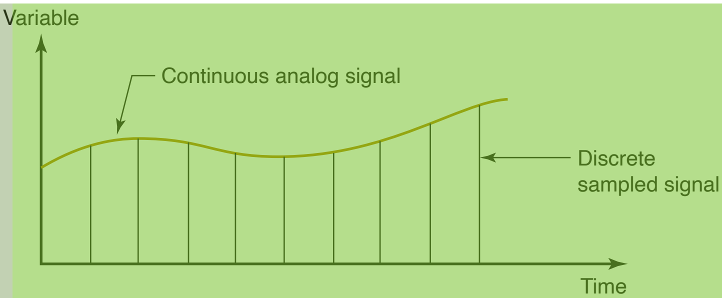


FIGURE 37.4 An analog-to-digital converter works by converting a continuous analog signal into a series of discrete sampled data.

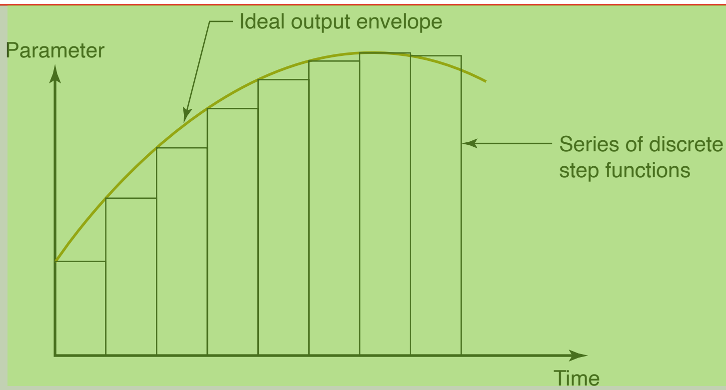


FIGURE 37.5 An analog-to-digital converter works by converting a continuous analog signal into a series of discrete sampled data.

continuous signal consists of a series of step functions, as in Figure 37.5, which are used to drive the analog actuator.

Many automated systems operate by turning on and off motors, switches, and other devices to respond to conditions and as a function of time. These control devices use binary variables. They can have either of two possible values, 1 or 0, interpreted as ON or OFF, object present or not present, high or low voltage level, and so on. 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 input interface*** is a device that reads binary data into the computer from an external source. It consists of a series of binary electrical contacts that indicate the status of a binary device such as a limit switch attached to the process. The status of each contact is periodically scanned by the computer to update values used by the control program. 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.

As mentioned earlier, discrete data sometimes exist in the form of a series of pulses. For example, an optical encoder (Section 37.3.2) emits its measurement of position and velocity as a series of pulses. 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. In addition to reading the output of an optical encoder, applications of pulse counters include counting the number of parts flowing along a conveyor past a photoelectric sensor. 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. Both the number and frequency of the pulses are controlled. 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.

37.2.4 PROCESS CONTROLLERS

Most process control systems use some type of digital computer as the controller. Whether control involves continuous or discrete parameters and variables, or a combination of continuous and discrete, a digital computer can be connected to the process to communicate and interact with it using the interface devices discussed in Section 37.2.3. 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 if necessary, to interrupt execution of a current program to service the incoming signal.
- The capability to transmit commands to the process that are implemented by means of actuators connected to the process. These commands may be the response to incoming signals from 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 term ***distributed process control*** is used to describe a control system in which multiple microcomputers are used to share the process control workload.
- 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. 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 37.6, are (1) ***input and output modules***, which connect the PLC to the industrial equipment to be controlled; (2) ***processor*** — the central processing unit (CPU), which executes the logic and sequencing functions to control the process by operating on the input signals and determining the proper output signals specified by the control program; (3) ***PLC memory***, which is connected to the processor and contains the logic and sequencing instructions; (4) ***power supply*** — 115 V AC is typically used to drive the PLC. In addition, (5) a ***programming device*** (usually detachable) is used to enter the program into the PLC.

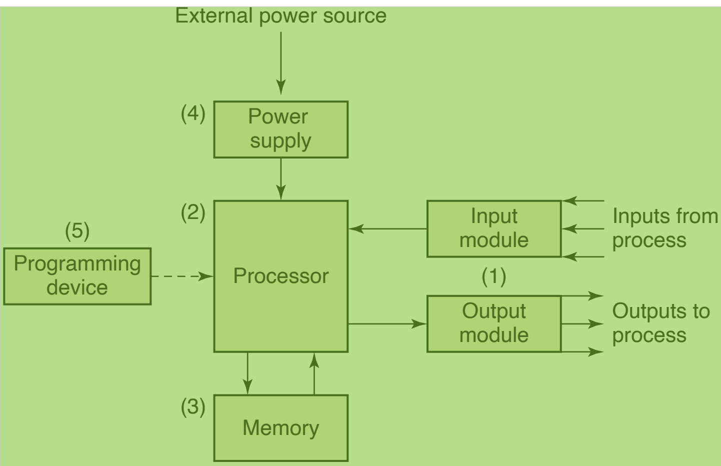


FIGURE 37.6 Major components of a programmable logic controller.

Programming involves entry of the control instructions to the PLC using the programming device. The most common control instructions include logical operations, sequencing, counting, and timing. Many control applications require additional instructions for analog control, data processing, and computations. A variety of PLC programming languages have been developed, ranging from ladder logic diagrams to structured text. A discussion of these languages is beyond the scope of this text, and the interested reader should consult the end-of-chapter references.

Advantages associated with programmable logic controllers 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, and (5) PLCs offer greater reliability and easier maintenance.

37.3 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 work head and a work part. The work head is a tool or other processing element, and the work part is the object being processed. The operating principle of NC is to control the motion of the work head relative to the work part and to control the sequence in which the motions are carried out. The first application of numerical control was in machining (Historical Note 37.1), and this is still an important application area. NC machine tools are shown in Figures 21.26 and 21.27.

Historical Note 37.1 *Numerical control (3), (5)*

The initial development work on numerical control is credited to John Parsons and Frank Stulen at the Parsons Corporation in Michigan in the late 1940s. Parsons was a machining contractor for the Air Force and had devised a means of using numerical coordinate data to move the worktable of a milling machine for producing complex parts for aircraft. On the basis of Parson's work, the U.S. Air Force awarded a contract to the company in 1949 to study the feasibility of the new control concept for machine tools. The project was subcontracted to the Massachusetts Institute of Technology to develop a prototype machine tool that utilized the new numerical data principle. The M.I.T. study confirmed that the concept was feasible and proceeded to adapt a three-axis vertical milling machine using combined analog-digital controls. The name ***numerical control*** (NC) was given to the system by which the machine tool motions were accomplished. The prototype machine was demonstrated in 1952.

The accuracy and repeatability of the NC system was far better than the manual machining methods then available. The potential for reducing nonproductive time in the machining cycle was also apparent. In 1956, the Air Force sponsored the development of NC machine tools at several different companies. These machines were placed in operation at various aircraft plants between 1958 and 1960. The advantages of NC soon became clear, and aerospace companies began placing orders for new NC machines.

The importance of part programming was clear from the start. The Air Force continued to encourage the development and application of NC by sponsoring research at M.I.T. for a part programming language to control NC machines. This research resulted in the development of ***APT*** in 1958 (APT stands for Automatically Programmed Tooling). APT is a part programming language by which a user could write the machining instructions in simple English-like statements, and the statements were coded to be interpreted by the NC system.

37.3.1 THE TECHNOLOGY OF NUMERICAL CONTROL

This section defines the components of a numerical control system and describes the coordinate axis system and motion controls.

Components of an NC System A numerical control system consists of three basic components: (1) part program, (2) machine control unit, and (3) processing equipment. The ***part program*** (the term commonly used in machine tool technology) is the detailed set of commands to be followed by the processing equipment. It is the program of instructions in the NC control system. Each command specifies a position or motion that is to be accomplished by the work head relative to the work part. A position is defined by its *x-y-z* coordinates. In machine tool applications, additional details in the NC program include spindle rotation speed, spindle direction, feed rate, tool change instructions, and other commands related to the operation. The part program is prepared by a ***part programmer***, a person who is familiar with the details of the programming language and also understands the technology of the processing equipment.

The ***machine control unit*** (MCU) in modern NC technology is a microcomputer that stores and executes the program by converting each command into actions by the processing equipment, one command at a time. The MCU consists of both hardware and software. The hardware includes the microcomputer, components to interface with the processing equipment, and certain feedback control elements. The software in the MCU includes control system software, calculation algorithms, and translation software to convert the NC part program into a usable format for the MCU. The MCU also permits the part program to be edited in case the program contains errors, or changes in cutting conditions are required. 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 work part into a completed part. It operates under the control of the MCU according to the instructions in the part program. The variety of applications and processing equipment are surveyed in Section 37.3.4.

Coordinate System and Motion Control in NC A standard coordinate axis system is used to specify positions in numerical control. The system consists of the three linear axes (x, y, z) of the Cartesian coordinate system, plus three rotational axes (a, b, c), as shown in Figure 37.7(a). The rotational axes are used to rotate the

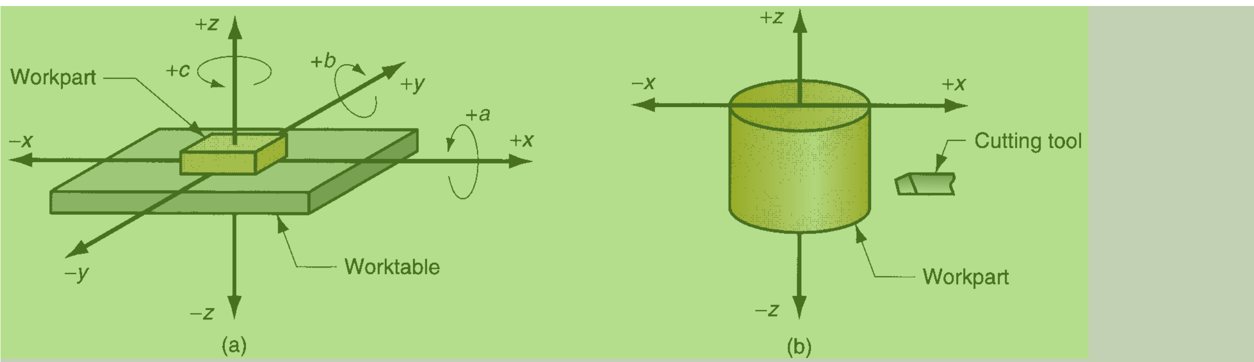


FIGURE 37.7 Coordinate systems used in numerical control: (a) for flat and prismatic work, and (b) for rotational work.

work part to present different surfaces for machining, or to orient the tool or work head at some angle relative to the part. Most NC systems do not require all six axes. The simplest NC systems (e.g., plotters, pressworking machines for flat sheet-metal stock, and component insertion machines) are positioning systems whose locations can be defined in an *x-y* plane. Programming of these machines involves specifying a sequence of *x-y* coordinates. By contrast, some machine tools have five-axis control to shape complex work part geometries. These systems typically include three linear axes plus two rotational axes.

The coordinates for a rotational NC system are illustrated in Figure 37.7(b). These systems are associated with turning operations on NC lathes. Although the work 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 workpiece is defined in the *x-z* plane, as shown in the figure.

In many NC systems, the relative movements between the processing tool and the work part 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 work head. Most machine tools and component insertion machines are based on this method of operation. In other systems, the work part is held stationary and the work head 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. ***Point-to-point systems***, also called ***positioning systems***, move the work head (or workpiece) 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 work head at the location, such as drilling or punching a hole. Thus, the program consists of a series of point locations at which operations are performed.

Continuous path systems provide continuous simultaneous control of more than one axis, thus controlling the path followed by the tool relative to the part. This permits the tool to perform a process while the axes are moving, enabling the system to generate angular surfaces, two-dimensional curves, or three-dimensional contours in the work part. This operating scheme is required in drafting machines, certain milling and turning operations, and flame cutting. In machining, continuous path control also goes by the name ***contouring***.

An important aspect of continuous path motion is ***interpolation***, which is concerned with calculating the intermediate points along a path to be followed by the work head relative to the part. Two common forms of interpolation are linear and circular. ***Linear interpolation*** is used for straight line paths, in which the part programmer specifies the coordinates of the beginning point and end point of the straight line as well as the feed rate to be used. The interpolator then computes the travel speeds of the two or three axes that will accomplish the specified trajectory. ***Circular interpolation*** allows the work head 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 concerned with whether the positions in the coordinate system are defined absolutely or incrementally. In ***absolute positioning***, the work head locations are always defined with respect to the origin of the axis system. In ***incremental positioning***, the next work head position is defined relative to the present location. The difference is illustrated in Figure 37.8.

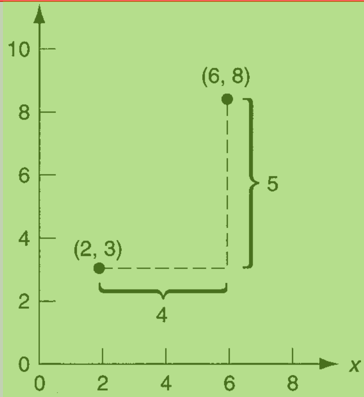


FIGURE 37.8 Absolute vs. incremental positioning. The work head is at point (2, 3) and is to be moved to point (6, 8). In absolute positioning, the move is specified by $x = 6$, $y = 8$; while in incremental positioning, the move is specified by $x = 4$, $y = 5$.

37.3.2 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 work part during processing. Consider how a simple positioning system, shown in Figure 37.9, might operate. The system consists of a worktable on which a work part is fixtured. The purpose of the table is to move the part relative to a tool or work head. To accomplish this purpose, the worktable is moved linearly by means of a rotating leadscrew that is driven by a motor. For simplicity, only one axis is shown in the sketch. To provide *x-y* capability, the system shown would be piggybacked on top of a second axis perpendicular to the first. The leadscrew has a certain pitch p, mm/thread (in/thread) or mm/rev (in/rev). Thus, the table is moved a distance equal to the leadscrew pitch for each revolution. The velocity at which the worktable moves is determined by the rotational speed of the leadscrew.

Two basic types of motion control are used in NC: (a) open loop and (b) closed loop, as shown in Figure 37.10. The difference is that an open-loop system operates without verifying that the desired position of the worktable has been achieved. A closed-loop control system uses feedback measurement to verify that the position of the worktable is indeed the location specified in the program. Open-loop systems are less expensive than closed-loop systems and are appropriate when the force resisting the actuating motion is minimal, as in point-to-point drilling, for example. Closed-loop systems are normally specified for machine tools that perform continuous path operations such as milling or turning, in which the resisting forces can be significant.

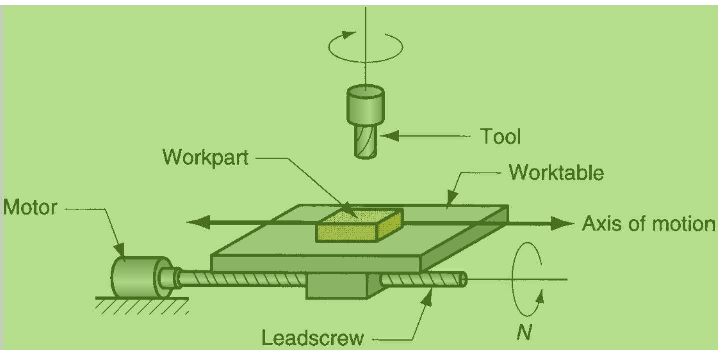


FIGURE 37.9 Motor and leadscrew arrangement in an NC positioning system.

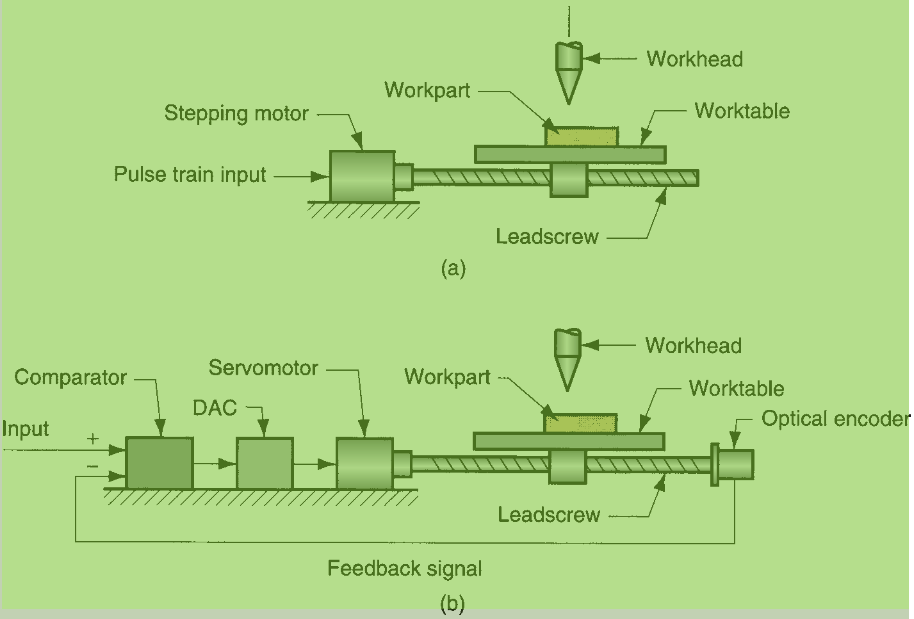


FIGURE 37.10 Two types of motion control in NC: (a) open loop and (b) closed loop.

Open-Loop Positioning Systems To turn the leadscrew, an open-loop positioning system typically 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 angles must conform to the relationship

$$\alpha = \frac{360}{n_s} \tag{37.4}$$

where α = step angle, degrees; and n_s = the number of step angles for the motor, which must be an integer. The angle through which the motor shaft rotates is given by

$$A_m = \alpha n_p \tag{37.5}$$

where A_m = angle of motor shaft rotation, degrees; n_p = number of pulses received by the motor; and α = step angle, here defined as degrees/pulse. Finally, the rotational speed of the motor shaft is determined by the frequency of pulses sent to the motor:

$$N_m = \frac{60\,\alpha\,f_p}{360} \tag{37.6}$$

where N_m = speed of motor shaft rotation, rev/min; f_p = frequency of pulses driving the stepper motor, Hz (pulses/sec), the constant 60 converts pulses/sec to pulses/min; the constant 360 converts degrees of rotation to full revolutions; and α = step angle of the motor, as before.

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

$$A_m = r_g A_{ls} \tag{37.7a}$$

and

$$N_m = r_g N_{ls} \tag{37.7b}$$

where A_m and N_m are the angle of rotation, degrees, and rotational speed, rev/min, of the motor, respectively; A_{ls} and N_{ls} are the angle of rotation, degrees, and rotational speed, rev/min, of the leadscrew, respectively; and r_g = gear reduction between the motor shaft and the leadscrew; for example, a gear reduction of 2 means that the motor shaft rotates through two revolutions for each rotation of the leadscrew.

The linear position of the table in response to the rotation of the leadscrew depends on the leadscrew pitch p, and can be determined as follows:

$$x = \frac{pA_{ls}}{360} \tag{37.8}$$

where x = x-axis position relative to the starting position, mm (in); p = pitch of the leadscrew, mm/rev (in/rev); and $A_{ls}/360$ = the number of revolutions (and partial revolutions) of the leadscrew. By combining Equations (37.5), (37.7a), and (37.8) and rearranging, the number of pulses required to achieve a specified x-position increment in a point-to-point system can be found:

$$n_p = \frac{360 r_g x}{p\alpha} = \frac{r_g n_s A_{ls}}{360} \tag{37.9}$$

The velocity of the worktable in the direction of the leadscrew axis can be determined as follows:

$$v_t = f_r = N_{ls}\, p \tag{37.10}$$

where v_t = table travel speed, mm/min (in/min); f_r = table feed rate, mm/min (in/min); N_{ls} = rotational speed of the leadscrew, rev/min; and p = leadscrew pitch, mm/rev (in/rev). The rotational speed of the leadscrew depends on the frequency of pulses driving the stepping motor:

$$N_{ls} = \frac{60 f_p}{n_s r_g} \tag{37.11}$$

where N_{ls} = leadscrew rotational speed, rev/min; f_p = pulse train frequency, Hz (pulses/sec); n_s = steps/rev, or pulses/rev, and r_g = gear reduction between the motor and the leadscrew. For a two-axis table with continuous path control, the relative velocities of the axes are coordinated to achieve the desired travel direction. Finally, the required pulse frequency to drive the table at a specified feed rate can be obtained by combining Equations (37.10) and (37.11) and rearranging to solve for f_p:

$$f_p = \frac{v_t n_s r_g}{60p} = \frac{f_r n_s r_g}{60p} = \frac{N_{ls} n_s r_g}{60} = \frac{N_m n_s}{60} \tag{37.12}$$

Example 37.1 Open-loop positioning

A stepping motor has 48 step angles. Its output shaft is coupled to a leadscrew with a 4:1 gear reduction (four turns of the motor shaft for each turn of the leadscrew). The leadscrew pitch = 5.0 mm. The worktable of a positioning system is driven by the leadscrew. The table must move a distance of 75.0 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, (b) motor speed, and (c) pulse frequency required to achieve the desired table speed.

Solution: (a) To move a distance $x = 75$ mm, the leadscrew must rotate through an angle calculated as follows:

$$A_{ls} = \frac{360x}{p} = \frac{360(75)}{5} = 5400°$$

With 48 step angles and a gear reduction of 4, the number of pulses to move the table 75 mm is

$$n_p = \frac{4(48)(5400)}{360} = \mathbf{2880\ pulses}$$

(b) Equation (37.10) can be used to find the leadscrew speed corresponding to the table speed of 400 mm/min,

$$N_{ls} = \frac{v_t}{p} = \frac{400}{5.0} = 80.0\ \text{rev/min}$$

The motor speed will be four times as fast:

$$N_m = r_g N_{ls} = 4(80) = \mathbf{320\ rev/min}$$

(c) Finally, the pulse rate is given by Equation (37.12):

$$f_p = \frac{320(48)}{60} = \mathbf{256\ Hz}$$

Closed-Loop Positioning Systems Closed-loop NC systems, Figure 37.10(b), use servomotors and feedback measurements to ensure that the desired position is achieved. A common feedback sensor used in NC (and also industrial robots) is the optical rotary encoder, illustrated in Figure 37.11. 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, which in turn is connected directly to the leadscrew. As the leadscrew rotates, the slots cause the light source to be seen by the photocell as a series of flashes, which are 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 using the pitch of the leadscrew.

The equations describing the operation of a closed-loop positioning system are analogous to those for an open-loop system. In the basic optical encoder, the angle between slots in the disk must satisfy the following requirement:

$$\alpha = \frac{360}{n_s} \tag{37.13}$$

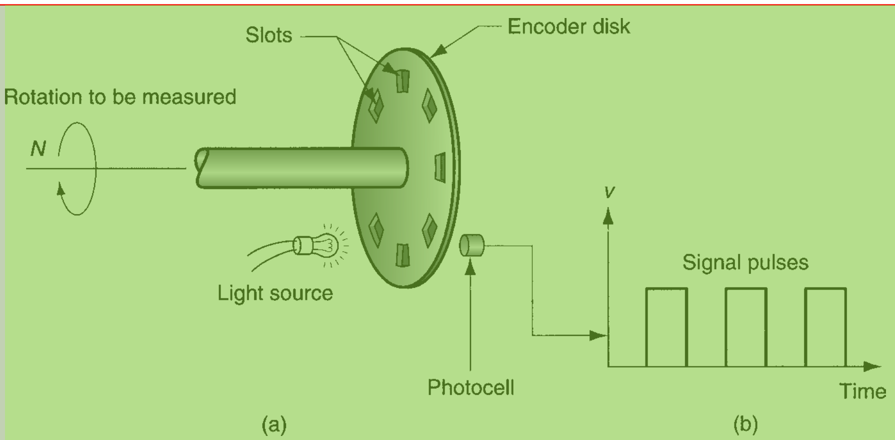


FIGURE 37.11 Optical encoder: (a) apparatus, and (b) series of pulses emitted to measure rotation of disk.

where α = angle between slots, degrees/slot; and n_s = the number of slots in the disk, slots/rev; and 360 = degrees/rev. For a certain angular rotation of the leadscrew, the encoder generates a number of pulses given by

$$n_p = \frac{A_{ls}}{\alpha} = \frac{A_{ls} n_s}{360} \tag{37.14}$$

where n_p = pulse count; A_{ls} = angle of rotation of the leadscrew, degrees; and α = angle between slots in the encoder, degrees/pulse. The pulse count can be used to determine the linear x-axis position of the worktable by factoring in the leadscrew pitch. Thus,

$$x = \frac{p n_p}{n_s} = \frac{p A_{ls}}{360} \tag{37.15}$$

Similarly, the feed rate at which the worktable moves is obtained from the frequency of the pulse train:

$$v_t = f_r = \frac{60 p f_p}{n_s} \tag{37.16}$$

where 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; and 60 converts seconds to minutes. The speed relationship given by Equation (37.10) is also valid for a closed-loop positioning system.

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. As with the open-loop system, a gear reduction between the servomotor and the leadscrew can also be used, so Equations (37.7 a,b) are applicable. A digital-to-analog converter is used to convert the digital signals used by the MCU into a continuous analog signal to operate the drive motor. Closed-loop NC systems of the type described here are appropriate when there is force resisting the movement of the table. Most metal-machining operations fall into this category, particularly those involving continuous path control such as milling and turning.

Example 37.2 NC Closed-loop positioning

An NC worktable is driven by a closed-loop positioning system consisting of a servomotor, leadscrew, and optical encoder. The leadscrew has a pitch = 5.0 mm and is coupled to the motor shaft with a gear ratio of 4:1 (four turns of the motor for each turn of the leadscrew). The optical encoder generates 100 pulses/rev of the leadscrew. The table has been programmed to move a distance of 75.0 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 75.0 mm (b) pulse rate, and (c) motor speed that correspond to the specified feed rate.

Solution: (a) Rearranging Equation (37.15) to find n_p.

$$n_p = \frac{xn_s}{p} = \frac{75(100)}{5} = \mathbf{1500\ pulses}$$

(b) The pulse rate corresponding to 400 mm/min can be obtained by rearranging Equation (37.16):

$$f_p = \frac{f_r n_s}{60p} = \frac{400(100)}{60(5)} = \mathbf{133.33\ Hz}$$

(c) Leadscrew rotational speed is the table velocity divided by the pitch:

$$N_{ls} = \frac{f_r}{p} 80 \text{ rev/min}$$

With a gear ratio $r_g = 4.0$, the motor speed $N = 4(80) =$ **320 rev/min**

Precision in Positioning Three critical measures of precision in positioning are control resolution, accuracy, and repeatability. These terms are most easily explained by considering a single axis of the position system.

Control resolution refers to 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. ***Control resolution*** is defined as the distance separating two adjacent control points in the axis movement. Control points are sometimes called ***addressable points*** because they are locations along the axis to which the worktable can be directed to go. It is desirable for the control resolution to be as small as possible. This depends on limitations imposed by (1) the electromechanical components of the positioning system, and/or (2) the number of bits used by the controller to define the axis coordinate location.

The electromechanical factors that limit resolution include leadscrew pitch, gear ratio in the drive system, and the step angle in a stepping motor (for an open-loop system) or the angle between slots in an encoder disk (for a closed-loop system). Together, these factors determine a control resolution, or minimum distance that the 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

$$CR_1 = \frac{p}{n_s r_g} \tag{37.17a}$$

where CR_1 = control resolution of the electromechanical components, mm (in); p = leadscrew pitch, mm/rev (in/rev); n_s = number of steps/rev; and 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. There is no gear reduction. Thus, control resolution for a closed-loop system is defined as follows:

$$CR_1 = \frac{p}{n_s} \tag{37.17b}$$

where n_s in this case refers to the number of slots in the optical encoder.

Although unusual in modern computer technology, the second possible factor that could limit control resolution is the number of bits defining the axis coordinate value. For example, this limitation may be imposed by the bit storage capacity of the controller. If B = the number of bits in the storage register for the axis, then the number of control points into which the axis range can be divided = 2^B. Assuming that the control points are separated equally within the range, then

$$CR_2 = \frac{L}{2^B - 1} \tag{37.18}$$

where CR_2 = control resolution of the computer control system, mm (in); and L = axis range, mm (in). The control resolution of the positioning system is the maximum of the two values; that is,

$$CR = \text{Max}\{CR_1, CR_2\} \tag{37.19}$$

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

When a positioning system is directed to move the worktable 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. It is convenient to assume that the errors form a statistical distribution about the control point that is an unbiased normal distribution with mean = 0. If it is also assumed that the standard deviation of the distribution is constant over the range of the axis under consideration, then nearly all of the mechanical errors (99.73%) are contained within ± 3 standard deviations of the control point. This is pictured in Figure 37.12 for a portion of the axis range, which includes three control points.

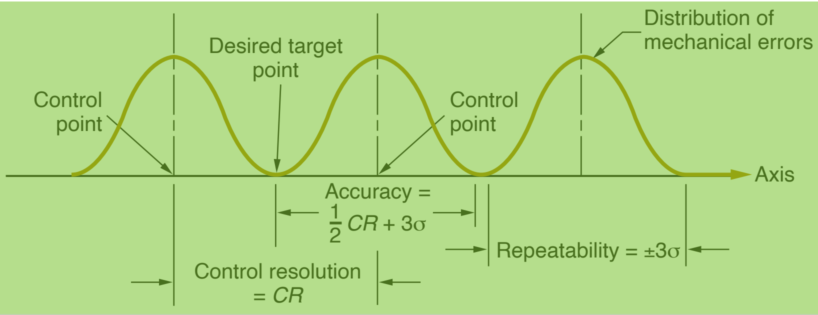


FIGURE 37.12 A portion of a linear positioning system axis, with definition of control resolution, accuracy, and repeatability.

Given these definitions of control resolution and mechanical error distribution, consider accuracy and repeatability. Accuracy is defined in a worst-case scenario in which the desired target point lies exactly between two adjacent control points. Since the system can only move to one or the other of the control points, there will be an error in the final position of the worktable. If the target were closer to one of the control points, then the table would be moved to the closer control point and the error would be smaller. It is appropriate to define accuracy in the worst case. The ***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; in equation form,

$$\text{Accuracy} = 0.5\,CR + 3\sigma \tag{37.20}$$

where CR = control resolution, mm (in); and σ = standard deviation of the error distribution, mm (in).

Repeatability refers to 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 encountered when the system attempts to position itself at the control point. Location errors are a manifestation of the mechanical errors of the positioning system, which are defined by an assumed normal distribution, as described above. Thus, the ***repeatability*** of any given axis of a positioning system can be defined as the range of mechanical errors associated with the axis; this reduces to

$$\text{Repeatability} = \pm 3\sigma \tag{37.21}$$

Example 37.3 Control resolution, accuracy, and repeatability

Referring back to Example 37.1, 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 550 mm, 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) Control resolution is the greater of CR_1 and CR_2 as defined by Equations (37.17a) and (37.18):

$$CR_1 = \frac{p}{n_s r_g} = \frac{5.0}{48(4)} = 0.0260 \text{ mm}$$

$$CR_2 = \frac{L}{2^B - 1} = \frac{550}{2^{16} - 1} = \frac{550}{65{,}535} = 0.0084 \text{ mm}$$

$$CR = \text{Max}\{0.0260, 0.0084\} = \mathbf{0.0260\ mm}$$

(b) Accuracy is given by Equation (37.20):

$$\text{Accuracy} = 0.5\,(0.0260) + 3(0.005) = \mathbf{0.0280\ mm}$$

(c) Repeatability $= \pm 3(0.005) = \pm\ \mathbf{0.015\ mm}$

37.3.3 NC PART PROGRAMMING

In machine tool applications, the task of programming the system is called NC part programming because the program is prepared for a given part. It is usually accomplished by someone familiar with the metalworking process who has learned the programming procedure for the particular equipment in the plant. For other processes, other terms may be used for programming, but the principles are similar and a trained individual is needed to prepare the program. Computer systems are used extensively to prepare NC programs.

Part programming requires the programmer to define the points, lines, and surfaces of the work part in the axis system, and to control the movement of the cutting tool relative to these defined part features. Several part programming techniques are available, the most important of which are (1) manual part programming, (2) computer-assisted part programming, (3) CAD/CAM-assisted part programming, and (4) manual data input.

Manual Part Programming For simple point-to-point machining jobs, such as drilling operations, manual programming is often the easiest and most economical method. Manual part programming uses basic numerical data and special alphanumeric codes to define the steps in the process. For example, to perform a drilling operation, a command of the following type is entered:

n010 x70.0 y85.5 f175 s500

Each "word" in the statement specifies a detail in the drilling operation. The *n*-word (n010) is simply a sequence number for the statement. The *x*- and *y*-words indicate the x and y coordinate positions ($x = 70.0$ mm and $y = 85.5$ mm). The *f*-word and *s*-word specify the feed rate and spindle speed to be used in the drilling operation (feed rate = 175 mm/min and spindle speed = 500 rev/min). The complete NC part program consists of a sequence of statements similar to the above command.

Computer-Assisted Part Programming Computer-assisted part programming involves the use of a high-level programming language. It is suited to the programming of more complex jobs than manual programming. The first part programming language was APT (Automatically Programmed Tooling), developed as an extension of the original NC machine tool research and first used in production around 1960.

In APT, the part programming task is divided into two steps: (1) definition of part geometry and (2) specification of tool path and operation sequence. In step 1, the part programmer defines the geometry of the work part by means of basic geometric elements such as points, lines, planes, circles, and cylinders. These elements are defined using APT geometry statements, such as

P1 = POINT/25.0, 150.0
L1 = LINE/P1, P2

P1 is a point defined in the *x-y* plane located at $x = 25$ mm and $y = 150$ mm. L1 is a line that goes through points P1 and P2. Similar statements can be used to define circles, cylinders, and other geometry elements. Most work part shapes can be described using statements like these to define their surfaces, corners, edges, and hole locations.

Specification of the tool path is accomplished with APT motion statements. A typical statement for point-to-point operation is

GOTO/P1

This directs the tool to move from its current location to a position defined by P1, where P1 has been defined by a previous APT geometry statement. Continuous path commands use geometry elements such as lines, circles, and planes. For example, the command

GORGT/L3, PAST, L4

directs the tool to go right (GORGT) along line L3 until it is positioned just past line L4 (of course, L4 must be a line that intersects L3).

Additional APT statements are used to define operating parameters such as feed rates, spindle speeds, tool sizes, and tolerances. When completed, the part programmer enters the APT program into the computer, where it is processed to generate low-level statements (similar to statements prepared in manual part programming) that can be used by a particular machine tool.

CAD/CAM-Assisted Part Programming The use of CAD/CAM takes computer-assisted part programming a step further by using a computer graphics system (CAD/CAM system) to interact with the programmer as the part program is being prepared. In the conventional use of APT, a complete program is written and then entered into the computer for processing. Many programming errors are not detected until computer processing. When a CAD/CAM system is used, the programmer receives immediate visual verification when each statement is entered, to determine whether the statement is correct. When part geometry is entered by the programmer, the element is graphically displayed on the monitor. When the tool path is constructed, the programmer can see exactly how the motion commands will move the tool relative to the part. Errors can be corrected immediately rather than after the entire program has been written.

Interaction between programmer and programming system is a significant benefit of CAD/CAM-assisted programming. There are other important benefits of using CAD/CAM in NC part programming. First, the design of the product and its components may have been accomplished on a CAD/CAM system. The resulting design database, including the geometric definition of each part, can be retrieved by the NC programmer to use as the starting geometry for part programming. This retrieval saves valuable time compared to reconstructing the part from scratch using the APT geometry statements.

Second, special software routines are available in CAD/CAM-assisted part programming to automate portions of the tool path generation, such as profile milling around the outside periphery of a part, milling a pocket into the surface of a part, surface contouring, and certain point-to-point operations. These routines are called by the part programmer as special ***macro*** commands. Their use results in significant savings in programming time and effort.

Manual Data Input Manual data input (MDI) is a method in which a machine operator enters the part program in the factory. The method involves use of a CRT display with graphics capability at the machine tool controls. NC part programming statements are entered using a menu-driven procedure that requires minimum training of the machine tool operator. Because part programming is simplified and does not require a special staff of NC part programmers, MDI is a way for small machine shops to economically implement numerical control into their operations.

37.3.4 APPLICATIONS OF NUMERICAL CONTROL

Machining is an important application area for numerical control, but the operating principle of NC can be applied to other operations as well. There are many industrial processes in which the position of a work head must be controlled relative to the part or product being worked on. The applications are divided into two categories: (1) machine tool applications and (2) nonmachine tool applications. It should be noted that the applications are not all identified by the name numerical control in their respective industries.

In the machine tool category, NC is widely used for machining operations such as turning, drilling, and milling (Sections 21.2, 21.3, and 21.4, respectively). The use of NC in these processes has motivated the development of highly automated machine tools called machining centers, which change their own cutting tools to perform a variety of machining operations under NC program control (Section 21.5). In addition to machining, other numerically controlled machine tools include (1) grinding machines (Section 24.1); (2) sheet metal pressworking machines (Section 19.5.2); (3) tube-bending machines (Section 19.7); and (4) thermal cutting processes (Section 25.3).

In the nonmachine tool category, NC applications include (1) tape-laying machines and filament-winding machines for composites (Sections 14.2.3 and 14.4.1); (2) welding machines, both arc welding (Section 30.1) and resistance welding (Section 30.2); (3) component placement and insertion machines in electronics assembly (Sections 34.3.1 and 34.3.2); (4) drafting machines; and (5) coordinate measuring machines for inspection (Section 40.6.1).

Benefits of NC relative to manually operated equipment in these applications include (1) reduced nonproductive time, which results in shorter cycle times, (2) lower manufacturing lead times, (3) simpler fixturing, (4) greater manufacturing flexibility, (5) improved accuracy, and (6) reduced human error.

37.4 Industrial Robotics

An industrial robot is a general-purpose programmable machine possessing certain anthropomorphic features. The most obvious anthropomorphic, or human-like, feature is the robot's mechanical arm, or manipulator. The control unit for a modern industrial robot is a computer that can be programmed to execute rather sophisticated subroutines, thus providing the robot with an intelligence that sometimes seems almost human. The robot's manipulator, combined with a high-level controller, allows an industrial robot to perform a variety of tasks such as loading and unloading production machine, spot welding, and spray painting. Robots are typically used as substitutes for human workers in these tasks. The first industrial robot was installed in a die-casting operation at Ford Motor Company. The robot's job was to unload die castings from the die-casting machine.

This section considers various aspects of robot technology and applications, including how industrial robots are programmed to perform their tasks.

37.4.1 ROBOT ANATOMY

An industrial robot consists of a mechanical manipulator and a controller to move it and perform other related functions. The mechanical manipulator consists of joints and links that can position and orient the end of the manipulator relative to its base. The controller unit consists of electronic hardware and software to operate the joints in a coordinated fashion to execute the programmed work cycle. ***Robot anatomy*** is concerned with the mechanical manipulator and its construction. Figure 37.13 shows one of the common industrial robot configurations.

Manipulator Joints and Links A joint in a robot is similar to a joint in a human body. It provides relative movement between two parts of the body. Connected to each joint are an input link and an output link. Each joint moves its output link relative to its input link. The robot manipulator consists of a series of link–joint–link combinations. The output link of one joint is the input link for the next joint. Typical industrial robots have five or six joints. The coordinated movement of these joints gives the robot its ability to move, position, and orient objects to perform useful work. Manipulator joints can be classified as linear or rotating, indicating the motion of the output link relative to the input link.

FIGURE 37.13 The manipulator of a modern industrial robot. (Photo courtesy of Adept Technology, Inc.)

Manipulator Design Using joints of the two basic types, each joint separated from the previous by a link, the manipulator is constructed. Most industrial robots are mounted to the floor. The base is link 0; this is the input link to joint 1 whose output is link 1, which is the input to joint 2 whose output link is link 2; and so forth, for the number of joints in the manipulator.

Robot manipulators can usually be divided into two sections: arm-and-body assembly and wrist assembly. There are typically three joints associated with the arm-and-body assembly, and two or three joints associated with the wrist. The function of the arm-and-body is to position an object or tool, and the wrist function is to properly orient the object or tool. Positioning is concerned with moving the part or tool from one location to another. Orientation is concerned with precisely aligning the object relative to some stationary location in the work area.

To accomplish these functions, arm-and-body designs differ from those of the wrist. Positioning requires large spatial movements, while orientation requires twisting and rotating motions to align the part or tool relative to a fixed position in the workplace. The arm-and-body consists of large links and joints, whereas the wrist consists of short links. The arm-and-body joints often consist of both linear and rotating types, while the wrist joints are almost always rotating types.

There are five basic arm-and-body configurations available in commercial robots, identified in Figure 37.14. The design shown in part (e) of the figure and in Figure 37.13

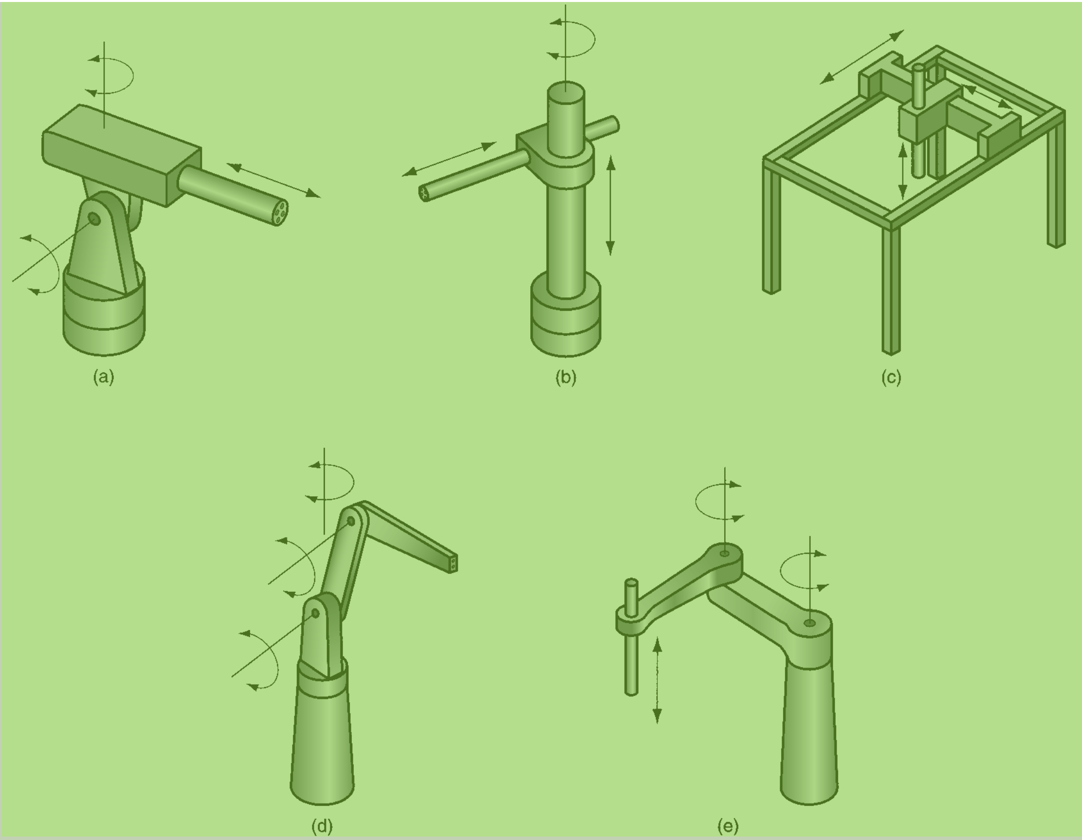


FIGURE 37.14 Five common anatomies of commercial industrial robots: (a) polar, (b) cylindrical, (c) Cartesian coordinate, (d) jointed-arm, and (e) SCARA, or selectively compliant assembly robot arm.

is called a SCARA robot, which stands for "selectively compliant assembly robot arm." It is similar to a jointed arm anatomy, except that the shoulder and elbow joints have vertical axes of rotation, thus providing rigidity in the vertical direction but relative compliance in the horizontal direction.

The wrist is assembled to the last link in any of these arm-and-body configurations. The SCARA is sometimes an exception because it is almost always used for simple handling and assembly tasks involving vertical motions. Therefore, a wrist is not usually present at the end of its manipulator. Substituting for the wrist on the SCARA is usually a gripper to grasp components for movement and/or assembly.

Work Volume and Precision of Motion One of the important technical considerations of an industrial robot is the size of its work volume. ***Work volume*** is defined as the envelope within which a robot manipulator can position and orient the end of its wrist. This envelope is determined by the number of joints, as well as their types and ranges, and the sizes of the links. Work volume is important because it plays a significant role in determining which applications a robot can perform.

The definitions of control resolution, accuracy, and repeatability developed in Section 37.3.2 for NC positioning systems apply to industrial robots. A robot manipulator is, after all, a positioning system. In general, the links and joints of robots are not nearly as rigid as their machine tool counterparts, and so the accuracy and repeatability of their movements are not as good.

End Effectors An industrial robot is a general-purpose machine. For a robot to be useful in a particular application, it must be equipped with special tooling designed for the application. An ***end effector*** is the special tooling that connects to the robot's wrist-end to perform the specific task. There are two general types of end effector: tools and grippers. A ***tool*** is used when the robot must perform a processing operation. The special tools include spot-welding guns, arc-welding tools, spray-painting nozzles, rotating spindles, heating torches, and assembly tools (e.g., automatic screwdriver). The robot is programmed to manipulate the tool relative to the work part being processed.

Grippers are designed to grasp and move objects during the work cycle. The objects are usually work parts, and the end effector must be designed specifically for the part. Grippers are used for part placement applications, machine loading and unloading, and palletizing. Figure 37.15 shows a typical gripper configuration.

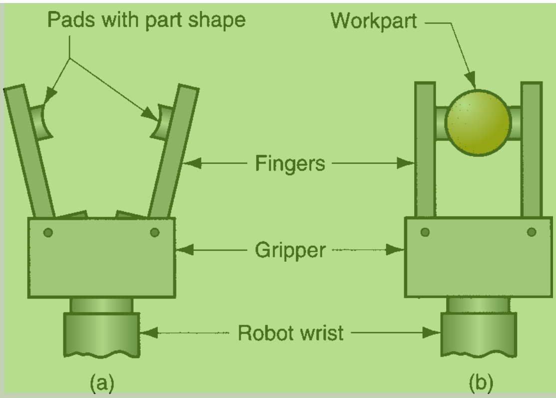


FIGURE 37.15 A robot gripper: (a) open and (b) closed to grasp a work part.

37.4.2 CONTROL SYSTEMS AND ROBOT PROGRAMMING

The robot's controller consists of the electronic hardware and software to control the joints during execution of a programmed work cycle. Most robot control units today are based on a microcomputer system. The control systems in robotics can be classified as follows:

1. ***Playback with point-to-point (PTP) control***. As in numerical control, robot motion systems can be divided into point-to-point and continuous path. The program for a point-to-point playback robot consists of a series of point locations and the sequence in which these points must be visited during the work cycle. During programming, these points are recorded into memory, and then subsequently played back during execution of the program. In a point-to-point motion, the path taken to get to the final position is not controlled.
2. ***Playback with continuous path (CP) control***. Continuous path control is similar to PTP, except motion paths rather than individual points are stored in memory. In certain types of regular CP motions, such as a straight line path between two point locations, the trajectory required by the manipulator is computed by the controller unit for each move. For irregular continuous motions, such as a path followed in spray painting, the path is defined by a series of closely spaced points that approximate the irregular smooth path. Robots capable of continuous path motions can also execute point-to-point movements.
3. ***Intelligent control***. Modern industrial robots exhibit characteristics that often make them appear to be acting intelligently. These characteristics include the ability to respond to sophisticated sensors such as machine vision, make decisions when things go wrong during the work cycle, make computations, and communicate with humans. Robot intelligence is implemented using powerful microprocessors and advanced programming techniques.

Robots execute a stored program of instructions that define the sequence of motions and positions in the work cycle, much like a part program in NC. In addition to motion instructions, the program may include instructions for other functions such as interacting with external equipment, responding to sensors, and processing data.

There are two basic methods used to teach modern robots their programs: leadthrough programming and computer programming languages. ***Leadthrough programming*** involves a "teach-by-showing" method in which the manipulator is moved by the programmer through the sequence of positions in the work cycle. The controller records each position in memory for subsequent playback. Two procedures for leading the robot through the motion sequence are available: powered leadthrough and manual leadthrough. In ***powered leadthrough***, the manipulator is driven by a control box that has toggle switches or press buttons to control the movements of the joints. Using the control box, the programmer moves the manipulator to each location, recording the corresponding joint positions into memory. Powered leadthrough is the common method for programming playback robots with point-to-point control. ***Manual leadthrough*** is typically used for playback robots with continuous path control. In this method, the programmer physically moves the manipulator wrist through the motion cycle. For spray painting and certain other jobs, this is a more convenient means of programming the robot.

Computer programming languages for programming robots have evolved from the use of microcomputer controllers. The first commercial language was introduced around 1979. Computer languages provide a convenient way to integrate certain nonmotion functions into the work cycle, such as decision logic, interlocking with other equipment, and interfacing with sensors. A more thorough discussion of robot programming is presented in reference [6].

37.4.3 APPLICATIONS OF INDUSTRIAL ROBOTS

Some industrial work lends itself to robot applications. The following are the important characteristics of a work situation that tend to promote the substitution of a robot in place of a human worker: (1) the work environment is hazardous for humans, (2) the work cycle is repetitive, (3) the work is performed at a stationary location, (4) part or tool handling would be difficult for humans, (5) it is a multishift operation, (6) there are long production runs and infrequent changeovers, and (7) part positioning and orientation are established at the beginning of the work cycle, since most robots cannot see.

Applications of industrial robots that tend to match these characteristics can be divided into three basic categories: (1) material handling, (2) processing operations, and (3) assembly and inspection.

Material handling applications involve the movement of materials or parts from one location and orientation to another. To accomplish this relocation task, the robot is equipped with a gripper. As noted earlier, the gripper must be custom-designed to grasp the particular part in the application. Material handling applications include material transfer (part placement, palletizing, depalletizing) and machine loading and/or unloading (e.g., machine tools, presses, and plastic molding).

Processing operations require the robot to manipulate a tool as its end effector. The applications include spot welding, continuous arc welding, spray coating, and certain metal cutting and deburring operations in which the robot manipulates a special tool. In each of these operations, the tool is used as the robot's end effector. An application of spot welding is illustrated in Figure 37.16. Spot welding is a common application of industrial robots in the automotive industry.

FIGURE 37.16 A portion of an automobile assembly line in which robots perform spot-welding operations. (Photo courtesy of Ocean/Corbis Images.)