Disadvantages of NC. There are certain commitments to NC technology that must be made by the machine shop that installs NC equipment, and these commitments, most of which involve additional cost to the company, might be seen as disadvantages. These include the following:

- *Higher investment cost*. An NC machine tool has a higher first cost than a comparable conventional machine tool. There are several reasons why: (1) NC machines include CNC controls and electronics hardware; (2) software development costs of the CNC controls manufacturer must be included in the cost of the machine; (3) more reliable mechanical components are generally used in NC machines; and (4) NC machine tools often possess additional features not included on conventional machines, such as automatic tool changers and part changers (Section 14.2.3).
- *Higher maintenance effort*. In general, NC equipment requires more maintenance than conventional equipment, which translates to higher maintenance and repair costs. This is due largely to the computer and other electronics that are included in a modern NC system. The maintenance staff must include personnel who are trained in maintaining and repairing this type of equipment.
- *Part programming*. NC equipment must be programmed. To be fair, it should be mentioned that process planning must be accomplished for any part, whether or not it is produced by NC. However, NC part programming is a special preparation step in batch production that is absent in conventional machine shop operations.
- *Higher utilization of NC equipment*. To maximize the economic benefits of NC, some companies operate multiple shifts. This might mean adding one or two extra shifts to the plant's normal operations, with the requirement for supervision and other staff support.

7.4 ANALYSIS OF POSITIONING SYSTEMS

An NC positioning system converts the coordinate axis values in the NC part program into relative positions of the tool and work part during processing. Consider the simple positioning system shown in Figure 7.11. The system consists of a cutting tool and a worktable on which a work part is fixtured. The table is designed to move the part relative to the tool. The worktable moves linearly by means of a rotating leadscrew or ball screw, which is driven by a stepper motor or servomotor (Section 6.2.1). For simplicity, only one

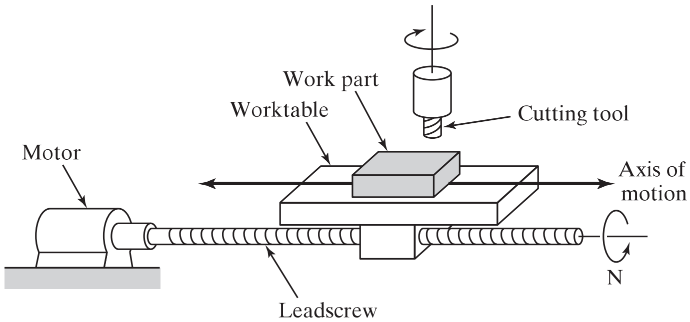

Figure 7.11 Motor and leadscrew arrangement in an NC positioning system.

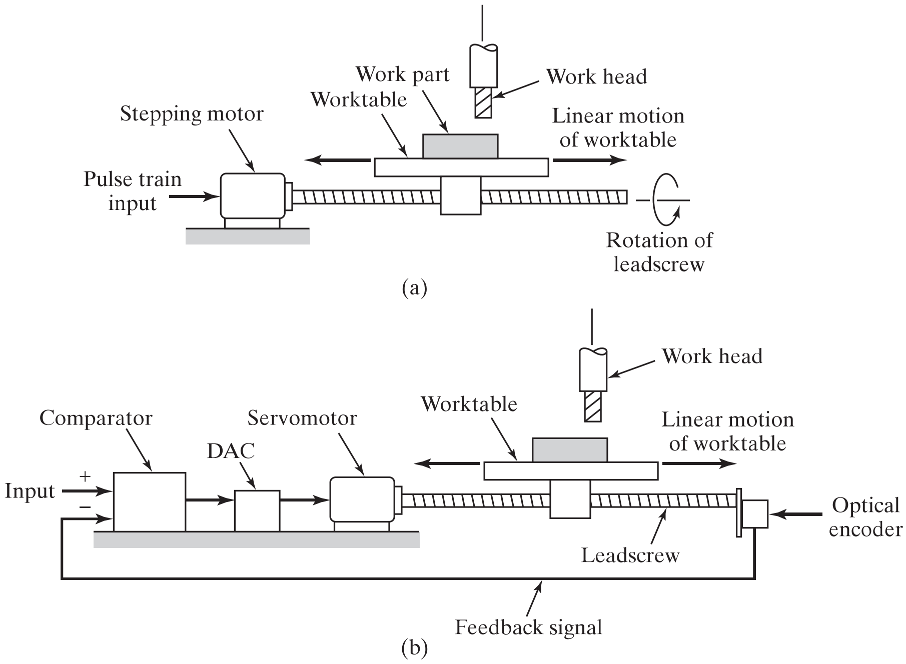

Figure 7.12 Two types of motion control in NC: (a) open loop and (b) closed loop.

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 screw has a certain pitch p, mm/thread (in/thread). Thus, the table moves a distance equal to the pitch for each revolution. The velocity of the worktable, which corresponds to the feed rate in a machining operation, is determined by the rotational speed of the screw.

Two types of control systems are used in positioning systems: (a) open loop and (b) closed loop, as shown in Figure 7.12. An open-loop system operates without verifying that the actual position achieved in the move is the same as the desired position. A closed-loop system uses feedback measurements to confirm that the final position of the worktable is the location specified in the program. Open-loop systems cost less than closed-loop systems and are appropriate when the force resisting the actuating motion is minimal. Closed-loop systems are normally specified for machines that perform continuous path operations such as milling or turning, in which there are significant forces resisting the forward motion of the cutting tool.

7.4.1 Open-Loop Positioning Systems

An open-loop positioning system typically uses a stepper motor to rotate the leadscrew or ball screw. A stepper motor is driven by a series of electrical pulses, which are generated by the MCU in an NC system. Each pulse causes the motor to rotate a fraction of one revolution, called the step angle. The possible step angles must be consistent with the relationship

$$\alpha = \frac{360}{n_s} \tag{7.3}$$

where α = step angle, °; 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

$$A_m = n_p \alpha \tag{7.4}$$

where A_m = angle of motor shaft rotation, °; n_p = number of pulses received by the motor; and α = step angle, °/pulse. The motor shaft is generally connected to the screw through a gearbox, which reduces the angular rotation of the screw. The angle of the screw rotation must take the gear ratio into account as

$$A_s = \frac{A_m}{r_g} = \frac{n_p \alpha}{r_g} \tag{7.5}$$

where A_s = angle of screw rotation, °; and r_g = gear ratio, defined as the number of turns of the motor for each single turn of the screw. That is,

$$r_g = \frac{A_m}{A_s} = \frac{N_m}{N_s} \tag{7.6}$$

where N_m = rotational speed of the motor, rev/min; and N_s = rotational speed of the screw, rev/min.

The linear movement of the worktable is given by the number of full and partial rotations of the screw multiplied by its pitch,

$$x = \frac{pA_s}{360} \tag{7.7}$$

where x = x-axis position relative to the starting position, mm (in); p = pitch of the screw mm/rev (in/rev); and $A_s/360$ = number of screw revolutions. The number of pulses required to achieve a specified x-position increment in a point-to-point system can be found using combinations of Equations (7.3), (7.5), and (7.7):

$$n_p = \frac{360xr_g}{p\alpha} = \frac{n_s x r_g}{p} \tag{7.8}$$

Control pulses are transmitted from the pulse generator at a certain frequency, which drives the worktable at a corresponding velocity or feed rate in the direction of the screw axis. The rotational speed of the screw depends on the frequency of the pulse train as

$$N_s = \frac{60f_p}{n_s r_g} \tag{7.9}$$

where N_s = screw rotational speed, rev/min; f_p = pulse train frequency, Hz; and n_s = steps per revolution or pulses per revolution. For a two-axis table with continuous path control, the relative velocities of the axes are coordinated to achieve the desired travel direction.

The table travel speed in the direction of screw axis is determined by the rotational speed as

$$v_t = f_r = N_s p \tag{7.10}$$

where v_t = table travel speed, mm/min (in/min); f_r = table feed rate, mm/min (in/min); N_s = screw rotational speed, rev/min; and p = screw pitch, mm/rev (in/rev).

The required pulse train frequency to drive the table at a specified linear travel rate can be obtained by combining Equations (7.9) and (7.10) and rearranging to solve for f_p:

$$f_p = \frac{v_t n_s r_g}{60p} = \frac{f_r n_s r_g}{60p} = \frac{N_m n_s}{60} = \frac{N_s n_s r_g}{60} \tag{7.11}$$

EXAMPLE 7.1 NC Open-Loop Positioning

The worktable of a positioning system is driven by a ball screw whose pitch = 6.0 mm. The screw is connected to the output shaft of a stepper motor through a gearbox whose ratio is 5:1 (five turns of the motor to one turn of the screw). The stepper motor has 48 step angles. The table must move a distance of 250 mm from its present position at a linear velocity = 500 mm/min. Determine (a) how many pulses are required to move the table the specified distance and (b) the required motor speed and pulse rate to achieve the desired table velocity.

Solution: (a) Rearranging Equation (7.7) to find the screw rotation angle A_s corresponding to a distance $x = 250$ mm,

$$A_s = \frac{360x}{p} = \frac{360(250)}{6.0} = 15{,}000^\circ$$

With 48 step angles, each step angle is

$$\alpha = \frac{360}{48} = 7.5^\circ$$

Thus, the number of pulses to move the table 250 mm is

$$n_p = \frac{360xr_g}{p\alpha} = \frac{A_s r_g}{\alpha} = \frac{15{,}000(5)}{7.5} = \mathbf{10{,}000\ pulses}$$

(b) The rotational speed of the screw corresponding to a table speed of 500 mm/min is determined from Equation (7.10):

$$N_s = \frac{v_t}{p} = \frac{500}{6} = \mathbf{83.333\ rev/min}$$

Equation (7.6) is used to find the motor speed:

$$N_m = r_g N_s = 5(83.333) = \mathbf{416.667\ rev/min}$$

The applied pulse rate to drive the table is given by Equation (7.11):

$$f_p = \frac{v_t n_s r_g}{60p} = \frac{500(48)(5)}{60(6)} = \mathbf{333.333\ Hz}$$

7.4.2 Closed-Loop Positioning Systems

A closed-loop NC system, illustrated in Figure 7.12(b), uses servomotors and feedback measurements to ensure that the worktable is moved to the desired position. A common feedback sensor used for NC (and also for industrial robots) is an optical encoder, depicted in Figure 7.13. An ***optical encoder*** is a device for measuring rotational speed that consists of a light source and a photodetector on either side of a disk. The disk contains slots uniformly spaced around the outside of its face. These slots allow the light source to shine through and energize the photodetector. The disk is connected to a rotating shaft whose angular position and velocity are to be measured. As the shaft rotates, the slots cause the light source to be seen by the photocell as a series of flashes. The flashes are converted into an equal number of electrical pulses. The optical encoder is connected directly to the leadscrew or ball screw, which drives the worktable. By counting the pulses and computing the frequency of the pulse train, the worktable position and velocity can be determined. There is usually a gear reduction between the servomotor and the screw driving the worktable.

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

$$\alpha = \frac{360}{n_s} \tag{7.12}$$

where α = angle between slots, °/slot; and n_s = number of slots in the disk, slots/rev. For a certain angular rotation of the encoder shaft, the number of pulses sensed by the encoder is given by

$$n_p = \frac{A_s}{\alpha} = \frac{A_s n_s}{360} \tag{7.13}$$

where n_p = pulse count emitted by the encoder; A_s = angle of rotation of the encoder shaft, °; and α = angle between slots, which converts to °/pulse. The pulse count can be used to determine the distance moved by the worktable along the x-axis (or y-axis):

$$\Delta x = \frac{p n_p}{n_s} = \frac{p A_s}{n_s \alpha} = \frac{p A_s}{360} \tag{7.14}$$

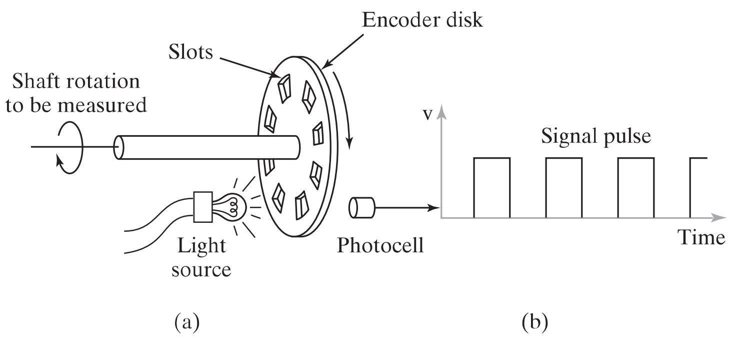

Figure 7.13 Optical encoder: (a) apparatus and (b) series of pulses emitted to measure rotation of disk.

where Δx = distance moved along the axis, mm (in); n_p and n_s are defined above; and p = screw pitch, mm/rev (in/rev).

The velocity of the worktable, which is normally the feed rate in a machining operation, is determined by the rotational speed of the screw, which in turn is driven by the servomotor:

$$v_t = f_r = N_s p = \frac{N_m p}{r_g} \tag{7.15}$$

where v_t = worktable velocity, mm/min (in/min); and f_r = feed rate, mm/min (in/min); N_s = screw rotational speed, rev/min; N_m = motor rotational speed, rev/min; r_g = *gear* reduction ratio.

At the worktable velocity or feed rate given by Equation (7.15), the pulse frequency emitted by the encoder is the following:

$$f_p = \frac{v_t n_s}{60p} = \frac{f_r n_s}{60p} \tag{7.16}$$

where f_p = frequency of the pulse train, Hz; and the constant 60 converts worktable velocity or feed rate from mm/sec (in/sec) to mm/min (in/min).

The pulse train 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 MCU to drive a servomotor, which in turn drives the worktable. A digital-to-analog converter (Section 6.3.2) is used to convert the digital signals used by the MCU into a continuous analog current that powers the drive motor. Closed-loop NC systems of the type described here are appropriate when a reactionary force resists the movement of the table. Metal cutting machine tools that perform continuous path cutting operations, such as milling and turning, fall into this category.

EXAMPLE 7.2 NC Closed-Loop Positioning

An NC worktable operates by closed-loop positioning. The system consists of a servomotor, ball screw, and optical encoder. The screw has a pitch of 6.0 mm and is coupled to the motor shaft with a gear ratio of 5:1 (five turns of the drive motor for each turn of the screw). The optical encoder generates 48 pulses/rev of its output shaft. The table has been programmed to move a distance of 250 mm at a feed rate = 500 mm/min. Determine (a) how many pulses should be received by the control system to verify that the table has moved exactly 250 mm, (b) the pulse rate of the encoder, and (c) the drive motor speed that corresponds to the specified feed rate.

Solution: (a) Rearranging Equation (7.14) to find n_p,

$$n_p = \frac{\Delta x n_s}{p} = \frac{250(48)}{6.0} = \mathbf{2{,}000\ pulses}$$

(b) The pulse rate corresponding to 500 mm/min is obtained by Equation (7.16):

$$f_p = \frac{f_r n_s}{60p} = \frac{500(48)}{60(6.0)} = \mathbf{66.667\ Hz}$$

(c) Motor speed = table velocity (feed rate) divided by screw pitch, corrected for gear ratio:

$$N_m = \frac{r_g f_r}{p} = \frac{5(500)}{6.0} = \mathbf{416.667\ rev/min}$$

Comment: Note that motor speed has the same numerical value as in Example 7.1 because the table velocity and motor gear ratio are the same.

7.4.3 Precision in Positioning Systems

To accurately machine or otherwise process a work part, an NC positioning system must possess a high degree of precision. Three measures of precision can be defined for an NC positioning system: (1) control resolution, (2) accuracy, and (3) repeatability. These terms are most readily explained by considering a single axis of the positioning system, as depicted in Figure 7.14. Control resolution refers to the control system's ability to divide the total range of the axis movement into closely spaced points that can be distinguished by the MCU. ***Control resolution*** is defined as the distance separating two adjacent addressable points in the axis movement. ***Addressable points*** are locations along the axis to which the worktable can be specifically directed to go. It is desirable for 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.

A number of electromechanical factors affect control resolution, including screw pitch, gear ratio in the drive system, and the step angle in a stepper motor for an open-loop system or the angle between slots in an encoder disk for a closed-loop system. For an open-loop positioning system driven by a stepper motor, these factors can be combined into an expression that defines control resolution as

$$CR_1 = \frac{p}{n_s r_g} \tag{7.17}$$

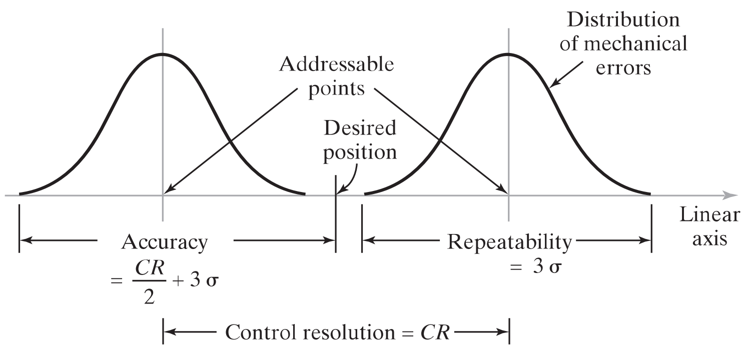

Figure 7.14 A portion of a linear positioning system axis, with definition of control resolution, accuracy, and repeatability.

where CR_1 = control resolution of the electromechanical components, mm (in); p = leadscrew pitch, mm/rev (in/rev); n_s = number of steps per revolution; and r_g = gear ratio between the motor shaft and the screw as defined in Equation (7.6). The same expression can be used for a closed-loop positioning system.

The second factor that limits control resolution is the number of bits used by the MCU to specify 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

$$CR_2 = \frac{L}{2^B - 1} \tag{7.18}$$

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,

$$CR = \text{Max}\{CR_1, CR_2\} \tag{7.19}$$

A desirable criterion is $CR_2 \leq CR_1$, meaning that the electromechanical system is the limiting factor that determines control resolution. The bit storage capacity of a modern computer controller is sufficient to satisfy this criterion except in unusual situations. Resolutions of 0.0025 mm (0.0001 in) are within the current state of CNC technology.

The ability of a positioning system to move the worktable to the exact location defined by a given addressable point is limited by mechanical errors that are due to various imperfections in the mechanical system. These imperfections include play between the screw and the worktable, backlash in the gears, and deflection of machine components. The mechanical errors are assumed to form an unbiased normal statistical distribution about the control point whose mean $\mu = 0$. It is further assumed that the standard deviation σ of the distribution is constant over the range of the axis under consideration. Given these assumptions, nearly all of the mechanical errors (99.73%) are contained within $\pm 3\sigma$ of the control point. This is pictured in Figure 7.14 for a portion of the axis range that includes two control points.

These definitions of control resolution and mechanical error distribution can now be used to define accuracy and repeatability of a positioning system. Accuracy is defined under worst case conditions in which the desired target point lies in the middle between two adjacent addressable points. Since the table can only be moved to one or the other of the addressable points, there will be an error in the final position of the worktable. This is the maximum possible positioning error, because if the target were closer to either one of the addressable points, then the table would be moved to the closer point and the error would be smaller. It is appropriate to define accuracy under this worst-case scenario. 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,

$$Ac = \frac{CR}{2} + 3\sigma \tag{7.20}$$

where Ac = accuracy, mm (in); CR = control resolution, mm (in); and σ = standard deviation of the error distribution. Accuracies in machine tools are generally expressed for a certain range of table travel, for example, ± 0.01 mm for 250 mm (± 0.0004 in. for 10 in) of table travel.

Repeatability refers to the ability of the positioning system to return to a given addressable 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 addressable point. Location errors are a manifestation of the mechanical errors of the positioning system, which follow a normal distribution, as assumed previously. Thus, the ***repeatability*** of any given axis of a positioning system is ± 3 standard deviations of the mechanical error distribution associated with the axis. This can be written as

$$Re = \pm 3\sigma \tag{7.21}$$

where Re = repeatability, mm (in).

EXAMPLE 7.3 Control Resolution, Accuracy, and Repeatability in NC

Suppose the mechanical inaccuracies in the open-loop positioning system of Example 7.1 are described by a normal distribution with standard deviation = 0.005 mm. The range of the worktable axis is 1,000 mm, and there are 16 bits in the binary register used by the digital controller to store the programmed position. Other relevant parameters from Example 7.1 are the following: pitch = 6.0 mm, gear ratio between motor shaft and screw = 5.0, and number of step angles in the stepper motor = 48. Determine the (a) control resolution, (b) accuracy, and (c) repeatability of the positioning system.

Solution: (a) Control resolution is the greater of CR_1 and CR_2 as defined by Equations (7.17) and (7.18).

$$CR_1 = \frac{p}{n_s r_g} = \frac{6.0}{48(5.0)} = 0.025 \text{ mm}$$

$$CR_2 = \frac{1{,}000}{2^{16} - 1} = \frac{1{,}000}{65{,}535} = 0.01526 \text{ mm}$$

$$CR = \text{Max}\{0.025, 0.01526\} = \mathbf{0.025\ mm}$$

(b) Accuracy is given by Equation (7.20):

$$Ac = 0.5(0.025) + 3(0.005) = \mathbf{0.0275\ mm}$$

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

7.5 NC PART PROGRAMMING

NC part programming consists of planning and documenting the sequence of processing steps to be performed by an NC machine. The part programmer must have a knowledge of machining (or other processing technology for which the NC machine is designed), as well as geometry and trigonometry. The documentation portion of part programming involves the input medium used to transmit the program of instructions to the NC machine control unit. The traditional input medium dating back to the first NC machines in the 1950s is 1-in wide punched tape. More recently, magnetic tape, floppy disks, and portable solid-state memory