37 AUTOMATION TECHNOLOGIES FOR MANUFACTURING SYSTEMS

Review Questions

37.1 Define the term *manufacturing system*.

Answer. The text defines manufacturing system as a collection of integrated equipment and human resources that performs processing and/or assembly operations on a starting work material, part, or set of parts. The integrated equipment consists of one or more production machines, material handling and positioning devices, and computer systems.

37.2 What are the three basic components of an automated system?

Answer. The three basic components of an automated system, according to the text, are (1) power, (2) a program of instructions, and (3) a control system to carry out the instructions.

37.3 What is the difference between a closed-loop control system and an open-loop control system?

Answer. The difference is that a closed-loop control system includes feedback of data related to the output of the process that is used to make control adjustments. An open-loop system does not have this feedback loop. The controller relies on the expectation that the actuator will have the intended effect on the output variable.

37.4 What is the difference between fixed automation and programmable automation?

Answer. 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. In programmable automation, the equipment is designed with the capability to change the program of instructions to allow production of different parts or products.

37.5 What is the difference between programmable automation and flexible automation?

Answer. The equipment in programmable automation is designed with the capability to change the program of instructions to allow production of different parts or products. Its disadvantage is that it must be used for batch production because of the changeover time to set up for the new batch. Flexible automation is an extension of programmable automation in which there is virtually no lost production time for setup changes and/or reprogramming. Any changes in the program and/or setup can be accomplished within the time needed to move the next work unit into position at the machine.

37.6 What is a *sensor*?

Answer. 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.

37.7 What is an *actuator* in an automated system?

Answer. 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.

37.8 What is a *contact input interface*?

Answer. As defined in the text, a contact input interface is a device that reads binary data into the computer from an external source.

37.9 What is a *pulse generator*?

Answer. A pulse generator is 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.

37.10 What is a *programmable logic controller*?

Answer. As defined in the text, 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.

37.11 What is *numerical control*?

Answer. As defined in the text, 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.

37.13 What is the difference between point-to-point and continuous path in a motion control system?

Answer. In point-to-point, the motion is from one location in space to the next with no regard for the path taken between starting and final locations. In continuous path, the trajectory of the movement is controlled.

37.14 What is the difference between absolute positioning and incremental positioning?

Answer. In absolute positioning, the locations are defined relative to the origin of the axis system. In incremental positioning, each succeeding location is defined relative to the previous location.

37.15 What is the difference between an open-loop positioning system and a closed-loop positioning system?

Answer. In a closed loop system, measurements of the output position are fed back to verify that it corresponds to the desired input value. In an open loop system, there is no feedback of the output value.

37.16 Under what circumstances is a closed-loop positioning system preferable to an open-loop system?

Answer. When there is a significant reaction force resisting the motion of the positioning system, a closed loop system is preferred.

37.17 What is a *stepping motor*?

Answer. A 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.

37.18 In an NC positioning system, how is the rotational motion of the drive motor converted into the linear motion of the work table?

Answer. The worktable is moved linearly by means of a rotating leadscrew or ball screw that is driven by a motor.

37.19 Explain the operation of an optical encoder.

Answer. An optical encoder is a sensor for measuring angular position and rotational velocity. It consists of a light source, a photodetector, and a disk containing a series of slots through which the light source can shine to energize the photodetector. The disk is connected, either directly or through a gear train, 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, which are converted into an equivalent series of electrical pulses. By counting the pulses and computing the frequency of the pulse train, angular position and rotational speed can be determined.

37.20 What is control resolution in the operation of a positioning system?

Answer. Control resolution is defined as the distance separating two adjacent control points in the axis movement. Control points are locations along the axis to which the worktable can be directed to go.

37.21 Why should the electromechanical system rather than the controller storage register be the limiting factor in control resolution?

Answer. Because the control resolution in the controller storage register can be increased simply by increasing the number of bits used to define the axis location.

37.22 What are the benefits of CAD/CAM part programming compared to computer-assisted part programming?

Answer. In computer-assisted part programming, 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 as each statement is entered, to determine whether it is correct. When part geometry is entered by the programmer, the element is graphically displayed. 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. Also, if the design of the part was created on a CAD/CAM system, the geometric definition of the part can be retrieved to use as the starting geometry for part programming, which saves considerable time compared to reconstructing the part from scratch. Finally, 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, surface contouring, and certain point-to-point operations.

37.23 What is manual data input in NC part programming?

Answer. Manual data input refers to a method of programming in which the machine tool operator accomplishes the programming of the NC machine using a menu-driven procedure. Programming is simplified to minimize the amount of training required by the operator.

37.24 Identify some of the nonmachine tool applications of numerical control.

Answer. The applications include (1) filament placement and filament winding machines for fiber reinforced polymer composites, (2) arc welding and resistance welding machines, (3) component placement machines for electronic assembly, and (4) coordinate measuring machines.

37.25 What are some of the benefits usually cited for NC compared to using manual alternative methods?

Answer. Advantages of NC include (1) reduced non-productive time, (2) lower manufacturing lead times, (3) simpler fixtures, (4) greater flexibility, (5) improved accuracy, and (6) reduced human error.

37.26 What is an *industrial robot*?

Answer. As defined by the International Standards Organization, an industrial robot is "an automatically controlled, reprogrammable, multipurpose manipulator programmable in three or more axes, which may be either fixed in place or mobile for use in industrial automation applications."

37.27 How is an industrial robot similar to numerical control?

Answer. They are both positioning systems that can be programmed and reprogrammed.

37.28 What is an *end effector*?

Answer. An end effector is the special tooling that is attached to the robot's wrist to perform a particular application. A gripper is one type of end effector.

37.29 In robot programming, what is the difference between powered leadthrough and manual leadthrough?

Answer. In powered leadthrough, a teach pendant that controls the drive motors of the individual joints is used to move the manipulator into the desired joint positions, which are then recorded into memory. In manual leadthrough, the manipulator is physically moved through the desired sequence of positions, which are recorded into memory for later execution.

Problems

Answers to problems labeled **(A)** are listed in an Appendix at the back of the book.

Open-Loop Positioning Systems

37.1 **(A)** (SI units) A ball screw with an 8-mm pitch drives a worktable in an NC positioning system. The screw is powered by a stepping motor with 180 step angles. The worktable is programmed to move a distance of 150 mm from its present position at a travel speed of 400 mm/min. Determine the (a) number of pulses to move the table the specified distance, (b) motor speed, and (c) pulse rate to achieve the desired table speed.

Solution: (a) $\alpha = 360/n_s = 360/180 = 2.0°$
$n_p = 360x/p\alpha = 360(150)/(8 \times 2.0) =$ **3375 pulses**

(b) $N_m = v_t/p$ = (400 mm/min)/(8 mm/rev) = **50 rev/min**

(c) $f_p = v_t n_s/60p = 400(180)/(60 \times 8) =$ **150 Hz**

37.2 **(A)** (SI units) In the previous problem, the mechanical inaccuracies in the open-loop positioning system can be described by a normal distribution whose standard deviation = 0.006 mm. The range of the worktable axis is 750 mm, and there are 12 bits in the binary register used by the digital controller to store the programmed position. For the positioning system, determine the (a) control resolution, (b) accuracy, and (c) repeatability. (d) What is the minimum number of bits that the binary register should possess so that the mechanical drive system is the limitation on control resolution?

Solution: (a) $CR_1 = p/n_s$ = 8 mm/180 = 0.0444 mm
$CR_2 = L/2^B = 750/2^{12} - 1 = 750/4095 = 0.183$ mm
$CR = \text{Max}\{CR_1, CR_2\} = \text{Max}\{0.0444, 0.183\} =$ **0.183 mm**

(b) Accuracy $Ac = 0.5\ CR + 3\sigma = 0.5(0.183) + 3(0.006) =$ **0.1096 mm**

(c) Repeatability $Re = \pm\ 3\sigma = \pm\ 3(0.006) =$ **± 0.018 mm**

(d) In order for the mechanical errors to be the limiting factor in control resolution in this problem, set $CR_1 = CR_2$.
Thus, $0.0444 = 750/(2^B - 1)$
$2^B - 1 = 750/0.0444 = 16{,}877$
$2^B = 16{,}877$
$B \ln 2 = \ln 16{,}877$
$0.69315\ B = 9.7337$
$B = 14.04$ Use ***B* = 15 bits**

37.3 (USCS units) A stepping motor has 120 step angles. Its output shaft is directly coupled to ball screw with pitch = 0.375 in. The screw drives a worktable that must move a distance of 8.0 in from its present position at a travel speed of 24 in/min. Determine the (a) number of pulses required to move the table the specified distance, (b) required motor speed, and (c) pulse rate to achieve the specified table speed.

Solution: (a) $\alpha = 360/n_s = 360/120 = 3.0°$
$n_p = 360x/p\alpha = 360(8.0)/(0.375 \times 3.0) =$ **2560 pulses**

(b) $N_m = v_t/p$ = (24 in/min)/(0.375 in/rev) = **64 rev/min**

(c) $f_p = v_t n_s/60p = 24(120)/(60 \times 0.375) =$ **128 Hz**

37.4 (USCS units) A stepping motor with 120 step angles is coupled to a leadscrew through a gear reduction of 8:1 (8 rotations of the motor for each rotation of the screw). The screw has 4 threads/in. The worktable driven by the screw must move a distance = 10.00 in at a feed rate of 30.0 in/min. Determine the (a) number of pulses required to move the table, (b) required motor speed, and (c) pulse rate to achieve the desired table speed.

Solution: (a) $\alpha = 360/n_s = 360/120 = 3.0°$
The screw pitch p = 0.25 in

$n_p = 360\ r_g\ x/p\alpha = 360(6)(10)/(0.25 \times 3.0) =$ **38,400 pulses**

(b) $N_m = r_g\ f_r/p = 8(30\text{ in/min})/(0.25\text{ in/rev}) =$ **1350 rev/min**

(c) $f_p = r_g f_r n_s/60p = 8(30)(120)/(60 \times 0.25) =$ **1920 Hz**

37.5 (USCS units) The positioning table for a component placement machine uses a stepping motor and ball screw mechanism. The design specifications require a table speed of 75 in/min and an accuracy of 0.0008 in. The pitch of the screw = 0.25 in, and the gear ratio = 2:1 (2 turns of the motor for each turn of the screw). The mechanical errors in the motor, gear box, ball screw, and table connection are characterized by a normal distribution with standard deviation = 0.0001 in. Determine (a) the minimum number of step angles in the stepping motor, and (b) the frequency of the pulse train required to drive the table at the specified speed.

Solution: (a) Accuracy Ac = $0.5\ CR + 3\sigma$
$0.0008 = 0.5\ CR + 3(0.0001) = 0.5\ CR + 0.0003$
$0.0008 - 0.0003 = 0.0005 = 0.5\ CR$
$CR = 0.001$ in
Assume $CR = CR_1$
$CR_1 = 0.001 = p/(r_g n_s) = 0.25/2n_s$
Minimum $n_s = 0.25/(2 \times 0.001) =$ **125 step angles**

(b) $f_p = r_g v_t n_s/60p = 2(75)(125)/(60 \times 0.25) =$ **1250 Hz**

37.6 **(A)** (SI units) Each axis of an *x-y* positioning table is driven by a stepping motor connected to a ball screw using a gear reduction of 2:1. The step angle on each stepping motor = 7.5°. Each ball screw has a pitch = 5.0 mm and provides an axis range = 500 mm. There are 15 bits in each binary register used by the controller to store position data for the two axes. (a) What is the control resolution of each axis? (b) What are the required rotational speeds and corresponding pulse train frequencies of each stepping motor in order to drive the table at 500 mm/min in a straight line from point (x = 0 mm, y = 0 mm) to point (x = 200 mm, y = 300 mm)? Ignore acceleration.

Solution: (a) $n_s = 360/7.5 = 48$ step angles
$CR_1 = p/r_g n_s = 5.0/(1.0 \times 48) = 0.104$ mm
$CR_2 = L/(2^B - 1) = 500/(2^{15} - 1) = 500/32{,}767 = 0.0153$ mm
$CR = \text{Max}\{0.104, 0.0153\} =$ **0.104 mm**

(b) $v_t = 500$ mm/min from (0, 0) to (200, 300)
$\Delta x = 200 - 0 = 200$ mm, $\Delta y = 300 - 0 = 300$ mm
Angle $A = \tan^{-1}(300/200) = 56.3°$
$v_{tx} = 500 \cos 56.3 = 277.4$ mm/min
$N_{mx} = r_g v_{tx}/p = 2.0(277.4)/5.0 =$ **110.94 rev/min**
$f_{px} = N_{mx} n_s/60 = 110.94(48)/60 =$ **88.75 Hz**
$v_{ty} = 500 \sin 56.3 = 416.0$ mm/min
$N_{my} = r_g v_{ty}/p = 2.0(416)/5.0 =$ **166.4 rev/min**
$f_{py} = N_{my} n_s/60 = 166.4(48)/60 =$ **133.1 Hz**

Closed-Loop Positioning Systems

37.7 **(A)** (USCS units) The worktable of a CNC machine tool is driven by a closed-loop positioning system that consists of a servomotor, ball screw, and optical encoder. The screw has 4 threads/in and is coupled directly to the motor shaft (gear ratio = 1:1). The optical encoder generates 180 pulses per motor revolution. The table is programmed to move a distance = 6.0 in at a feed rate = 25.0 in/min. (a) How many pulses are received by the control system to verify that the table has moved the programmed distance? Determine the (b) pulse rate and (c) motor speed that correspond to the specified feed rate.

Solution: (a) $p = 0.25$ in, $x = pn_p/n_s$; rearranging, $n_p = xn_s/p = 6.0(180)/0.25 =$ **4320 pulses**

(b) $f_p = f_r n_s/60p = 25(180)/60(0.25) =$ **300 Hz**

(c) $N_m = f_r/p = 25/0.25 =$ **100 rev/min**

37.8 (SI units) A ball screw connected directly to a DC servomotor drives a positioning table. The screw pitch = 8 mm, and the optical encoder attached to it emits 120 pulses/rev of the screw. Determine the (a) control resolution of the system, expressed in linear travel distance of the table axis; (b) frequency of the pulse train emitted by the optical encoder when the servomotor operates at 10 rev/s; and (c) travel speed of the table at the same motor speed.

Solution: (a) $CR_1 = p/n_s = 8/120 =$ **0.067mm**

(b) $N_m = N_s = 10$ rev/s because the motor is connected directly to the ball screw
$f_p = N_m\, n_s = 10(120) =$ **1200 Hz**

(c) $v_t = N_m\, p = 10(8) =$ **80 mm/s**

37.9 (USCS units) A ball screw coupled directly to a dc servomotor is used to drive one of the table axes of a CNC milling machine. The screw has 4 threads/in. The optical encoder attached to the screw emits 180 pulses/rev of the screw. (a) What is the control resolution of the system, expressed in linear travel distance of the table axis? If the motor rotates at 1000 rev/min, determine the (b) frequency of the pulse train emitted by the optical encoder and (c) travel speed of the table.

Solution: (a) $CR = p/n_s = (0.25)/180 =$ **0.00139 in**

(b) $N_m = N_s = 1000$ rev/min because the motor is connected directly to the ball screw
$f_p = N_s n_s/60 = 1000(180)/60 =$ **3000 Hz**

(c) $v_t = N_s\, p = 1000(0.25) =$ **250 in/min**

37.10 (USCS units) Solve the previous problem only the servomotor is connected to the ball screw through a gear box whose reduction ratio = 4:1.

Solution: (a) $CR = p/n_s = (0.25)/180 =$ **0.00139 in**

(b) $f_p = N_m\, n_s/60r_g = 1000(180)/60(4) =$ **750 Hz**

(c) $v_t = N_m\, p/r_g = 1000(0.25)/4 =$ **62.5 in/min**

37.11 **(A)** (SI units) A milling operation is performed on a CNC machining center. Total travel distance = 300 mm in a direction parallel to one of the axes of the worktable. Cutting speed = 1.25 m/s and chip load = 0.07 mm. The milling cutter has four teeth, and its diameter =

20.0 mm. The axis uses a DC servomotor whose output shaft is coupled directly to a ball screw with pitch = 6.0 mm (gear ratio = 1:1). The optical encoder connected to the screw emits 180 pulses per revolution. Determine the (a) feed rate during the cut, (b) rotational speed of the motor, and (c) pulse rate of the encoder at the feed rate in part (a).

Solution: (a) Spindle speed $N = (1.25 \times 10^3$ mm/s)/(20π mm/rev) = 19.89 rev/s
From Eq. (21.14) in Chapter 21, feed rate $f_r = N f n_t$ = 19.89(0.07)(4) = **5.569 mm/s**

(b) Motor speed $N_m = f_r/p$ = (5.569 mm/s)/(6 mm/rev) **= 0.928 rev/s = 55.69 rev/min**

(c) Pulse rate $f_p = n_s N_m$ = 180(0.928) = **167.07 Hz**

37.12 (SI units) The y-axis of a CNC milling machine table is driven by a ball screw coupled to a DC servomotor with a gear reduction of 2:1 (2 turns of the motor shaft for each turn of the screw). The screw has 2 threads per cm, and the optical encoder directly connected to it emits 100 pulses per revolution. To execute a certain programmed instruction, the table must move from point (x = 25.0 mm, y = 28.0) to point (x = 155.0 mm, y = 275.0 mm) in a straight-line trajectory at a feed rate = 200 mm/min. For the y-axis only, determine the (a) control resolution of the mechanical system, (b) rotational speed of the motor, and (c) frequency of the pulse train emitted by the optical encoder at the desired feed rate.

Solution: (a) With 2 threads per cm, pitch p = 0.5 cm = 5 mm
One pulse of the optical encoder = $1/n_s$ rotation of the ball screw
$CR_1 = p/n_s$ = 5.0/100 = **0.050 mm**

(b) Move from (25, 28) to (155, 275) at 200 mm/min
Δx = 155 – 25 = 130 mm, Δy = 275 – 28 = 247 mm
Angle $A = \tan^{-1}(247/130) = \tan^{-1}(1.9) = 62.24°$

f_{ry} = 200 sin 62.24 = 200(0.8849) = 176.98 mm/min
Ball screw $N_{sy} = f_{ry}/p$ = 176.98/5 = 35.396 rev/min
Motor speed $N_{my} = r_g f_{ry}/p$ = 2(176.98)/5 = **70.792 rev/min**

(c) Pulse frequency corresponds to rotational speed of ball screw:
$f_{py} = n_s N_{sy}/60$ = 100(35.396)/60 = **58.99 Hz**

Industrial Robotics

37.13 **(A)** (SI units) The largest axis of a Cartesian coordinate robot has a total range of 1200 mm. It is driven by a pulley system capable of a mechanical accuracy of 0.25 mm and repeatability of ±0.15 mm. Determine the minimum number of binary register bits required in the robot's control memory for this axis.

Solution: Repeatability = $\pm 3\sigma$ = 0.15 mm
σ = 0.15/3 = 0.05 mm
Accuracy = 0.25 mm = 0.5 $CR + 3\sigma$ = 0.5 CR + 0.15
0.5 CR = 0.25 – 0.15 = 0.10
CR = 0.20
$CR = CR_2 = L/(2^B - 1) = 1200/(2^B - 1)$
$1200/(2^B - 1) = 0.20$
$2^B - 1 = 1200/0.20 = 6000$
$2^B = 6001$

$B \ln 2 = \ln 6001$
$0.69315\,B = 8.6997$ **B = 12.55 → 13 bits**

37.14 (SI units) A stepping motor is attached directly to a ball screw that drives the linear joint of an industrial robot (no gear reduction). The joint must have an accuracy = 0.20 mm. The pitch of the ball screw = 6.0 mm. The mechanical errors in the system (due to backlash of the screw) can be represented by a normal distribution with standard deviation = 0.04 mm. Specify the minimum number of step angles that the motor must have in order to meet the accuracy requirement.

Solution: Repeatability = $\pm 3\sigma = \pm 3(0.04) = \pm 0.12$ mm
Accuracy = 0.20 mm = $0.5\,CR + 3\sigma = 0.5\,CR + 0.12$
$0.5\,CR = 0.20 - 0.12 = 0.08$
$CR = 0.16$ mm
Assume $CR = CR_1 = p/r_g n_s$
Minimum $n_s = p/(r_g\,CR) = 6.0/(1 \times 0.16) = 37.5 \rightarrow$ ***n_s* = 38 step angles**

37.15 (USCS units) The designer of a polar configuration robot is considering the portion of the manipulator consisting of a rotational joint connected to its output link. The output link is 30 in long, and the rotational joint has a range of 75°. The accuracy of the joint-link combination, expressed as a linear measure at the end of the link that results from rotating the joint, is specified as 0.035 in. The mechanical inaccuracies of the joint result in a repeatability = ±0.030° of rotation. It is assumed that the link is perfectly rigid, so there are no additional errors due to deflection. (a) Show that the specified accuracy can be achieved, given the repeatability error. (b) Determine the minimum number of bits required in the binary register of the robot's control memory to achieve the specified accuracy.

Solution: (a) Repeatability = $\pm 3\sigma = \pm 0.030°$.
$0.030° = 2\pi(0.030)/360 = 0.0005236$ rad
End-of-link movement = $L\,A$ where A = angle of movement in radians
$L\,A = 30(0.0005236) = 0.0157$ in
Accuracy = $0.5\,CR + 3\sigma = 0.5\,CR + 0.0157$
Specified accuracy = 0.030
$0.030 = 0.5\,CR + 0.0157$
$0.5\,CR = 0.030 - 0.0157 = 0.0143$
$CR = 0.0143/0.5 = 0.0286$ in
Since CR is positive, the specified accuracy should be possible to achieve.

(b) Given $CR = 0.0286$ from part (a), total range = 75°
Converting this to an arc distance, range = $(2\pi(75)/360) \times 35 = 45.815$ in
$CR = L/(2^B - 1) = 0.0286$
$45.815/(2^B - 1) = 0.0286$
$2^B - 1 = 45.815/0.0286 = 1601.9$
$2^B = 1601.9$
$B \ln 2 = \ln 1601.9$
$0.6931\,B = 7.379$ **B = 10.65 → 11 bits**