COMPUTER NUMERICAL CONTROL (CNC)

INTRODUCTION

Definition

Computer Numerical Control (CNC) is one in which the functions and motions of a machine tool are controlled by means of a prepared program containing coded alphanumeric data. CNC can control the motions of the workpiece or tool, the input parameters such as feed, depth of cut, speed, and the functions such as turning spindle on/off, turning coolant on/off.

Applications

The applications of CNC include both for machine tool as well as non-machine tool areas. In the machine tool category, CNC is widely used for lathe, drill press, milling machine, grinding unit, laser, sheet-metal press working machine, tube bending machine etc. Highly automated machine tools such as *turning center and machining center* which change the cutting tools automatically under CNC control have been developed. In the non-machine tool category, CNC applications include welding machines (arc and resistance), coordinate measuring machine, electronic assembly, tape laying and filament winding machines for composites etc.

Advantages and Limitations

The benefits of CNC are (1) high accuracy in manufacturing, (2) short production time, (3) greater manufacturing flexibility, (4) simpler fixturing, (5) contour machining (2 to 5 -axis machining), (6) reduced human error. The drawbacks include high cost, maintenance, and the requirement of skilled part programmer.

ELEMENTS OF A CNC

A CNC system consists of three basic components (Figure 2):

1. Part program
2. Machine Control Unit (MCU)
3. Machine tool (lathe, drill press, milling machine etc)

Part Program

The part program is a detailed set of commands to be followed by the machine tool. Each command specifies a position in the Cartesian coordinate system (x,y,z) or motion (workpiece travel or cutting tool travel), machining parameters and on/off function. Part programmers should be well versed with machine tools, machining processes, effects of process variables, and limitations of CNC controls. The part program is written manually or by using computer-assisted language such as APT (Automated Programming Tool).
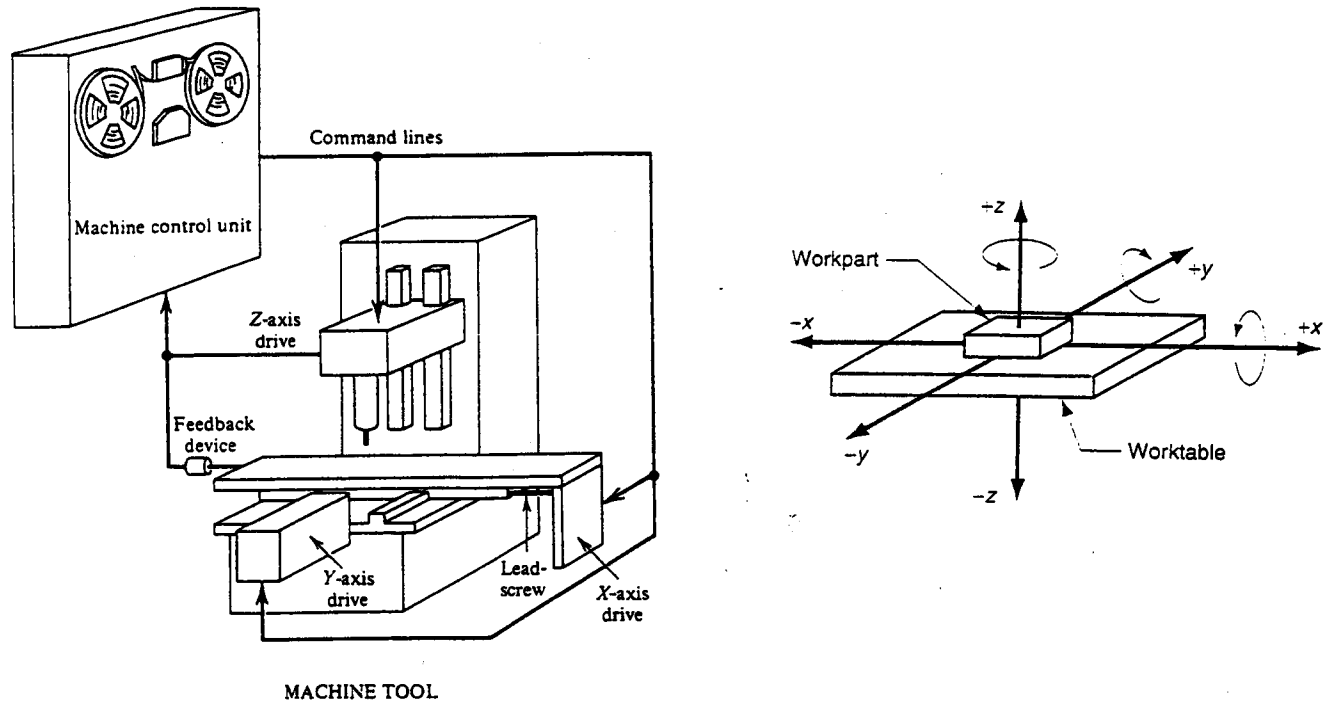
Figure 2. A typical numerical control system for a milling machine

Machine Control Unit

The machine control unit (MCU) is a microcomputer that stores the program and executes the commands into actions by the machine tool. The MCU consists of two main units: the data processing unit (DPU) and the control loops unit (CLU). The DPU software includes control system software, calculation algorithms, translation software that converts the part program into a usable format for the MCU, interpolation algorithm to achieve smooth motion of the cutter, editing of part program (in case of errors and changes). The DPU processes the data from the part program and provides it to the CLU which operates the drives attached to the machine leadscrews and receives feedback signals on the actual position and velocity of each one of the axes. A driver (dc motor) and a feedback device are attached to the leadscrew. The CLU consists of the circuits for position and velocity control loops, deceleration and backlash take up, function controls such as spindle on/off.

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Machine Tool

The machine tool could be one of the following: lathe, milling machine, laser, plasma, coordinate measuring machine etc. Figure 3 shows that a right-hand coordinate system is used to describe the motions of a machine tool. There are three linear axes (x,y,z), three rotational axes (i,j,k), and other axes such as tilt (θ) are possible. For example, a 5-axis machine implies any combination of x,y,z, i,j,k,and θ.

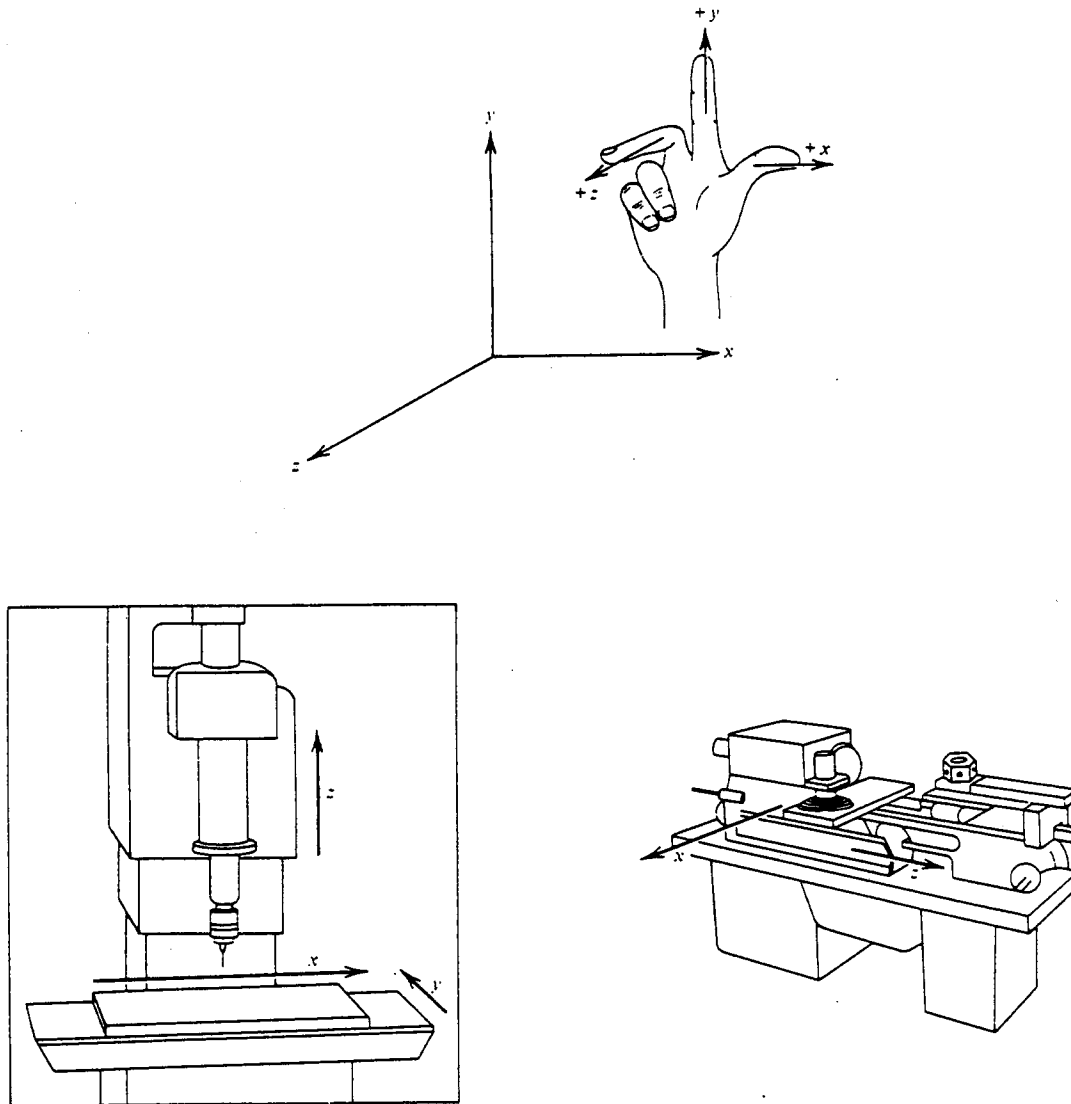Figure 3. Right-hand coordinate system used in drill press and lathe

PRINCIPLES OF CNC

Basic Length Unit (BLU)

Each BLU unit corresponds to the position resolution of the axis of motion. For example, 1 BLU = 0.0001" means that the axis will move 0.0001" for every one electrical pulse received by the motor. The BLU is also referred to as Bit (binary digit).

Pulse = BLU = Bit

Point-to-Point Systems

Point-to-point systems are those that move the tool or the workpiece from one point to another and then the tool performs the required task. Upon completion, the tool (or workpiece) moves to the next position and the cycle is repeated (Figure 4). The simplest example for this type of system is a drilling machine where the workpiece moves.

In this system, the feed rate and the path of the cutting tool (or workpiece) have no significance on the machining process. The accuracy of positioning depends on the system's resolution in terms of BLU (basic length unit) which is generally between 0.001" and 0.0001".
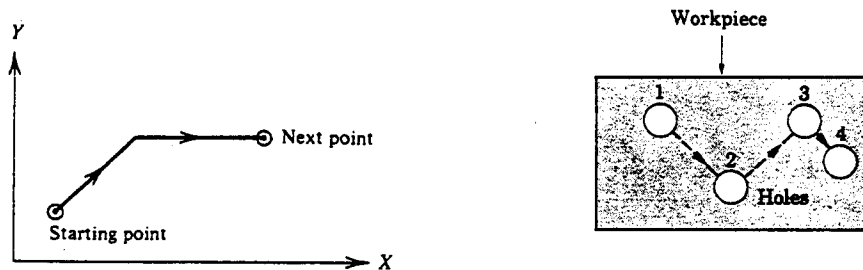

Figure 4. Cutter path between holes in a point-to-point system

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Example 1

The XY table of a drilling machine has to be moved from the point (1,1) to the point (6,3). Each axis can move at a velocity of 0.5"/sec, and the BLU is 0.0001", find the travel time and resolution.

Travel time in X-axis is (6-1)/0.5 = 10 sec, in Y-axis is (3-1)/0.5 = 4 sec.
Travel time = 10 sec
Resolution = BLU = 0.0001

Continuous Path Systems (Straight cut and Contouring systems)

These systems provide continuous path such that the tool can perform while the axes are moving, enabling the system to generate angular surfaces, two-dimensional curves, or three-dimensional contours. Example is a milling machine where such tasks are accomplished (Figure 5). Each axis might move continuously at a different velocity. Velocity error is significant in affecting the positions of the cutter (Figure 5). It is much more important in circular contour cutting where one axis follows sine function while the other follows cosine function. Figure 6 illustrates point-to-point and continuous path for various machines.
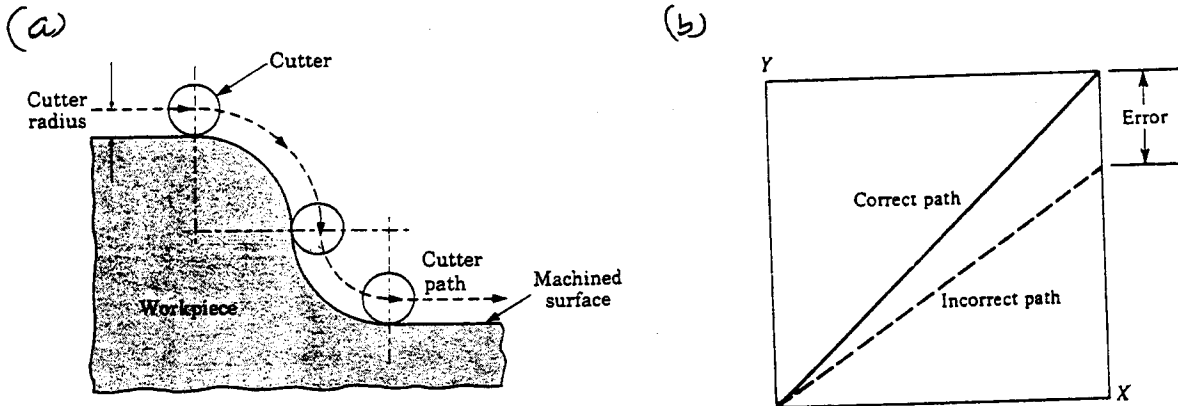
(a)   (b)

Figure 5. (a) Continuous path cutting and (b) Position error caused by the velocity error

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Example 2

A CNC milling machine has to cut a slot located between the points (0,0) and (4,3) on the XY-plane where the dimensions are in inches. If the speed along the slot is to be 0.1 in/sec, find the cutting time and axial velocities.

Distance traveled along the slot $= (16+9)^{1/2} = 5"$

Cutting time $= 5/0.1 = 50$ sec

$V_x = xV/(x^2+y^2)^{1/2} = 4(0.1)/5 = 0.08$ in/sec
$V_y = yV/(x^2+y^2)^{1/2} = 3(0.1)/5 = 0.06$ in/sec

If the velocity is Y-axis is off by 10%, what would be the new position ?

New velocity in y is $0.9 \times 0.06 = 0.054$ in/sec

In 50 sec, the y- will move a distance $[50(0.054)] = 2.7$ in.

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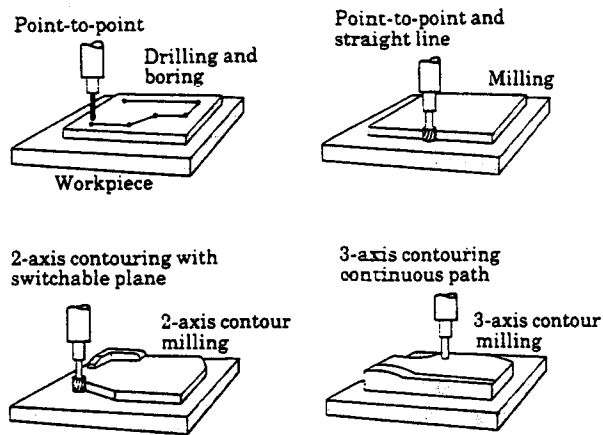
Figure 6.   Schematic illustration of drilling, boring, and milling with various paths.

Interpolator

The input speed of 1 in/sec in example 2 is converted into the velocity components by an interpolator called the linear interpolator whose function is to provide the velocity signals to x and y directions. Similarly we have circular and parabolic interpolators.   See Figure 7.

Figure 7.   Types of interpolation (a) linear, (b) continuous path approximated by incremental straight lines, and (c) circular

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Incremental and Absolute systems

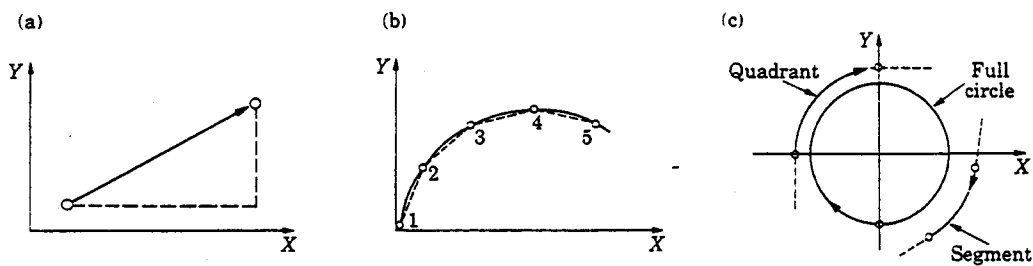CNC systems are further divided into incremental and absolute systems (Figure 8). In incremental mode, the distance is measured from one point to the next. For example, if you want to drill five holes at different locations, the x-position commands are x + 500, + 200, + 600, - 300, -700, -300. An absolute system is one in which all the moving commands are referred from a reference point (zero point or origin). For the above case, the x-position commands are x 500,700, 1300, 1000, 300, 0. (Figure 8). Both systems are incorporated in most CNC systems. For an inexperienced operator, it is wise to use incremental mode.
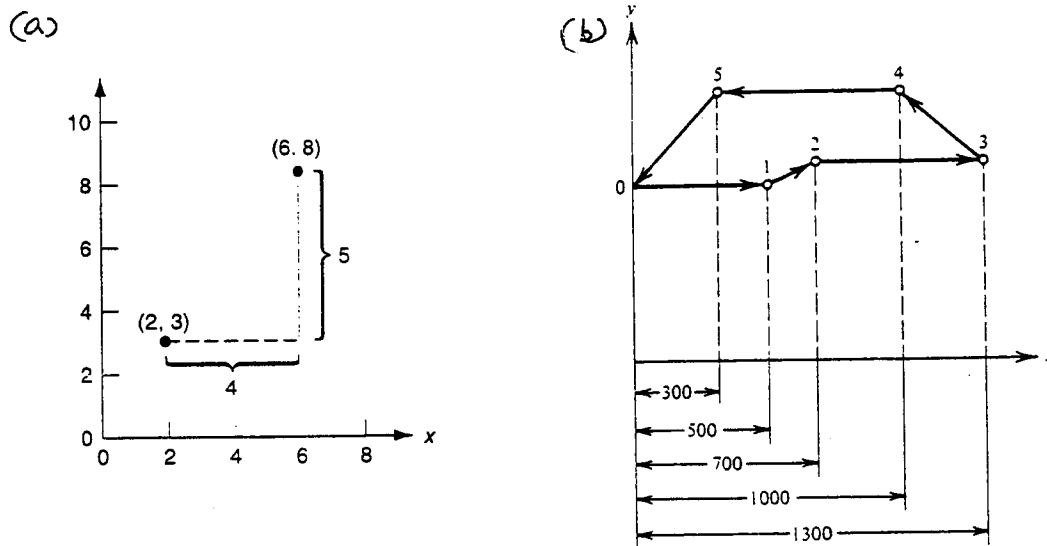
Figure 8.   (a) Absolute versus incremental; In absolute positioning, the move is specified by x = 6, y = 8; in incremental, the move is specified by x=4, y=5 for the tool to be moved from (2,3) to (6,8)

(b) Drilling 5-holes at different locations

The absolute system has two significant advantages over the incremental system:

1.   Interruptions caused by, for example, tool breakage (or tool change, or checking the parts), would not affect the position at the interruption.

If a tool is to be replaced at some stage, the operator manually moves the table, exchanges the tool, and has to return the table to the beginning of the segment in which the interruption has occurred. In the absolute mode, the tool is automatically returned to the position. In incremental mode, it is almost impossible to bring it precisely to that location unless you repeat the part program

2.   Easy change of dimensional data

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The incremental mode has two advantages over the absolute mode.

1.   *Inspection of the program is easier because the sum of position commands for each axis must be zero.* A nonzero sum indicates an error . Such an inspection is impossible with the absolute system.

2.   *Mirror image programming (for example, symmetrical geometry of the parts) is simple by changing the signs of the position commands.*

Open Loop Control Systems

The open-loop control means that there is no feedback and uses stepping motors for driving the leadscrew. A stepping motor is a device whose output shaft rotates through a fixed angle in response to an input pulse (Figure 9). The accuracy of the system depends on the motor's ability to step through the exact number. The frequency of the stepping motor depends on the load torque. The higher the load torque, lower would be the frequency. Excessive load torque may occur in motors due to the cutting forces in machine tools. Hence this system is more suitable for cases where the tool force does not exist (Example: laser cutting).
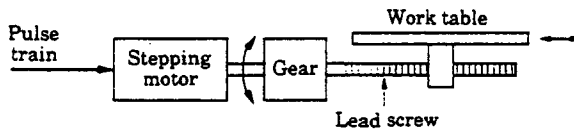
Figure 9.   Open loop control system

The stepping motor is driven by a series of electrical pulses generated by the MCU. Each pulse causes the motor to rotate a fraction of one revolution. The fraction is expressed in terms of the step angle, α, given by

α = 360/N, degrees where N = number of pulses required for one revolution

If the motor receives "n" number of pulses then the total angle,

A = n (360/N), degrees

In terms of the number of revolutions, it would be (n/N)

If there is a 1:1 gear ratio between the motor and the leadscrew, then the leadscrew has (n/N) revolutions. If the pitch of leadscrew is p (in/rev), then the distance traveled axially, say x,

x = p(n/N)

can be used to achieve a specified x-increment in a point-to-point system.

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The pulse frequency, f, in pulses/sec determines the travel speed of the tool or the workpiece.

60 f = N (RPM) where N = number of pulses per revolution,
RPM = RPM of the lead screw

The travel speed, V, is then given by V = p (RPM) where p pitch in in/rev

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Example 3

A stepping motor has N = 150, p = 0.2"/rev; If n = 2250 pulses, what is the distance traveled in x-direction ? What should be the pulse frequency for a travel speed of 16 in./min ?

$$x = (0.2) (2250)/150 = 3"$$

$$16 = 0.2 (RPM), \text{ from which, RPM} = 80$$

$$f = (150) (80)/60 = 200 \text{ Hz}$$

Example 4

A stepping motor of 200 steps per revolution is mounted on the leadscrew of a drilling machine. If the pitch is 0.1 in/rev.,

a.   What is the BLU ?
b.   If the motor receives a pulse frequency of 2000 Hz, what is the speed of the table ?

a.   BLU = 0.1/200 = 0.0005"

b.   Table speed = (p) (RPM) = (0.1) (60) (2000)/200 = 60 in/min

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Closed-loop Control Systems

Closed -loop NC systems are appropriate when there is a force resisting the movement of the tool/workpiece. Milling and turning are typical examples. In these systems (Figure 10) the DC servomotors and feedback devices are used to ensure that the desired position is achieved. The feedback sensor used is an optical encoder shown in Figure 11. The encoder consists of a light source, a photodetector, and a disk containing a series of slots. The encoder is connected to the leadscrew. As the screw turns, the slots cause the light to be seen by the

photodetector as a series of flashs which are converted into an equivalent series of electrical pulses which are then used to characterize the position and the speed. The equations remain essentially the same as open-loop except that the angle between the slots in the disk is the step angle, α.

Both the input to the control loop and the feedback signals are a sequence of pulses, each pulse representing a BLU unit. The two sequences are correlated by a comparator and gives a signal, by means of a digital-to-analog converter, (a signal representing the position error), to operate the drive motor (DC servomotor).
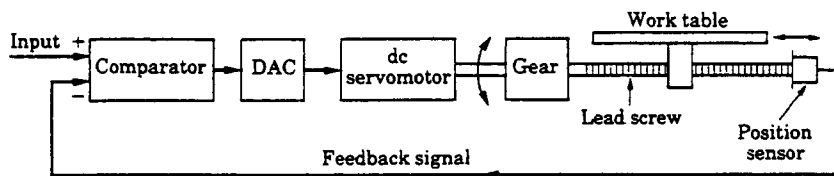
Figure 10. Closed loop control system
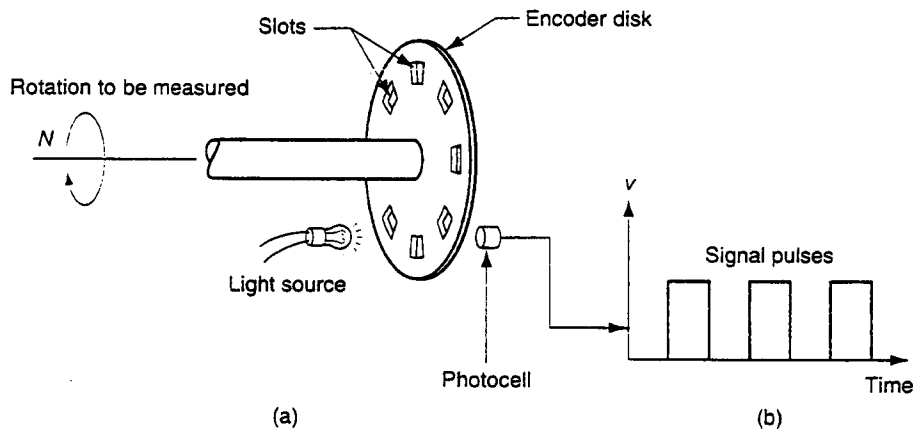
Figure 11. Optical Encoder (a) Device (b) Series of pulses emitted

Example 5

Consider a CNC worktable driven by a closed-loop control system consisting of a servomotor, leadscrew, and optical encoder. The leadscrew has a pitch, p = 0.2" and is coupled to the motor shaft with a screw to motor gear ratio of 1:4. The encoder generates 150 pulses per revolution of the leadscrew. If the number of pulses and the pulse rate received by the control system are 2250 and 200 Hz respectively, calculate

   a.   **Table speed**
   b.   **Motor speed in RPM**
   c.   **Distance traveled by the table**

a.   V= p(RPM) = 0.2(RPM) = (0.2) (60 f)/N = (0.2) (60) (200)/150 = 16 in/min

b.   RPM of the leadscrew = (60) (200)/(150) = 80
     RPM of the motor = 320

c.   x = p(n/N) = (0.2) (2250)/150 = 3"

Example 6

A dc servomotor is coupled to a leadscrew which drives the table of a CNC machine tool. A digital encoder, mounted at the end of the screw, emits 500 pulses per revolution. If the pitch is 5 mm per rev, and the motor rotates 600 rpm (1:1 gear ratio), calculate the

a.   **Table speed**
b.   **BLU**
c.   **Frequency of pulses transmitted by the encoder**

a.   V= p(RPM) = 5 (600) = 3000 mm/min = 3 m/min

b.   BLU = 5/500 = 0.01 mm

c.   RPM = 600 = (60f)/N = 60 f/500 from which f = 5000 Hz

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PRECISION IN CNC MACHINING

The combined characteristics of the machine tool and the control determine the precision of positioning. Three critical measures of precision are:

- o   Resolution
- o   Accuracy
- o   Repeatability

Control resolution (BLU) is the distance separating two adjacent points in the axis movement (the smallest change in the position). The electromechanical components of the positioning system that affect the resolution are the leadscrew pitch, the gear ratio, and the step angle in the stepping motor (open loop) or the angle between the slots in the encoder (closed-loop). The control resolution for a 1:1 gear ratio of a stepped motor is,

$$\text{Resolution} = p/N \quad \text{where } p = \text{pitch, and } N = 360/\alpha$$

Features smaller than the control resolution could not be produced. The programming resolution can not exceed the control resolution.

Accuracy of a CNC system depends on the resolution, the computer control algorithms, and the machine inaccuracies. The inaccuracy due to the resolution is considered to be (1/2)BLU on the average. The control algorithm inaccuracy is due to the rounding off the errors in the computer which is insignificant. The machine inaccuracy could be due to several reasons (described below). The designer minimizes this inaccuracy to be under (1/2)BLU and hence

$$\text{Accuracy} = (1/2) \text{ Resolution} + \text{Machining inaccuracy} = \text{BLU}$$

Repeatability is a statistical term associated with accuracy. It refers to the capability of a positioning system to return to a programmed point, and is measured in terms of the errors associated with the programmed point. The deviation from the control point (error) usually follows a normal distribution in which case the repeatability may be given as $+/- 3\sigma$ where σ is the standard deviation. The repeatability is always better than the accuracy. The mechanical inaccuracy can be considered as the repeatability. Figure 12 shows the difference between the accuracy and the repeatability.

Machining Inaccuracy

Cutting tool deflection, machine tool chatter, mechanical linkage between the leadscrew and the tool, and thermal deformations are the chief contributing factors. The leadscrew transmits the power to the table or toolholder by means of a nut that engages the leadscrew. This will create what is known as "backlash" due to the friction between the screw and the nut. If the nut consists of ball bearings, the friction is reduced. Thermal deformations are significant. For example, a temperature difference of 1°C along 1000 mm can cause an error of 0.01 mm.

| Low Accuracy Low Repeatability | Low Accuracy High Repeatability | High Accuracy High Repeatability |
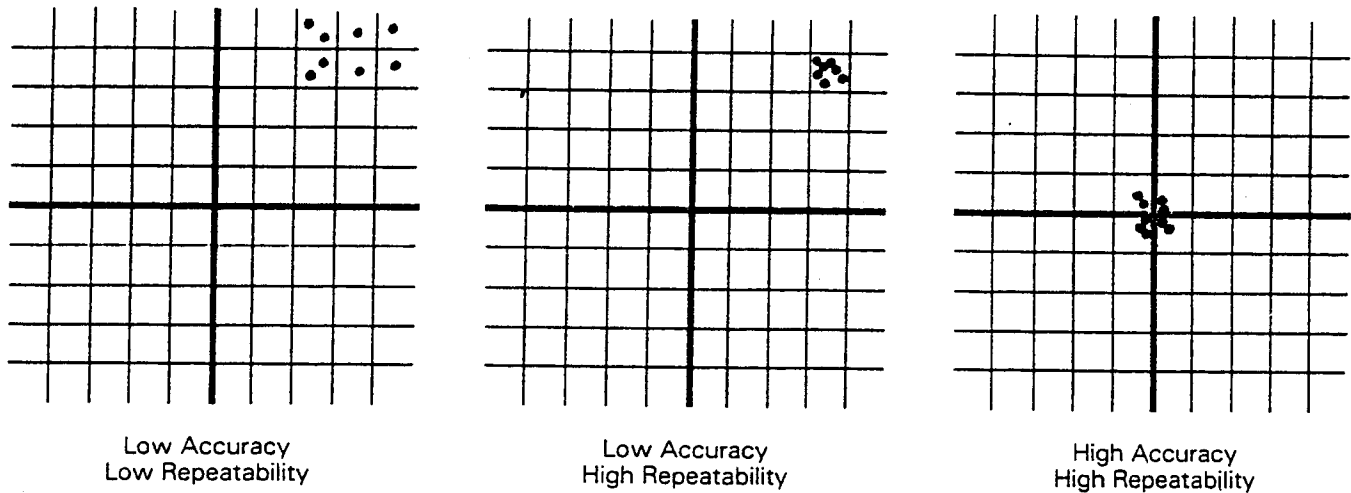
Figure 12. Diagram showing the difference between accuracy and repeatability

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Example 7

What is the control resolution for a 4:1 gear ratio (motor: leadscrew), pitch of leadscrew 0.2 in/rev, and the motor receives 600 pulses per revolution ?

Since the motor shaft rotates 4 times faster than the leadscrew, N = 600/4 = 150
Resolution = 0.2/150 = 0.001333"

What would be the accuracy and repeatability if the machining inaccuracy is about (1/2)BLU ?

Accuracy = 0.001333/2 + 0.001333/2= 0.001333"

Repeatability = +/- 0.00067"

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PART PROGRAMMING FOR CNC

The transfer of an engineering blueprint of a product to a part program can be performed manually using a calculator or with the assistance of a computer language. A part programmer must have an extensive knowledge of the machining processes and the capabilities of the machine tools. In this section, we describe how the part programmers execute manually the part programs.

First, the machining parameters are determined. Second, the optimal sequence of operations is evaluated. Third, the tool path is calculated. Fourth, a program is written. Each line of the program, referred to as a block, contains the required data for transfer from one point to the next.

A typical line for a program is given below.

N100 G91 X -5.0 Y7.0 F100 S200 T01 M03 (EOB)

The significance of each term is explained below.

Sequence Number, N

Consisting of typically three digits, its purpose is to identify the specific machining operation through the block number particularly when testing a part program.

Preparatory Function, G

It prepares the MCU circuits to perform a specific operation. The G-codes (some) are shown in Table 1. G91 implies incremental mode of operation.

Dimension Words

1. Distance dimension words, X,Y,Z

2. Circular dimension words, I,J,K for distances to the arc center

3. Angular dimensions, A,B,C

While (1) and (3) are expressed either by incremental or absolute mode, (2) is always in given in incremental mode. All angular dimensions are specified in revolutions or degrees.

In the above block, X moves a distance of 5 in. in the negative direction while Y moves a distance of 7 in. in the positive direction. Other axes remain stationary. In some systems, actual distances are used. In others, the dimension words are programmed in BLUs.

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Feedrate, F

It is expressed in in/min or mm/min and is used in contouring or point-to-point or straight-cut systems. For example, a feedrate of F100 implies 100 in/min or 100 mm/min. Feedrates are independent of spindle speed.

In linear motions, the feedrate of the cutting tool is not corrected for the cutter radius. But in circular motions, the feedrate should be corrected for the tool radius as follows:

$$F = [(\text{part contour radius} \pm \text{tool radius})/\text{part contour radius}] (\text{required feedrate})$$

For cutting around the outside of a circle, the plus sign in the above equation is used, and the feedrate is increased. For cutting around the inside of a circle, the minus sign is used, and the feedrate is decreased.

Example 8

See Figure 5(a). If the required feedrate is 6 in/min, part contour radius is 1.5 in, and the cutter diameter is 1 in, what is the feedrate athe top and bottom circles ?

Feedrate at the top is to be 8 in/min and at the bottom is to be 4 in/min.

Spindle speed, S

Programmed in rev/min, it is expressed as RPM or by a three-digit code number that is related to the RPM.

Toolword, T

Consisting of a maximum of five digits, each cutting tool has a different code number. The tool is automatically selected by the automatic tool changer when the code number is programmed in a block.

Miscellaneous Function, M

Consisting of two digits, this word relates to the movement of the machine in terms of spindle on/off, coolant on/off etc shown in Table 2.

EOB

The EOB character is used at the end of each block to complete a line.

Table .1 Preparatory commands (G-code)

G00	Point-to-point positioning
G01	Linear interpolation
G02	Clockwise circular interpolation
G03	Counter-clockwise circular interpolation
G04	Dwell
G05	Hold
G33	Thread cutting, constant lead
G40	Cancel tool nose radius compensation
G41	Tool nose radius compensation – left
G42	Tool nose radius compensation – right
G43	Cutter length compensation
G44	Cancel cutter length compensation
G70	Dimensions in inches
G71	Metric dimensions
G90	Absolute dimensions
G91	Incremental dimensions
G92	Datum offset

Table .2 Miscellaneous commands (M-code)

M00	Program stop
M01	Optional stop
M02	End of program
M03	Spindle start clockwise
M04	Spindle start counter-clockwise
M05	Spindle stop
M06	Tool change
M07	Mist coolant on
M08	Flood coolant on
M09	Coolant off
M10	Clamp
M11	Unclamp
M13	Spindle clockwise, coolant on
M14	Spindle counter-clockwise, coolant on
M30	End of tape, rewind

Tables 1 and 2:   G and M codes used in CNC systems

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4-7-2 G Functions (SEICOS-MII)

G code	Group	Function
G00		Positioning (rapid traverse)
G01	01	Linear interpolation (cutting feed)
G02		Circular interpolation CW
G03		Circular interpolation CCW
G04		Dwell
G07	00	SIN interpolation (designation of virtual axis)
G09		Exact stop check
G10		Offset amount and work zero point offset amount setting
G17		Designation of X-Y plane
G18	02	Designation of Z-X plane
G19		Designation of Y-Z plane
G20	06	Inch input
G21		Metric input
G22	04	Stored stroke limit ON
G23		Stored stroke limit OFF
G27		Return to reference point
G28		Return to reference point
G29	00	Return from reference point
G30		Return to 2nd reference point
G31		Skip function
G40	07	Tool diameter compensation cancel
G41		Tool diameter compensation to left
G42		Tool diameter compensation to right
G43		Tool length compensation "+"
G44	08	Tool length compensation "-"
G49		Tool length compensation cancel
G45		Tool offset expansion
G46	00	Tool offset reduction
G47		Tool offset double expansion
G48		Tool offset double reduction
G50	11	Scaling cancel
G51		Scaling

G codes with " " are set when the power is turned on.

G40, G49 and G80 are set by resetting the NC unit.

G code	Group	Function
G52	00	Local coordinate system setting
G53		Machine coordinate system selection
G54	12	Work coordinate system 1 selection
G55		Work coordinate system 2 selection
G56		Work coordinate system 3 selection
G57		Work coordinate system 4 selection
G58		Work coordinate system 5 selection
G59		Work coordinate system 6 selection
G60	00	One directional positioning
G61	13	Exact stop check mode
G63		Tapping mode
G64		Continuous cutting mode
G65	00	Macro call
G66	14	Macro modal call A
G67		Macro modal call cancel
G73	09	Peck drilling cycle
G74		Reverse tapping cycle
G76		Fine boring
G80		Canned cycle cancel
G81		Drilling cycle, spot boring
G82		Drilling cycle, counter boring
G83		Peck drilling cycle
G84		Tapping cycle
G85		Boring cycle
G86		Boring cycle
G87		Back boring cycle
G88		Boring cycle
G89		Boring cycle
G90	03	Absolute programming
G91		Incremental programming
G92	00	Programming of absolute zero point
G98	10	Initial level return (canned cycle)
G99		R point level return (canned cycle)
G501	15	Programmable mirror image cancel
G511		Programmable mirror image

(*: Optional function)

M	Function name	M	Function name
00	Program stop	*33	Idle cutting time reduction (modal)
01	Optional stop	*34	Idle cutting time reduction (unmodal)
02	End of program	*35	Automatic start ON
03	Spindle forward	*36	Automatic start OFF
04	Spindle reverse	*37	
05	Spindle stop	*38	Spindle no-load detect function stop
06	Tool change ATC	*39	M38 cancel
*07	Mist coolant start	*40	Tool nose air blow ON
08	Flood coolant start	*41	Tool nose air blow OFF
09	Mist coolant stop	*42	
*10	Mist coolant attitude 1	*43	
*11	Mist coolant attitude 2	*44	
*12	Work count	*45	Spare tool offset enabled
13	Spindle forward & coolant start	*46	Spare tool offset disabled
14	Spindle reverse & coolant start	*47	Jet coolant start
15	M13/M14 stop	48	Feed rate override enabled
*16	Measurement air blow ON	49	Feed rate override 100%
*17	Measurement air blow OFF	*50	Oil hole coolant start
*18	Measuring spindle orientation	*51	
19	Spindle orientation	*52	Tool breakage detect
*20	Machining time monitoring	*53	
*21		*54	
*22		*55	
*23		*56	
*24		*57	
*25		*58	
*26	Melodia (1)	*59	
*27	Melodia (2)	*60	Work change APC
*28	Setting load level 0	*61	
*29	Setting load level 1	*62	
30	End of tape	*63	
*31	Chip conveyor start	*64	
*32	M33 cancel	*65	

M	Function name	M	Function name
*66			
*67			
*68	Additional axis clamp		
*69	Additional axis uncalmp		
*70	M70 output		
*71	M71 output		-
*72	M72 output		
*73	M73 output		
*74	Skip selection OFF		
*75	Skip selection ON		
*76			
*77			
*78	Additional axis clamp		
*79	Additional axis unclamp		
*80	Tool nose air blow ON		
*81			
*82			
*83			
*84			
*85			
*86	Measurement NG tool breakage detect		
*87			
*90			
*91			
*92			
*93			
*94			
*95			
*96			
*97			
98	Subprogram call		
99	End of subprogram		

M	Maintenance mode		
*100	Arm swing-in to spindle side		
*101			
*102	Arm advance		
*103	Arm turn CW		
*104	Arm turn CCW		
*105	Arm retract		
*106	Arm slide to home position		
*107			
*108	Arm slide to magazine side		
*109			
*110			
*111			
*112			
*113			
*114			
*115			
*116			
*117			
*118			
*119	Orientation		
*120	Magazine positioning pin OUT		
*121	Magazine positioning pin IN		
*122			
*123			
*124	Pallet slider advance (APC)		
*125	Pallet unclamp (APC)		
*126	Pallet slider retract (APC)		
*127	Pallet right turn (APC)		
*128	Pallet left turn (APC)		
*129	Pallet unclamp (APC)		