MODULE II

NUMERICAL CONTROL

INTRODUCTION

Numerical control defined

Numerical control can be defined as a form of programmable automation in which the process is controlled by numbers, letters, and symbol. In NC, the numbers form a program of instructions designed for a particular work part or job. When the job changes, the program of instructions is changed. This capability to change the program for each new job is what gives NC its flexibility. It is much easier to write new programs than to make major changes in the production equipment.

NC technology has been applied to a wide variety of operations, including drafting, assembly, inspection, sheet metal press working, and spot welding. However, numerical control finds its principal applications in metal machining processes. The machined work parts are designed in various sizes and shapes, and most machined parts produced in industry today are made in small to medium-size batches. To produce each part, a sequence of drilling operations may be required, or a series of turning or milling operations. The suitability of NC for these kinds of jobs is the reason for the tremendous growth of numerical control in the metal-working industry over the last 25 years.

BASIC COMPONENTS OF AN NC SYSTEM

An operational numerical control system consists of the following three basic components:

1. Program of instructions
2. Controller unit, also called a machine control unit (MCU)
3. Machine tool or other controlled process

The general relationship among the three components is illustrated in Figure. The program of instructions serves as the input to the controller unit, which in turn commands the machine tool or other process to be controlled. We will discuss the three components in the sections below.

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Program of instructions

The program of instructions is the detailed step-by-step set of directions which tell the machine tool what to do. It is coded in numerical or symbolic form on some type of input medium that can be interpreted by the controller unit. The most common input medium today is l-in.-wide punched tape. Over the years, other forms of input media have been used, including punched cards, magnetic tape, and even 35-mm motion picture film.

There are two other methods of input to the NC system which should be mentioned. The first is by manual entry of instructional data to the controller unit. This method is called manual data input, abbreviated MDI, and is appropriate only for relatively s1fuple Jobs where the order will not be repeated. The second other method of input is by means

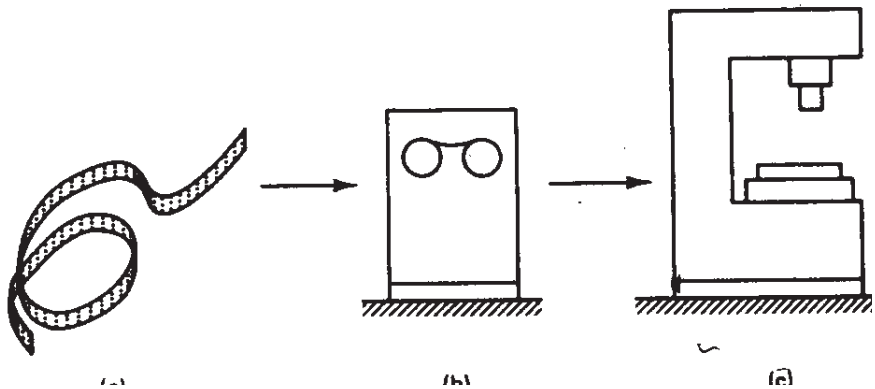


FIGURE Three basic components of a numerical control system: (a) program of instruction; (b) controller unit; (c) machine tool.

of a direct link with a computer. This is called direct numerical control, or DNC,.

The program of instructions is prepared by someone called a part programmer. The programmer's job is to provide a set of detailed instructions by which the sequence of processing steps is to be performed. For a machining operation, the processing steps involve the relative movement between the cutting tool and the workpiece.

Controller unit

The second basic component of the NC system is the controller unit. This

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consists of the electronics and hardware that read and interpret the program of instructions and convert it into mechanical actions of the machine tool. The typical elements of a conventional NC controller unit include the tape reader, a data buffer signal out-put channels to the machine tool, feedback channels from the machine tool, and the sequence controls to coordinate the overall operation of the foregoing elements. It should be noted that nearly all modern NC systems today are sold with a microcomputer as the controller unit. This type of NC is called computer numerical control (CNC).

The tape reader is an electromechanical device for winding and reading the punched tape containing the program of instructions. The data contained on the tape are read into the data buffer. The purpose of this device is to store the input instructions in logical blocks of information. A block of information usually represents one complete step in the sequence of processing elements. For example, one block may be the data required to move the machine table to a certain position and drill a hole at that location.

The signal output channels are connected to the servomotors and other controls in the machine tool. Through these channels, the instructions are sent to the machine tool from the controller unit. To make certain that the instructions have been properly executed by the machine, feedback data are sent back to the controller via the feedback channels. The most important function of this return loop is to assure that the table and work part have been properly located with respect to the tool.

Sequence controls coordinate the activities of the other elements of the controller unit. The tape reader is actuated to read data into the buffer from the tape, signals are sent to and from the machine tool, and so on. These types of operations must be synchronized and this is the function of the sequence controls.

Another element NC system, which may be physically part of the controller unit or part of the machine tool, is the control panel. The control panel or control console contains the dials and switches by which the machine operator runs the NC system. It may also contain data displays to provide information to the operator. Although the NC system is an automatic system, the human operator is still needed to turn the machine on and off, to change tools (some NC systems have automatic

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tool changers), to load and unload the machine, and to perform various other duties. To be able to discharge these duties, the operator must be able to control the system, and this is done through the control panel.

Machine tool or other controlled process

The third basic component of an NC system is the machine tool or other controlled process. It is the part of the NC system which performs useful work. In the most common example of an NC system, one designed to perform machining operations, the machine tool consists of the workable and spindle as well as the motors and controls necessary to drive them. It also includes the cutting tools, work fixtures, and other auxiliary equipment needed in the machining operation.

NC machines range in complexity from simple tape-controlled drill presses to highly sophisticated and versatile machining centers. The NC machining center was first introduced in the late 1950s. It is a multifunction machine which incorporates several timesaving features into a single piece of automated production equipment. First, a machining center is capable of performing a variety of different operations: drilling, tapping, reaming, milling, and boring. Second, it has the capacity to change tools automatically under tape command. A variety of machining operations means that a variety of cutting tools are required. The tools are kept in a tool drum or other holding device. When the tape calls a particular tool, the drum rotates to position the tool for insertion into the spindle. The automatic tool changer then grasps the tool and places it into the spindle chuck. A third capability of the NC machining center is work piece positioning. The machine table can orient the job so that it can be machined on several surfaces, as required. Finally, a fourth feature possessed by some machining centers is the presence of two tables or pallets on which the work piece can be fixtured. While the machining sequence is being performed on one work part, the operator can be unloading the previously completed piece, and loading the next one. This improves machine tool utilization because the machine does not have to stand idle during loading and unloading of the work parts.

THE NC PROCEDURE

To utilize numerical control in manufacturing, the following steps must be accomplished.

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1. *Process Planning*. The engineering drawing of the workpart must be interpreted in terms of the manufacturing processes to be used. this step is referred to as process planning and it is concerned with the preparation of a route sheet. The route sheet is a listing of the sequence of operations which must be performed on the workpart. It is called a route sheet because it also lists the machines through which the part must be routed in order to accomplish the sequence of operations. We assume that some of the operations will be performed on one or more NC machines.

2. *Part programming*. A part programmer plans the process for the portions of the job to be accomplished by NC. Part programmers are knowledgeable about the machining process and they have been trained to program for numerical control. They are responsible for planning the sequence of machining steps to be performed by NC and to document these in a special format. There are two ways to program for NC:

Manual part programming

Computer-assisted part programming

In manual programming, the machining instructions are prepared on a form called a part program manuscript. The manuscript is a listing of the relative cutter/work piece positions which must be followed to machine the part. In computer-assisted part programming, much of the tedious computational work required in manual part programming is transferred to the computer. This is especially appropriate for complex work piece geometries and jobs with many machining steps. Use of the computer in these situations results in significant savings in part programming time.

3. *Tape preparation*. A punched tape is prepared from the part programmer's NC process plan. In manual part programming, the punched tape is prepared directly from the part program manuscript on a typewriter like device equipped with tape punching capability. In computer-assisted part programming, the computer interprets the list of part programming instructions, performs the necessary calculations to convert this into a detailed set of machine tool motion commands, and then controls a tape punch device to prepare the tape for the specific NC machine.

4. *Tape verification*. After the punched tape has been prepared, a method is

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usually provided for checking the accuracy of the tape. Some times the tape is checked by running it through a computer program which plots the various tool movements (or table movements) on paper. In this way, major errors in the tape can be discovered. The "acid test" of the tape involves trying it out on the machine tool to make the part. A foam or plastic material is sometimes used for this tryout. Programming errors are not uncommon, and it may require about three attempts before the tape is correct and ready to use.

5. *Production*. The final step in the NC procedure to use the NC tape in production. This involves ordering the raw workparts specifying and preparing the tooling and any special fixturing that may be required, and setting up The NC machine tool for the job. The machine tool operator's function during production is to load the raw workpart in the machine and establish the starting position of the cutting tool relative to the workpiece. The NC system then takes over and machines the part according to the instructions on tape. When the part is completed, the operator removes it from the machine and loads the next part.

NC COORDINATE SYSTEMS

In order for the part programmer to plan the sequence of positions and movements of the cutting tool relative to the workpiece, it is necessary to establish a standard axis system by which the relative positions can be specified. Using an NC drill press as an example, the drill spindle is in a fixed vertical position, and the table is moved and controlled relative to the spindle. However, to make things easier for the programmer, we adopt the viewpoint that the workpiece is stationary while the drill bit is moved relative to it. Accordingly, the coordinate system of axes is established with respect to the machine table.

Two axes, x and y, are defined in the plane of the table, as shown in Figure . The z axis is perpendicular to this plane and movement in the z direction is controlled by the vertical motion of the spindle. The positive and negative directions of motion of tool relative to table along these axes are as shown in Figure 7. A. NC drill presses are classified as either two-axis or three-axis machines, depending on whether or not they have the capability to control the z axis.

A numerical control milling machine and similar machine tools (boring mill.

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for example) use an axis system similar to that of the drill press. However, in addition to the three linear axes, these machines may possess the capacity to control

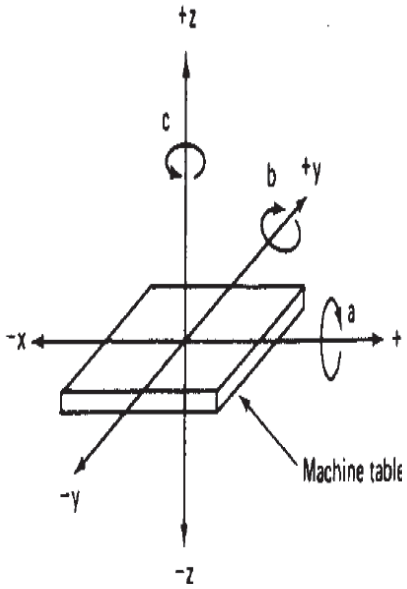


FIGURE NC machine tool axis system for milling and drilling operations.

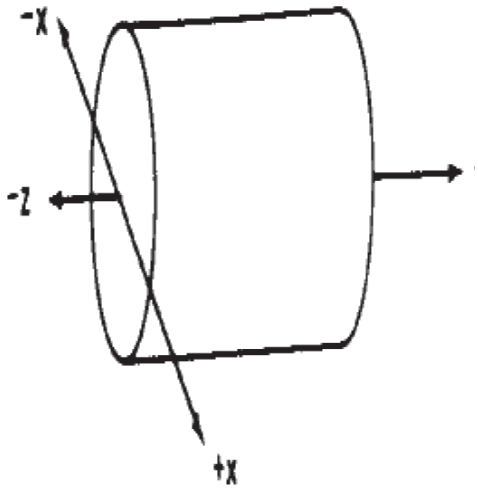


FIGURE NC machine tool axis system for turning operation.

one or more rotational axes. Three rotational axes are defined in NC: the a, b, and c axes. These axes specify angles about the x, y, and z axes, respectively. To distinguish positive from negative angular motions, the "right-hand rule" can be used. Using the right hand with the thumb pointing in the positive linear axis

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direction (x, y, or z), the fingers of the hand are curled to point in the positive rotational direction.

For turning operations, two axes are normally all that are required to command the movement of the tool relative to the rotating work piece. The z axis is the axis of rotation of the work part, and x axis defines the radial location of the cutting tool. This arrangement is illustrated in Figure.

The purpose of the coordinate system is to provide a means of locating the tool in relation to the work piece. Depending on the NC machine, the part programmer may have several different options available for specifying this location.

Fixed zero and floating zero

The programmer must determine the position of the tool relative to the origin (zero point) of the coordinate system. NC machines have either of two methods for specifying the zero point. The first possibility is for the machine to have a fixed zero. In this case, the origin is always located at the same position on the machine. Usually, that position is the southwest comer (lower left-hand comer)of the table and all tool locations will be defined by positive x and y coordinates.

The second and more common feature on modern NC machines allows the machine operator to set the zero point at any position on the machine table. This feature is called floating zero. The part programmer is the one who decides where the zero point should be located. The decision is based on part programming convenience. For example, the work part may be symmetrical and the zero point should be established at the center of symmetry.

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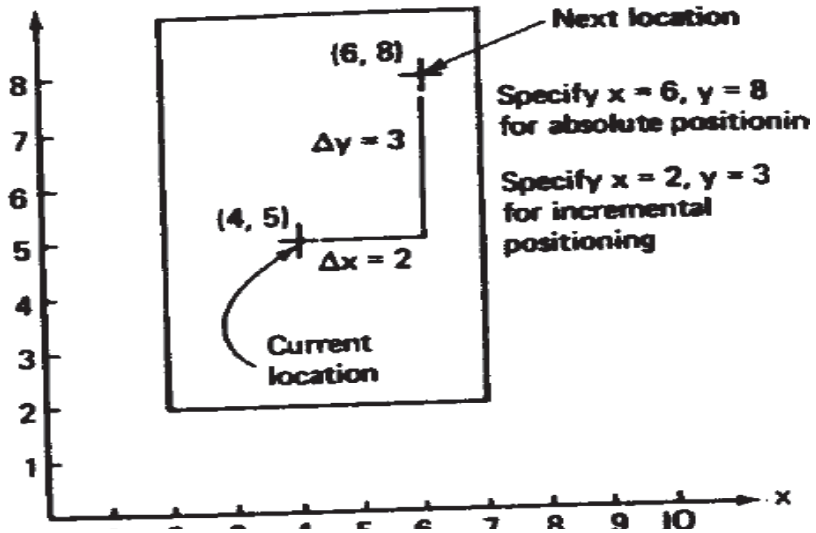


FIGURE Absolute versus incremental positioning.

The location of the zero point is communicated to the machine operator. At the beginning of the job, the operator moves the tool under manual control to some "target point" on the table. The target point is some convenient place on the work piece or table for the operator to position the tool. For example, it might be a predrilled hole in the work piece. The target point has been referenced to the zero point by the part programmer. In fact, the programmer may have selected the target point as the zero point for tool positioning. When the tool has been positioned at the target point, the machine operator presses a "zero" button on the machine tool console, which tells the machine where the origin is located for subsequent tool movements.

Absolute positioning and incremental positioning

Another option sometimes available to the part programmer is to use either an absolute system of tool positioning or an incremental system. Absolute positioning means that the tool locations are always defined in relation to the zero point. If a hole is to be drilled at a spot that is 8 in. above the x axis and 6in. to the right of the y axis, the coordinate location of the bole would be specified as x = +6.000 and y = +8.000. By contrast, incremental positioning means that the next tool location must be defined with reference to the previous tool location. If in our drilling example, suppose that the previous hole had been drilled at an absolute

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position of x = +4.000 and y = +5.000. Accordingly, the incremental position instructions would be specified as x = +2.000 and y = +3.000 in order to move the drill to the desired spot. Figure illustrates the difference between absolute and incremental positioning.

NC MOTION CONTROL SYSTEMS

In order to accomplish the machining process, the cutting tool and workpiece must be moved relative to each other. In NC, there are three basic types of motion control systems: -

1. Point-to-point
2. Straight cut
3. Contouring

Point-to-point systems represent the lowest level of motion control between the tool and workpiece. Contouring represents the highest level of control.

Point-to-point NC

Point-to-point (PTP) is also sometimes called a positioning system. In PTP, the objective of the machine tool control system is to move the cutting tool to a predefined location. The speed or path by which this movement is accomplished is not import in point-to-point NC. Once the tool reaches the desired location, the machining operation is performed at that position.

NC drill presses are a good example of PTP systems. The spindle must first be positioned at a particular location on the work piece. This is done under PTP control. Then the drilling of the hole is performed at the location, and so forth. Since no cutting is performed between holes, there is no need for controlling the relative motion of the tool and work piece between hole locations. Figure illustrates the point-to-point type of control.

Positioning systems are the simplest machine tool control systems and are therefore the least expensive of the three types. However, for certain processes, such as drilling operations and spot welding, PIP is perfectly suited to the task and any higher level of control would be unnecessary.

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Straight-cut NC

Straight-cut control systems are capable of moving the cutting tool parallel to one of the major axes at a controlled rate suitable for machining. It is therefore appropriate for performing milling operations to fabricate workpieces of rectangular configurations. With this type of NC system it is not possible to combine movements in more than a Single axis direction. Therefore, angular cuts on the workpiece would not be possible. An example of a straight-cut operation is shown in Figure.

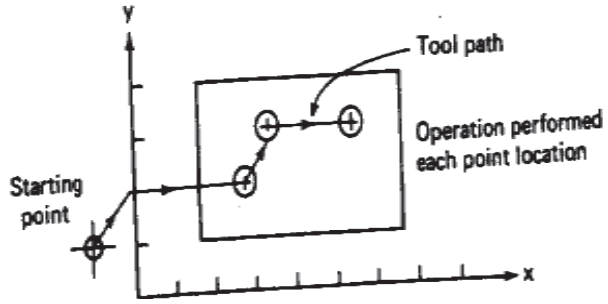


FIGURE Point-to-point (positioning) NC system.

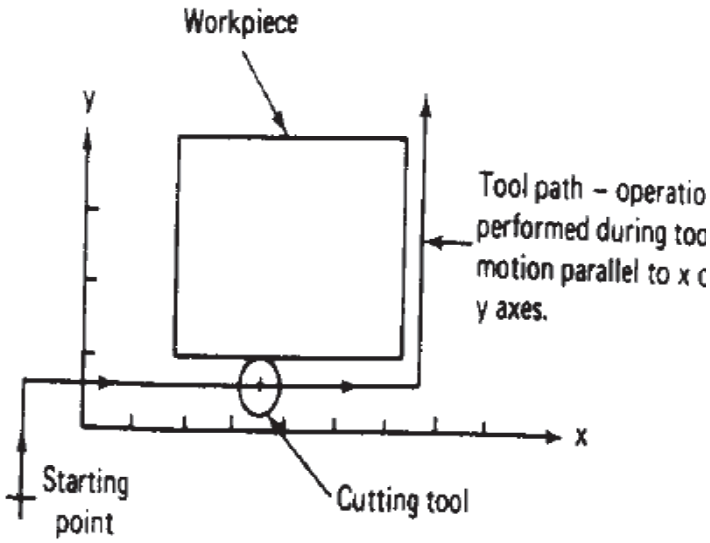


FIGURE Straight-cut system.

An NC machine capable of straight cut movements is.-also capable of PTP movements.

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Contouring NC

Contouring is the most complex, the most flexible, and the most expensive type of machine tool control. It is capable of performing both PTP and straight-cut operations. In addition, the distinguishing feature of contouring NC systems is their capacity for simultaneous control of more than one axis movement of the machine tool. The path of the cutter is continuously controlled to generate the desired geometry of the workpiece. For this reason, contouring systems are also called continuous-path NC systems. Straight or plane surfaces at any orientation, circular paths, conical shapes, or most any other mathematically definable form are possible under contouring control. Figure illustrates the versatility of continuous path NC. Milling and turning operations are common examples of the use of contouring control.

In order to machine a curved path in a numerical control contouring system, the direction of the feed rate must continuously be changed so as to follow the path. This is accomplished by breaking the curved path into very short straight-line segments that approximate the curve. Then the tool is commanded to machine each segment in succession. What results is a machined outline that closely approaches

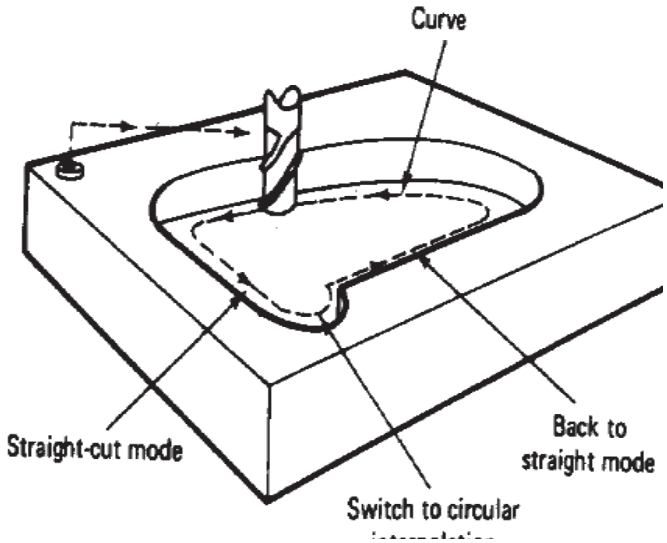


FIGURE Contouring (continuous path) NC system for two-dimensional operations.

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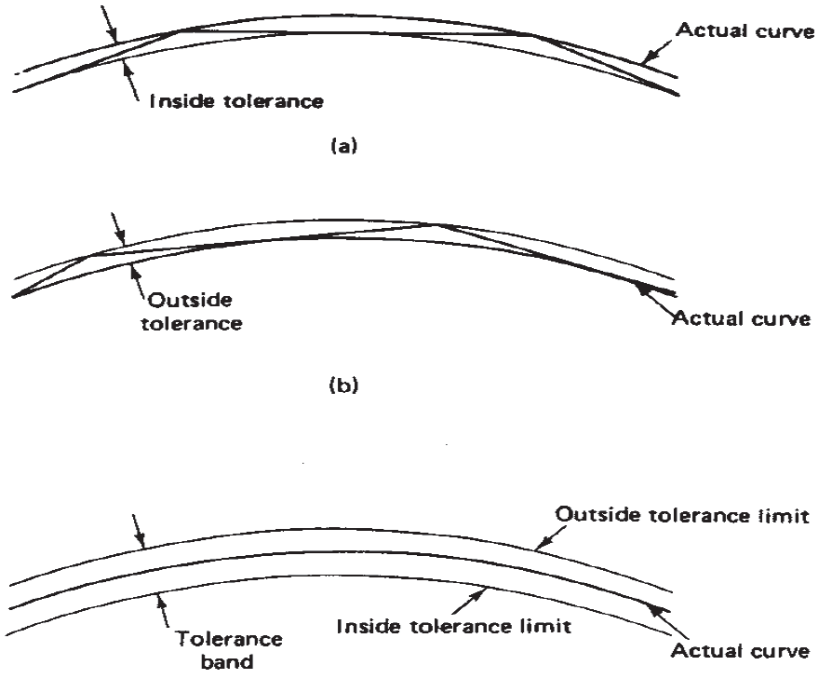


FIGURE Approximation of a curved path in NC by a series of straight-line segments.

The accuracy of the approximation is controlled by the "tolerance" between the actual curve and the maximum deviation of the straight-line segments. In (a), the tolerance is defined on the inside of the curve. It is also possible to define the tolerance on the outside of the curve, as in (b). Finally, the tolerance can be specified on both inside and outside, as shown in (c).

the desired shape. The maximum error between the two can be controlled by the length of the individual line segments, as illustrated in Figure.

APPLICATIONS OF NUMERICAL CONTROL

Numerical control systems are widely used in industry today, especially in the metalworking industry. By far the most common application of NC is for metal cutting machine tools. Within this category, numerically controlled equipment has been built to perform virtually the entire range of material removal processes, including:

Milling

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Drilling and related processes

Boring

Turning

Grinding

Sawing

Within the machining category, NC machine tools are appropriate for certain jobs and inappropriate for others. Following are the general characteristics of production jobs in metal machining for which numerical control would be most appropriate:

1. Parts are processed frequently and in small lot sizes.

2. The part geometry is complex.

3. Many operations must be performed on the part in its processing.

4. Much metal needs to be removed.

5. Engineering design changes are likely.

6. Close tolerances must be held on the workpart.

7. It is an expensive part where mistakes in processing would be costly.

8. The parts require 100% inspection

It has been estimated that most manufactured parts are produced in lot sizes of 50 or fewer. Small-lot and batch production jobs represent the ideal situations for the application of NC. This is made possible by the capability to program the NC machine and to save that program for subsequent use in future orders. If the NC programs are long and complicated (complex part geometry, many operations, much metal removed), this makes NC all the more appropriate when compared to manual methods of production. If engineering design changes or shifts in the production schedule are likely, the use of tape control provides the flexibility needed to adapt to these changes. Finally, if quality and inspection are important issues (close tolerances, high part cost, 100% inspection required), NC would be most suitable, owing to its high accuracy and repeatability.

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In order to justify that a job be processed by numerical control methods, it is not necessary that the job possess every one of these attributes. However, the more of these characteristics that are present, the more likely it is that the part is a good candidate for NC.

In addition to metal machining, numerical control has been applied to a variety of other operations. The following, although not a complete list, will give the reader an idea of the wide range of potential applications of NC:

Pressworking machine tools

Welding machines

Inspection machines

Automatic drafting

Assembly machines

Tube bending

Flame cutting

Plasma arc cutting

Laser beam processes

Automated knitting machines

Cloth cutting

Automatic riveting

Wire-wrap machines

Advantages of NC

Following are the advantages of numerical control when it is utilized in the type of production jobs described.

1. *Reduced nonproductive time*. Numerical control has little or no effect on the basic metal, cutting (or other manufacturing) process. However; NC can increase the proportion of time the machine is engaged in the actual process. It accomplishes this by means of fewer setups, less time in setting up, reduced work piece handling time, automatic tool changes on some machines, and so on.

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In a University of Michigan survey reported by Smith and Evans, a comparison was made between the machining cycle times for conventional machine tools versus the cycle times for NC machines. NC cycle times, as a percentage of their conventional counterparts, ranged from 35% for five-axis machining centers to 65% for presswork punching. The advantage for numerical control tends to increase with the more complex processes.

2. *Reduced fixturing*. NC requires fixtures which are simpler and less costly to fabricate because the positioning is done by the NC tape rather than the jig or fixture

3. *Reduced manufacturing lead time*. Because jobs can be set up more quickly with NC and fewer setups are generally required with NC, the lead time to deliver a job to the customer is reduced.

4. *Greater manufacturing flexibility*. With numerical control it is less difficult to adapt to engineering design changes alterations of the production schedule, changeovers in jobs for rush orders, and so on.

5. *Improved quality control*. NC is ideal for complicated workparts where the chances of human mistakes are high. Numerical control produces parts with greater accuracy, reduced scrap, and lower inspection requirements. 6. *Reduced inventory*. Owing to fewer setups and shorter lead times with numerical control, the amount of inventory carried by the company is reduced.

7. *Reduced floor space requirements*. Since one NC machining center can often accomplish the production of several conventional machines, the amount of floor space required in an NC shop is usually less than in a conventional shop.

Disadvantages of NC

Along with the advantages of NC, there are several features about NC which must be considered disadvantages:

1. *Higher investment cost*. Numerical control machine tools represent a more sophisticated and complex technology. This technology costs more to buy than its non-NC counterpart. The higher cost requires manufacturing managements to use these machines more aggressively than ordinary equipment. High machine utilization

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is essential on order to get reasonable returns on investment. Machine shops must operate their NC machines two or three sifts per day to achieve this high machine utilization.

2. *Higher maintenance cost*. Because NC is a more complex technology and because NC machines are used harder, the maintenance problem becomes more acute. Although the reliability of NC systems has been improved over the years, maintenance costs for NC machines will generally be higher than for conventional machine tools.

3. *Finding and/or training NC personnel*. Certain aspects of numerical control shop operations require a higher skill level than conventional operations. Part programmers and NC maintenance personnel are two skill areas where available personnel are in short supply. The problems of finding, hiring, and training these people must be considered a disadvantage to the NC shop.

The ladder logic diagram is an excellent way to represent the combinatorial 10 control problems in which the output variables are based directly on the values of inputs. As indicated by Example 9.6, it can also be used to display sequential control (timer) problems, although the diagram is somewhat more difficult to interpret and analyze for this purpose. The ladder diagram is the principal technique for setting up the control programs in PLCs.

PROGRAMMABLE LOGIC CONTROLLERS

A programmable logic controller (PLC) can be defined as a microcomputer-based controller that uses stored instructions in programmable memory to implement logic sequencing, timing, counting, and arithmetic functions through digital or anal input/output (I/O) modules, for controlling machines and processes. PLC applications are found in both the process industries and discrete manufacturing. Examples of applications in process industries include chemical processing, paper mill operations, and food production. PLCs are primarily associated with discrete manufacturing industries to control individual machines, machine cells, transfer lines, material handling equipment, and automated storage systems. Before the PLC was introduced around 1970 hard-wired controllers composed of relays, coils, counters, timers, and similar components were used to implement this type of

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industrial control. Today, many older pieces of equipment are being retrofitted with PLCs to replace the original hard wired controllers, often making the equipment more productive and reliable than when it was new.

In this section, we describe the components, programming, and operation of the PLC. Although its principal applications are in logic control and sequencing (discrete control), many PLCs also perform additional functions, surveyed later in the section.

Components of the PLC

A schematic diagram of a PLC is presented in Figure. The basic components of the PLC are the following: (1) processor, (2) memory unit, (3) power supply, (4) I/O module, and (5) programming device. These components are housed in a suitable cabinet designed for the industrial environment.

The processor is the central processing unit (CPU) of the programmable controller. It executes the various logic and sequencing functions by operating on the PLC inputs to determine the appropriate output signals. The CPU consists of one or more microprocessors similar to those used in PCs and other data processing equipment. The difference is that they have a real-time operating system and are programmed to facilitate I/O transactions and execute ladder logic functions. In addition, PLCs are hardened so that the CPU and other electronic components will operate in the electrically noisy environment of the factory.

Connected to the CPU is the PLC memory unit, which contains the programs of logic, sequencing, and I/O operations. It also holds data files associated with these programs, including I/O status bits, counter and timer constants, and other variable and parameter values. This memory unit is referred to as the user or application memory because its contents are entered by the user. In addition, the processor also contains the operating system memory, which directs the execution of the-control program and c60rdinates I/O operations. The operating system is entered by the PLC manufacturer and cannot be accessed or altered by the user.

A power supply of 115 V ac is typically used to drive the PLC (some units operate on 230 V ac). The power supply converts the 115 V ac into direct current

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(dc) voltages of ±5 V. These low voltages are used to operate equipment that may have much higher voltage and power ratings than the PLC itself. The power supply often includes a battery backup that switches on automatically in the event of an external power source failure.

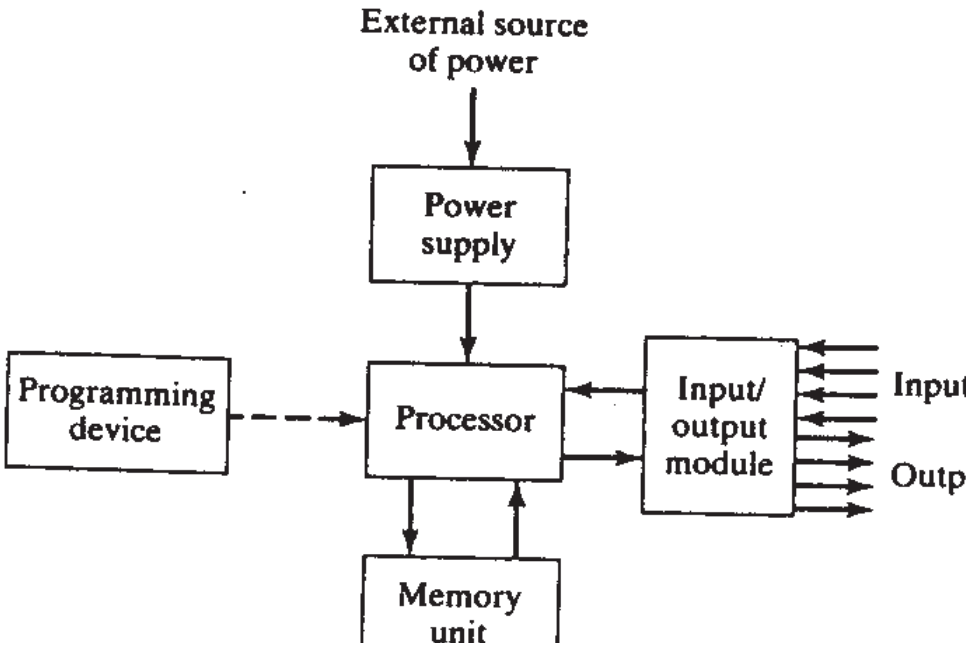


Figure Components of a PLC.

The input/output module provides the connections to the industrial equipment or process that is to be controlled. Inputs to the controller are signals from limit switches, push-buttons, sensors, and other on/off devices. Outputs from the controller are on/off signals to operate motors, valves, and other devices required to actuate the process. In addition, many PLCs are capable of accepting continuous signals from analog sensors and generating signals suitable for analog actuators. The size of a PLC is usually rated in terms of the number of its I/O terminals, as indicated in Table.

The PLC is programmed by means of a programming device. The programming device is usually detachable from the PLC cabinet so that it can be shared among different controllers. Different PLC manufacturers provide different devices, ranging from simple teach-pendant type devices, similar to those used in robotics, to special PLC programming keyboards and displays. Personal computers can also be used to program PLCs. A PC used for this purpose sometimes remains

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connected to the PLC to serve a process monitoring or supervisory function and for conventional data processing applications related to the process.

PLC Operating Cycle

As far as the PLC user is concerned, the steps in the control program are executed simultaneously and continuously. In truth, a certain amount of time is required for the PLC processor to execute the user program during one cycle of operation. The typical operating cycle of the PLC, called a scan, consists of three parts: (1) input scan, (2) program scan, and (3) output scan. During the input scan, the inputs to the PLC are read by the processor and the status of these inputs is stored in memory. Next, the control program is executed during the program scan. The input values stored in memory are used in the control logic calculations to determine the values of the outputs. Finally, during the output scan, the outputs are updated to agree with the calculated values. The time to perform the scan is called the scan time, and this time depends on the number of inputs that must be read, the complexity of control functions to be performed, and the number of outputs that must be changed. Scan time also depends on the clock speed of the processor. Scan times typically vary between 1 and 25 sec.

One of the potential problems that can occur during the scan cycle is that the value of an input can change immediately after it has been sampled. Since the program uses the input value stored in memory, any output values that are dependent on that input are determined incorrectly. There is obviously a potential risk involved in this mode of operation. However, the risk is minimized because the time between updates is so short that it is unlikely that the output value being incorrect for such a short time will have a serious effect on process operation. The risk becomes most significant in processes in which the response times are very fast and where hazards can occur during the scan time. Some PLCs have special features for making "immediate" updates of output signals when input variables are known to cycle back and forth at frequencies faster than the scan time.

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TABLE Typical Classification of PLCs by Number of Input/Output Terminals

PLC Size	I/O Count
Large PLC	≥ 1024
Medium PLC	< 1024
Small PLC	< 256
Micro PLC	≤ 32
Nano PLC	≤ 16

Additional Capabilities of the PLC

The PLC has evolved to include several capabilities in addition to logic control and sequencing. Some of these additional capabilities available on many commercial PLCs include

- *Analog control*. Proportional-integral-derivative (PID) control is available on some programmable controllers. These control algorithms have traditionally been implemented using analog controllers. Today the analog control schemes are approximated using the digital computer, with either a PLC or a computer process controller.
- *Arithmetic functions*. These functions are addition, subtraction, multiplication, and division. Use of these functions permits more complex control algorithms to be developed than what is possible with conventional logic and sequencing elements.
- *Matrix functions*. Some PLCs have the capability to perform matrix operations on stored values in memory. The capability can be used to compare the actual values of a set of inputs and outputs with the values stored in the PLC memory to determine if some error has occurred.
- *Data processing and reporting*. These functions are typically associated with business applications of PCs. PLC manufacturers

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have found it necessary to include these PC capabilities in their controller products, as the distinction between PCS and PLCs blurs.

Programming the PLC

Programming is the means by which the user enters the control instructions to the PLC through the programming device. The most basic control instructions consist of switching, logic, sequencing, counting, and timing. Virtually all PLC programming methods provide instruction sets that include these functions. Many control applications require additional instructions to accomplish analog control of continuous processes, complex control logic, data processing and reporting, and other advanced functions not readily performed by the basic instruction set. Owing to these differences in requirements, various PLC programming languages have been developed. A standard for PLC programming was published by the International Electro technical Commission in 1992, entitled International Standard for Programmable Controllers (IEC 1131-3). This standard specifies three graphical languages and two text-based languages for programming PLCs, respectively: (1) ladder logic diagrams, (2) function block diagrams, (3) sequential functions charts. (4) instruction list, and (5) structured text. Table 9.9 lists the five languages along with the most suitable application of each. IEC 1131-3 also states that the five languages must be able to interact with each other to allow for all possible levels of control sophistication in any given application.

TABLE Features of the Five PLC Languages Specified in the IEC 1131-3 Standard

Language	Abbreviation	Type	Applications Best Suited for
Ladder logic diagram	(LD)	Graphical	Discrete control
Function block diagram	(FBD)	Graphical	Continuous control
Sequential function chart	(SFC)	Graphical	Sequencing
Instruction list	(IL)	Textual	Discrete control
Structured text	(ST)	Textual	Complex logic, computations, etc.

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Ladder Logic Diagram. The most widely used PLC programming language today involves ladder diagrams (LDs), examples of which are shown in several previous figures. Ladder diagrams are very convenient for shop personnel who are familiar with ladder and circuit diagrams but may not be familiar with computers and computer programming. To use ladder logic diagrams, they do not need to learn an entirely new programming language.

Direct entry of the ladder logic diagram into the PLC memory requires the use of a keyboard and monitor with graphics capability to display symbols representing the components and their interrelationships in the ladder logic diagram. The PLC keyboard is often designed with keys for each of the individual symbols. Programming is accomplished by inserting the appropriate components into the rungs of the ladder diagram. The components are of two basic types: contacts and coils, as described in Section 9.2. Contacts represent input switches, relay contacts, and similar elements. Coils represent loads such as motors, solenoids, relays, timers, and counters. In effect, the programmer inputs the ladder logic circuit diagram rung by rung into the PLC memory with the monitor displaying the results for verification.

Function Block Diagrams. A function block diagram (FED) provides a means of inputting high-level instructions. Instructions are composed of operational blocks. Each block has one or more inputs and one or more outputs. Within a block, certain operations take place on the inputs to transform the signals into the desired outputs. The function blocks include operations such as timers and counters, control computations using equations (e.g., proportional-integral-derivative control), data manipulation, and data transfer to other computer-based systems. We leave further description of these function blocks to other references, such as Hughes and the operating manuals for commercially available PLC products.

Sequential Function Charts. The sequential function chart (SFC, also called the Grafcet method) graphically displays the sequential functions of an automated system as a series of steps and transitions from one state of the system to the next. The sequential function chart is described in Boucher . It has become a standard method for documenting logic control and sequencing in much of Europe. However, its use in the United States is more limited, and we refer the reader to the cited

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reference for more details on the method.

Instruction List. Instruction list (IL) programming also provides a way of entering the ladder logic diagram into PLC memory. In this method, the programmer uses a low-level computer language to construct the ladder logic diagram by entering statements

TABLE Typical Low-Level Language Instruction Set for a PLC

STR	Store a new input and start a new rung of the ladder.
AND	Logical AND referenced with the previously entered element. This is interpreted as a series circuit relative to the previously entered element.
OR	Logical OR referenced with the previously entered element. This is interpreted as a parallel circuit relative to the previously entered element.
NOT	Logical NOT or inverse of entered element.
OUT	Output element for the rung of the ladder diagram.
TMR	Timer element. Requires one input signal to initiate timing sequence. Output is delayed relative to input by a duration specified by the programmer in seconds. Resetting the timer is accomplished by interrupting (stopping) the input signal.
CTR	Counter element. Requires two inputs: One is the incoming pulse train that is counted by the CTR element, the other is the reset signal indicating a restart of the counting procedure.

that specify the various components and their relationships for each rung of the ladder diagram. Let us explain this approach by introducing a hypothetical PLC instruction set. Our PLC "language" is a composite of various manufacturers' languages. It contains fewer features than most commercially available PLCs. We assume that the programming device consists of a suitable keyboard for entering the individual components on each rung of the ladder logic diagram. A monitor capable of displaying each ladder rung (and perhaps several rungs that precede it) is useful to verify the program. The instruction set for our PLC is presented in Table with a concise explanation of each instruction.

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