1

Introduction

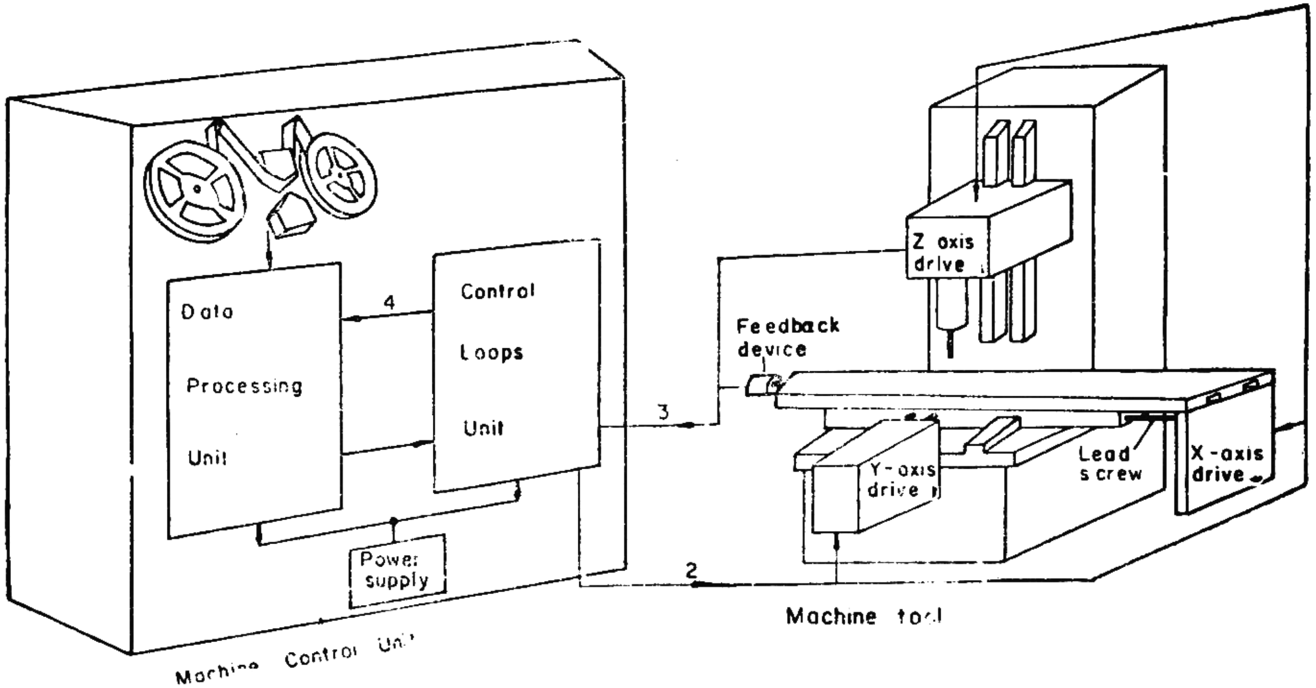
1-1. Defintions and Basic Information

Controlling a machine tool by means of prepared program, which consists of blocks, or series of numbers, is know as numerical control, or N/C. These numbers define the required position of each slide, its feeds, cutting speeds, etc. Those numbers which define the part dimensions are taken from a drawing of the machined product. In manufacturing of more complicated parts, the system has to calculate automatically additional data points, which is done yb means of an interpolator.

Taking into consideration the above, the simplest definition of numerical control is that of the EIA (Electronic Industries Association).

> "A system in which actions are controlled by the direct insertion of numerical data at some point. The system must automatically interpret at least some portion of this data."

In a typical N/C system the numerical data which is required for producing a part is maintained on a punched tape. The data is arranged in a form of blocks of information, where each block contains the numerical data information required to produce one segment of the workpiece. The punched tape is moved forward by one block each time a cutting of a segment is completed. The block contains, in coded form, all the information needed for processing a segment of the workpiece, as the segment length, its cutting speed, feed, etc. Dimensional information (length, width and radii of circles) and the contour form (linear, circular or other) have to be taken from the drawing. Dimensions are given separately for each axis of motion (X, Y, etc.). Cutting speed, feed and auxiliary



(1) Desired direction, position, feed (axes velocity) and auxiliary functions. (2) Axes feed (velocity) and stepping commands. (3) Actual velocity and position information. (4) Starting and termination signals of data reading.

Fig. 1-1. Numerical Control System.

functions (coolant on and off, spindle direction, clamp, gear changes, etc.) are programmed according to surface finish and tolerance requirements.

Preparing the data for N/C machine tool requires a parts programmer. The parts programmer must possess knowledge and experience in mechanical engineering fields. Knowledge of tools, cutting fluids, fixture design techniques, use of machineability data and process engineering, are all of considerable importance. The part programmer must be familiar with the functions of N/C processes. He also has to decide on the optimal sequence of operations and to write a program in manual or in computer-based language, as APT. His program is punched on a tape by means of a special perforating device (Flexowriter) or with the aid of a computer.

The N/C system has to read and decode the tape's information, to provide the decoded instructions to the control loops of the machine axes-of-motion, and to control the machine tool actions. The system also has to advance the tape each time the previous instructions were fulfilled, that is at the end of each segment of the workpiece.

A N/C machine-tool system contains the Machine Control Unit (MCU) and the machine tool itself, as is shown in Fig. 1-1. The MCU may be considered to consist of two main units. The

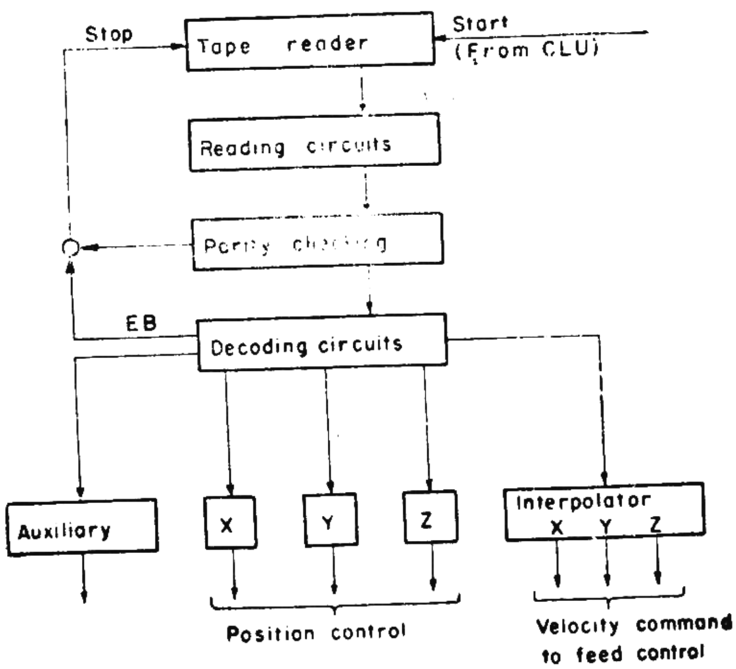


Fig. 1-2. The Data Processing Unit.

Data Processing Unit (DPU) and the Control Loops Unit (CLU). The DPU is that portion of the N/C system in which the coded information received from a tape reader passes through decoding circuits and gives data to the CLU. Such data contains the required new position of each axis, its direction of motion, feed (if necessary) and auxiliary function control-signals. On the other hand, the CLU provides a signal announcing that the previous operation is completed and that the DPU has to begin reading a set of new data. The CLU operates the driving devices of the machine lead screws, and receives feedback signals about the actual position and velocity of each one of the axes. Each lead screw which is under control is equipped with a separate driving device, and with a separate feedback device (where the latter exists only in a closed-loop system).

Thus, we see that a DPU (Fig. 1-2) includes, at least, the following working parts :

Data input device, such as punched-tape reader.

Data reading circuits and parity checking logic.

Decoding circuits for distributing data among the controlled axes.

Interpolator, which supplies current velocity commands between two data points taken from the drawing.

A CLU (Fig. 1-3) consists of the following circuits :

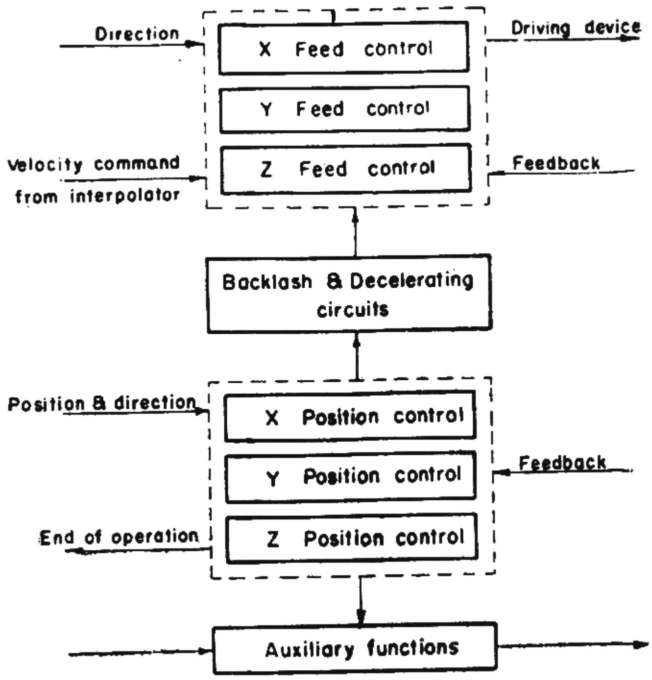


Fig. 1-3. The Control Loops Unit.

Position control loops for all the axes of motion; each axis has a separate control loop.

Velocity control loops, where feed-control is required

Decelerating and backlash takeup circuits

Auxiliary functions control, such as coolant on/off, gear changes, or spindle on/off control.

By *axis of motion* we mean an axis in which the cutting tool can be moved with respect to a workpiece. This movement is achieved by the motion of the machine tool slides. The main three axes of motion will be referred to as X, Y and Z axes. The X and Y axes of motion are horizontal and at right angles to each other. The X-axis is from left to right, and the Y-axis is from front to back. The Z-axis of motion is perpendicular to both X and Y, in order to create a right-hand co-ordinate system, as it may be seen from Fig. 1-4. A positive command at the Z-axis moves the cutting tool away from the workpiece. The location of the origin ($X=Y=Z=0$) may be a fixed or an adjustable one.

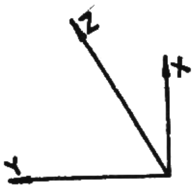


Fig. 1-4. A Right-Hand Coordinate System·

If, in addition to the primary slide motions, there exist secondary linear slide motions, they may be designated U, V and W. Rotary motions around the axes parallel to X, Y and Z are designated a, b, and c respectively.

In N/C machine tools, not as in conventional machines, each axis of motion is equipped with a separate driving device which replaces the handwheel. The driving device may be a dc motor, a hydraulic system, or a stepping motor, where the type selected is determined mainly by power requirmeents of the machine.

Compared with a conventional machine tool, the N/C system is taking the place of the hand-actions of the operator. It does not substitute his brain, since the N/C is not a mechanical thinking device. All thinking operations that were formerly done by the operator are now registered on the punched tape.

Inspection of the product dimensions is done in a typical N/C system by means of a feedback device. In hand operation the producing of a part is done by moving a cutting tool around a workpiece by means of handwheels, which are guided by an operator. Contour cuttings are done by an expert operator on sight. On the other hand, the operator of N/C machine tools has not to be a skilled machinist. He has only to monitor the operation of the machine, to operate the tape reader and usually replace the workpiece. But as he has to work with a sophisticated and expensive system—intelligence, clear thinking and especially good judgment are essential qualifications of the operator.

The binary number system has now become an important, element in modern technology and is now extensively used in digital computers and in N/C of various machine tools. But to understand what is happening now, it is desired to go backward in time to the beginnings of the concepts of number systems, control and computers. It can be said that one of the first using the binary system was Francis Bacon who used a binary code for conveying secret messages. Later J.M. Jacquard designed a system of punched cards to operate looms, but this method is already known for nearly 2,500 years and used till today in a primitive form in the manufacture of Persian rugs.

One of the earliest efforts at automatic control occurred around 1650 in Holland when rotating drums were equipped with pins for the automatic ringing of chimes. These were later miniaturized and perfected in the popular music boxes.

The first automatic player piano, patented by M. Fourneaux in 1863, utilized a 30 cm. (12 in.) wide roll of paper, perforated so that air could be drawn through the holes to actuate the appropriate keys.

The earliest player pianos could produce notes only of uniform intensity. By 1930, however, they had been so developed as to simulate pedal control, amplify variations and generally to produce music of the coloration that distinguishes one pianist from another.

One of the last models produced contained eight extra-hole channels on each side of the 82 regular keyboard channels. These extra channels were able to control the sound intensity, tone pedal actuation, tape speed and several other variables.

This parallel to the later development of machine-tool N/C is close and significant.

In the early 1700's, M. Falcon invented a perforated-card-controlled knitting machine. Each of many cards was chain-synchronized to the action of the knitting machine. Each hole in a given card set up a mechanical linkage which caused a needle associated with a particular column on the card to pull a specific colour of thread through the cloth at that location. Falcon's invention was inherently limited to low production.

As mentioned, in 1807, J.M. Jacquard invented an improved card-controlled knitting and weaving machine permitting higher output and lower unit costs, which continues to be widely used in modern production. For higher volume production, knitting machines utilized gearlike discs with patterns of peripheral teeth. Such machines are analogues to automatic screw machines or tracer machines in the metal cutting industries.

In the late 1800's, Charles Babbage designed the first sophisticated digital computer; its development, however, was never completed. The faster, more accurate and more flexible computer appeared in 1945 when the ENIAC was developed for the Army Ordnance Department. This was a rather slow machine without internally stored programs, and, therefore, had to be sequenced from external information provided by the input medium.

In the early 1900's Herman Hollerith had developed a punched-card system of data storage. During World War II, John von Neumann designed the stored-program digital computer which has now become an essential part of our commercial and industrial complex.

1-2. Need and Advantages of N/C

Before, during and especially after World War II, the U.S. Air Force felt more and more the need to manufacture complicated but accurate aircraft parts, which could only with difficulty be produced by the conventional machine tools. The first steps in development of a suitable machine tool was done at the Parsons Company in Traverse City, Michigan, and it was accomplished by the Massachusetts Institute of Technology (MIT), Servomechanism Laboratory. By 1952 these research efforts had produced a N/C milling machine with three-axes control, which is believed to be the first successful N/C machine.

Thus, we see that the main reasons for the need to develop control systems for machine tools are the high accuracy in the manufacturing of complicated control parts, and saving of working time.

The accuracy is most important when two parts that have to be adapted one to another are produced, as for example a cyclinder and a piston of a motor, and also for the manufacture of exchangeable parts especially in the aircraft and motor industries. Producing a part that has to be cut within an accuracy of 0·01 mm or better may take a considerable amount of time on the part of the worker, who has to stop the cutting process frequently and measure the part dimensions in order to ensure that he did not over-cut the material. It was proved that the time wasted on measurements is frequently 70 to 80 per cent of the total working time. N/C machines are saving that time, while keeping limits of the accuracy of the parts or even improving it.

A futher saving of time is achieved while passing from one operation to another during the workpiece cutting. On manual working of a machine tool, the work must be stopped at such points, since the operator has to go over to next step. The rate of production is decreased as well during the time because of the worker's fatigue. In N/C systems these problems do not exist at all, and moreover—as in N/C machines the accuracy is repeatable, time is saved for inspection too.

Contour cuttings in three dimensions, or often even in two dimensions, are not to be made on manual operation. Even when it is possible, the worker has to operate the two handwheels of the table simultaneously while keeping the required accuracies. It is obvious that in such work the N/C machine saves a considerable amount of time and improves the accuracy compared with manual operation.

The question is, if before the N/C machine generation there was any controlled machine tool which fulfilled the above mentioned needs ? It is well known that controlled copying machines already exist for many years. This machine includes a stylus that moves on a master-copy, while the stylus is fitted through an arm to the cutting tool which produces the part. The stylus may be directly connected to cutting tool or through a pantograph. The main disadvantage of this copying method is the time spent in producing the master-copy, as it is made without automation and it has to be produced to a special high degree of accuracy.

Automatic control is also applied to transfer machines. The machines stand in line, while the product is transferred from one machine to the other, while each machine is performing a certin cycle of operations. The cycle of operations is simple and fixed and the process is completely automatic. This system has the following disadvantages :

(*a*) Quite high investment in the machines and equipment.

(*b*) A long preparation time for each production series.

(*c*) Inflexibility of the process, since each machine is planned to make a certain fixed cycle of operations. If the part configuration is changed—the machine adjustment must be rebuilt or altered.

(*d*) A big stock of parts is required for the process, since a part is maintained in each machine.

(*e*) Much longer production time.

The transfer line is suitable only for mass production, where parts are produced in millions, while in producing small quantities the machine has to be designed to be able to make many operations, and this requires are high degree of flexibility.

The machine's high flexibility is of a very high importance in modern industry and especially for aircrafts manufacture. Here the production is usually made in small quantities. Due to the rapid technological changes, a series of only maximum hundreds of the same model of planes are built. This means that the N/C machine has to be economical in use especially for small quantity of parts. When a new product is required, only the part-program has to be changed, which is a relatively simple solution for a small production series.

The automatic lathe, which is quite flexible, is already in use for many years. The setup of the required dimensions of the parts are established by pairs of microswitches and stoppers, one pair for each segment termination. The correct placement of a microswitch establishes the dimensions and tolerance of the part. The required feed, cutting speed and auxiliary functions are programmed, in an appropriate code, on a plug-board. The plug-board (shown in Fig. 2-8, Chapter 2) is made of matrix of sockets, where information is "written" by means of plugs. Each row is referred to one segment of the workpiece The rows are scanned in sequence, hence the method is also called a sequence control, where the appropriate limiting switch provides the signal for proceeding to the next row. In this manner the scanning is advanced in the sequence necessary to accomplish the metal removal required to obtain the part configuration desired.

The sequence controlled automatic lathe is flexible, but its main disadvantage is that the limiting switches and stoppers for adapting the machine to produce a new product, requires many working hours and a highly skilled and experienced operator. In addition it should be noticed that, as the number of limiting switches and stoppers is limited, the maximum number of programmed operations of a part is also limited. The automatic lathe can be used for medium production series of 30 pieces or more, but will not be the ideal solution for small series of say 4 or 5 pieces. On the other hand, it has been found that in many cases it may be more economical to produce even one piece only by N/C machines than by conventional methods, as such a part is required from time to time.

In conclusion, the N/C machine tool has the following advantages, compared with other methods :

(*a*) A full flexibility ; a simple adaption for producing a new part.

(*b*) Accuracy is kept through all range of speeds and feeds ; the accuracy is repeatable.

(*c*) A shorter production time.

(*d*) Possibility of manufacturing a part of any contour (by a suitable N/C machine).

(*e*) An easy adjustment of the machine. Adjustment requires less time than in other methods.

(*f*) The need for a highly skilled and experienced operator is avoided.

(*g*) The operator has free time ; this time may be used for looking after other machine operations.

(*h*) It is economically worthwhile to use even for production of one part.

On the other hand, the main disadvantages of a N/C system are :

(*i*) A relatively high price.

(*ii*) More complicated maintenance ; a special maintenance crew is desirable.

(*iii*) A highly skilled and properly trained part programmer is needed.

Numerical control is applied today to drilling machine, lathes, boring machines, milling machines, flame cutters, rotary tables, grinders, etc.

1-3. Classification of N/C Systems

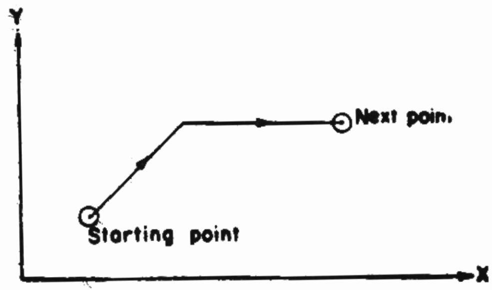
The classification of N/C machine tool systems can be done in four ways :

1. *According to the type of machine* : Point-to-point positioning and contouring (or continuous-path).
2. *According to the structure of control circuits* : Analogue or digital.
3. *According to the programming* : Incremental or absolute.
4. *According to the type of control loops* : Open-loop or closed-loop.

1-3·1. Point-to-point and Contouring

Point-to-point system. The simplest example of a point-to-point N/C machine tool is a drilling machine. In a drilling machine the workpiece is moved along the axes of motion until the centre of the hole to be drilled is exactly beneath the drill. Then the drill is automatically moved towards the workpiece (with a spindle speed and feed which can be controlled), the hole is drilled, and the drill moves out in a rapid traverse speed. The workpiece moves to a new point and the above sequence of actions is repeated. In more general terms a description of a point-to-point operation will be the the following :

The workpiece is moved with respect to the cutting tool until arriving at a numerically defined position and then the motion is stopped. The cutting tool performs its job when the axes are without motion, and then the workpiece moves to the next point, and the cycle is repeated.



1-5. Cutter path between the holes in a point-to-point system.

In a point-to-point system, the path of the cutting tool and its feed while travelling from one point to the next one are without any significance. Therefore, this system would require only position-loops for controlling the final position of the tool when reaching the place to be drilled. The path from the starting point to the final position is not controlled, as is illustrated in Fig. 1-5. The data for desired position is given by co-ordinate values and the resolution depends on the system.

Contouring systems. In contouring, or continuous-path, control of the cutting tool is performed while the axes of motion are moving, as, for example, in a milling machine. All axes of motion might move simultaneously, each one at a different speed, while this speed may be changed even within the path between two given points. For example, cutting of a circular contour requires a sine rate change of speed in one axis, while the speed of the other axis is changed at a cosine rate.

In contouring machines, the path of the cutting tool and its feed are establishing the desired contour of the part and at the same time the feed also affects the surface finish. Since, in this case, a feed error in an axis causes an error at the cutter path (Fig. 1·6), the system has to contain in addition to the position-control loops, velocity-control loops as well. Each axis of motion is equipped with a separate position loop and velocity-control loop for controlling the desired dimension and feed respectively. Dimensional information-command is given on the tape separately for each axis, and is fed through the DPU to the appropriate position loop, but the programmed feed is that of the contour, and has to be processed for providing the proper feed commands for each axis. This is done by means of an interpolator, which is a portion of the DPU and is used only in a contouring system.

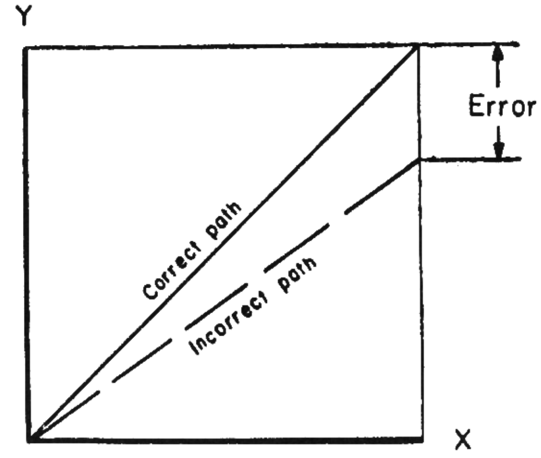


Fig. 1-6. A velocity error causes to a position error in a contouring system.

For illustrating the interpolator function, consider a two-axes system, where a straight cut is to be made along the path of Fig. 1-6, that is the X-axis must move p units simultaneously when q units actuate the Y-axis. The contour formed by the axes movement has to be cut in a feed rate of f length-units per second. The numerical data of p, q and f is programmed on the tape and is fed into the interpolator. The interpolator will then provide signals f_x and f_y, usually in a pulsed form, proportional to :

$$f_x = \frac{p.f}{\sqrt{p^2+q^2}} \qquad \ldots(1\text{-}1)$$

and

$$f_y = \frac{q.f}{\sqrt{p^2+q^2}} \qquad \ldots(1\text{-}2)$$

Thus we see that the interpolator function is to obtain intermediate data points lying between those taken from the drawing. In N/C systems, three types of interpolators exist : linear, circular and parabolic, where the most common in use are the linear and circular ones.

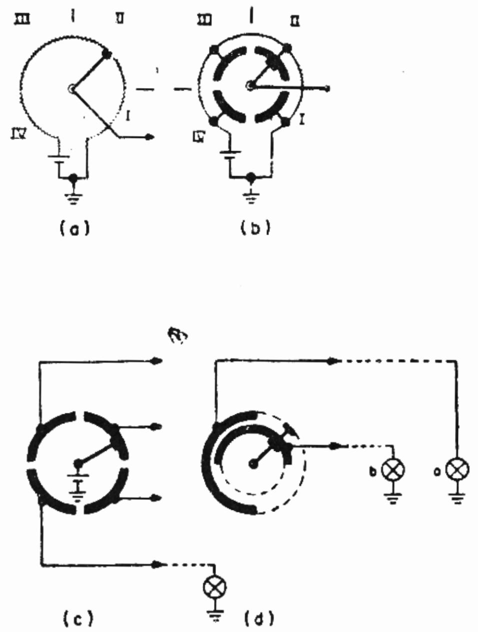
Straight-cut system. Some point-to-point machines are equipped with milling capabilities also. This leads us to a third type of control, in which a contouring control is done from point to point. This system is called a straight-cut system since the cutting tool can move only along straight lines which are parallel to the main axes of motion of the machine tool, as for example in a shaping machine. Cutting of the workpiece is done while the cutting tool is moving, but the latter can move along either the X, Y or Z axis. In a straight-cut system the feed is programmed on the tape, and may be selected by the programmer. In this system, velocity-control loops, for feed control of the axes of motion, are used, but they are relatively simple as they only have to establish the finished surface quality and not the dimensions of the part. Therefore, in this case an error of up to ± 10 per cent from the programmed feed is still permitted. An interpolator is not required for the straight-cut system as no simultaneous operation of the axes is necessary.

1·3·2. Analogue and digital control

Control systems may be divided into analogue and digital systems. In an analogue control system the quantities may be varied continuously, while in digital systems they are varied discreetly, such as the presence or absence of a quantity. The shortest cycle of presence-absence is the resolution of the digital system and establishes its accuracy. In digital systems of machine tools, each such cycle of information provides a voltage-pulse where each pulse represents a basic length unit which determines the system resolution. Typical basic length units are 0·001 inch or 0·01 mm. Therefore, theoretically, the digital system is of a finite accuracy, while the analogue information can accept any value. Actually, the accuracy achieved in the analogue system depends, of course, on the accuracy of the various components used to construct the electronic circuits, and on the precision of sensors which are used. Practically, in a digital system it is easier to obtain higher accuracies, as will be illustrated by the example below.

Let us consider a pointer which moves in a circle. The problem How to distinguish in which quadrant of the circle the pointer is positioned, and to transfer this information to a remote measuring system.

The simplest solution of this problem is to couple a circular potentiometer so that its slider moves together with the pointer, as is shown in Fig. 1-7(*a*). The resultant output voltage is transmitted by wire to the remote receiving station which is equipped with a suitable instrumentation for distinguishing the desired voltage-ranges. For example, if a battery of 6 volts is applied, and voltage at the receiving end is between 0 to 1·5 volts, the pointer is positioned in the 1st quadrant (I); if the voltage is between 1·5 to 3 volts the pointer is positioned in the 2nd quadrant (II), etc. The information transferred by this method is called analogue information, and the system is referred to as an analogue system.



(*a*) Analogue solution, (*b*) Digital solution.
(*c*) Binary solution. (*d*) Binary coded system.

Fig. 1-7. Quadrant distinguishing.

The main disadvantages of the analogue system are that changes in the voltage source or in the resistance of the transmission lines will cause errors in the decoding of the information at the receiving end, especially at cross-over points between the quadrants; *e.g.*, if the battery voltage is decreased by 25 per cent, the 4th quadrant will never be decoded and the system is completely out of order. To obtain an accuracy of 1 per cent, the voltage source and the line resistances are permitted to vary in less than 1 per cent, thus we see that in practice, high accuracies will be difficult to achieve in an analogue system.

An alternative method consists of replacing the potentiometer by a constant resistor network as is shown in Fig. 1-7(*b*). Since the resistances are of equal values, each quadrant is represented by a constant voltage, which is fixed within the quadrant range. The cross over from one quadrant to the second one is done by a ***jump***, which means a discreet change. The information transferred by this system is a ***digital*** information. It is apparent that this system is more reliable than the analogue one. If a battery of 6 volts is applied, the four quadrants are represented by the numbers 0, 2, 4 and 6 volts. The permitted error range can now be up to ± 1 volt, which is a large value as compared with the analogue system. But it should be noted that for the 4th quadrant (IV) it means that a maximum error of only 16 per cent is permitted at the voltage source, and this allowable error is decreased with the increasing of the desired distinguished ranges.

For increasing the allowed error range to ± 50 per cent in each one of the quadrants, the information may be transferred by the aid of 4 channels (in addition to a common line), as is shown in Fig. 1-7 (*c*). A voltage is appearing each time in only one of the channels, while the other channels are at 0 voltage. This form, in which the information can exist or not, is called a digital ***binary*** information. Four control lamps may be coupled to the channels, where only one of them will be turned on each time, according to the appropriate quadrant. This system is very reliable since now a discrimination between only two definite states is required; no voltage at all or enough voltage to turn on a lamp.

The disadvantage of the above described binary system is the increased number of transmission lines. This disadvantage may be partly overcome by using suitable combinations of the channel information, which requires a special kind of rotary switch, as is illustrated by Fig. 1-7 (*d*). As there are four possible combinations of voltage and no-voltage on two lines, the necessary information about possible positions can be transferred by two lines only. This form of transmitting a knowledge is called a digital ***binary coded*** information. Compared with the pure binary method, this system has the disadvantage that the information has to be decoded either by a decoding network, or by the operator with the aid of a suitable table like that shown in Table 1-1.

TABLE 1-1

Coded Information

Quadrant	*Lamps a*	*Lamps b*
I	0	0
II	0	1
III	1	1
IV	1	0

In Table 1-1, a "1" denotes a burning lamp, and a "0" refers to the dark state. The binary coded method is the most efficient and reliable one, hence is commonly used in digital systems.

Both digital and analogue controls are used in N/C systems of machine tools. To decide the control type may sometimes be a little difficult, as any digital control contains an anaglogue component and vice versa. The input to N/C systems is always digital, as the dimensions that are taken from the drawing are given in numbers, which is a digital form. On the other hand, the output of a N/C system is always analogue, as the slides of the machine tool are moving in a continuous and smooth form. Therefore, each one of the system types contains an analogue and digital information unit. However, the type of control, digital or analogue, is called by the type of information appearing at the control loop inputs. Whenever a sequence of pulses is applied—the control is digital, and if the input is continuously variable—the control is analogue. When the control is in a closed-loop form, it is obvious that the information received from the feedback measuring system has to be of the same nature as that which is applied at the loop input.

Henceforth, all N/C systems that will be discussed will be digital control systems.

1-3·3. Incremental and absolute systems

N/C systems may be further divided into incremental and absolute systems. An incremental system is one in which the reference point to the next instruction is the end point of the preceding operation. Each dimensional data is applied to the system as a distance-increment, measured from the preceding point at which the axis of motion was present ; *e.g.*, suppose that two holes have to be drilled. Their distances, as measured from the origin along the X-axis, are 20 and 50 mm respectively. The command for the second move would be to move by 30 mm (since the last position of the drill has remained at that point from the preceding operation, *i.e.* 20 mm from the origin).

An absolute system is one in which all moving commands are referred to one reference point, which is the origin, and will be called the zero point. All position commands are given as absolute distances from that zero point. Notice that in the previous example the second movement command would now be 50 mm. The zero point may be defined as a point outside the workpiece, or at a corner of the part. If a mounting fixture is used, it could be a point on the fixture or on the machine table.

The zero point may be either a floating or a fixed point. A zero floating point allows the operator, by pushing a button, to select arbitrarily the zero reference point at any point within the limits of the machine tool table. The control unit retains no information on the location of any previous zeros. The zero floating point permits the operator to locate quickly a fixture anywhere on the table of the machine.

When a N/C system has not a floating zero it might have alternatively a zero offset. In a zero offset system the zero point can be shifted to any point of the machine tool table, but the control unit retains information on the location of the fixed zero. The zero offset is done by manual dialing of co-ordinate values into the control unit. This information is stored and is added to (or subtracted from) the machine position thus altering the programmed path of the cutting tool.

As a matter of fact absolute systems may be sub-divided into a pure absolute and absolute programming systems. By the term *pure absolute* we mean a system in which both programmed dimensions and feedback signal are referred to a single point. It, therefore, requires a measuring device which produces information in absolute form. As an example of such a device consider the switch of Fig. 1-7 (*d*). By coupling it, for example, to a leadscrew of a moving axis, and regarding Table 1-1, we obtain an identification of the axis position, within one rotation of the leadscrew (of course the resolution is low). The pure absolute system is mainly used for rotary table control. Most of the so called absolute systems are not equipped with an absolute measuring device, but with an incremental measuring device, like the one shown in Fig. 1·8. It provides 4 voltage pulses per revolution. For getting information about the pointer position, a pulse counter has to be provided, but the measuring device itself does not supply this information. Since most absolute systems are of this type, henceforth the term "absolute system" will refer to an absolute programming system, in which all programmed dimensions refer to a single starting point.

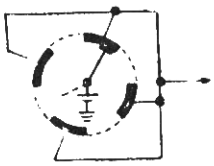


Fig. 1-8. Incremental measuring device.

The main advantage of the absolute system asc ompared with the incremental one, is in cases of interruptions that force the operator to stop the machine. By interruption we mean cutting tool breakage, manual interference, stopping the work for unprogrammed checking, etc. With an absolute system, in the case of an interruption, the machine table is manually moved and the cause of the interruption is eliminated. When restarting the program, the table is automatically returned to its last position (the punched tape is moved one block back), and the operation proceeds from the same place that it was interrupted. With an incremental system any time the work is interrupted, before switching on again, the operator must bring the tool manually to the exact place of the last operation in which the interruption occurred. This may mean attempting to bring a cutting tool back to a point with an accuracy of 0·01 mm or less. It would propably be more practical to go back to the starting point of the program and to repeat all operations prior to the place where the interruption occurred.

A further comparison between incremental and absolute systems will be discussed in Chapter 6.

Incremental systems are not often used for controlling point-to-point machine tools. It is estimated that considerably more than 90 per cent of point-to-point N/C machines presently installed use absolute programming. But on the other hand, incremental controls may be generally cheaper to build.

1·3·4. Open-loop and closed-loop systems

Every control process, and N/C system too, may bed esigned as an open- or a closed-loop control. The term open-loop control means that, since the loop is open there is no feedback and the action of the controller has no reference to the result it produces.

The open-loop N/C systems are always of digital type and are using stepping motors for driving the slides. A stepping motor (see Chapter 4) is defined as one whose output shaft rotates through a fixed angle in response to an input pulse. The stepping motors are the simplest way for converting digital electrical signals into proportional moment, and so they are a relatively cheap solution to the control problem. Since there is no check on the slide position, the system accuracy is solely a function of the motor's ability to step through the exact number of steps provided at the input.

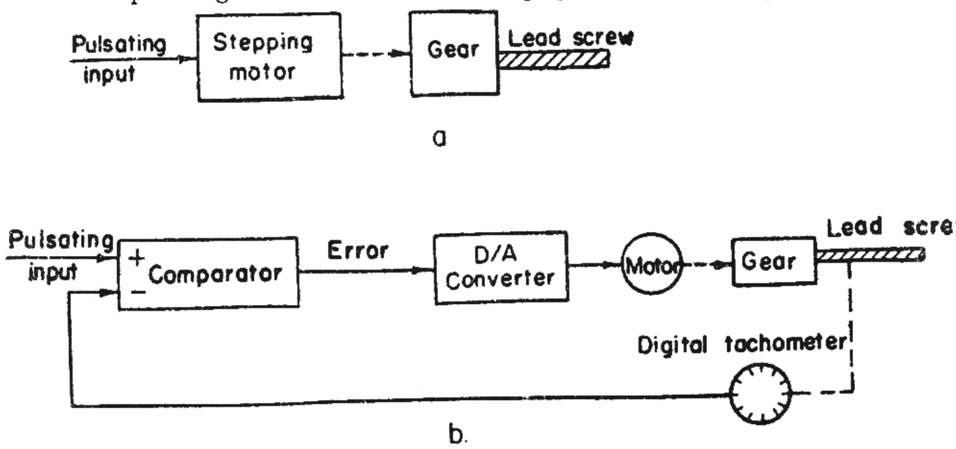


Fig. 1-9. Open-loop (*a*) closed-loop and (*b*) digital control.

Fig. 1·9 compares an open-loop and a closed-loop digital control for one axis of motion. The closed-loop control measures the axis actual position (and also its velocity, in contouring systems) and compares it with the desired reference position (and velocity, in contouring systems). The difference between the actual and the desired values is the error, and the control is designed in such a way as to eliminate or to reduce the error to a minimum. In this case the system is a negative-feeeback one.

In a digital control system the input and feedback signals may be sequences of pulses, each pulse representing a unit of length, say 0·01 mm, while the pulse rate is proportional to the axis velocity. The comparator correlates the two sequences and gives, by means of a digital-to-analogue (D/A) converter, a signal representing the position error of the system, which is used to drive a servomotor. The feedback device, which is denoted here as a digital tachometer, is mounted on the end of the leadscrew, and supplies a pulsating output. The rate of pulses per minute, provided by the digital tachometer is proportional to the rpm of the leadscrew. A digital tachometer may consist of a rotating disc divided into segments, which are opaque and transparent successively. A photocell and a lamp are placed in both sides of the disc. Each change in light intensity falling on the photocell when the disc rotates, provides an output pulse. Such a device is called an incremental encoder and is typically used in digital controls.

Extreme care must be taken during the design of a closed-loop control system. By increasing the amount of feedback signal (more pulses per one revolution of the leadscrew) the loop is made more sensitive. That is known as increasing the open-loop gain. By excessively increasing the open-loop gain the closed-loop system may become unstable, which should be avoided.

The design of control and choice of the loop type, to meet critical performance and cost specifications, require a knowledge of the nature of the controlled machine and load torque. The allowable positioning error, accuracy repeatability and response time, also have to be taken into consideration, where an optimum performance is required.

1·4. Data Feeding Methods

In any N/C machine tool system, the information required to produce a part has to be converted into a form that can be read by the N/C system. The converted information must be stored in a storage device, in such a way that it would be ready to be read when called upon by the N/C system. The storage device can be a punched tape, a magnetic tape, punched cards, or a command plug-board. In many N/C systems there is a possibility of inserting information manually as well, but care must be taken that such interruption between two successive commands is inserted only after the completion of the previous operation.

1·4·1. Punched tape

Feeding data to a N/C machine tool system by a punched tape is the most common method used. The tape may be a paper or a plastic tape, where the latter is used when the paper tape is liable to damage due to chips or other dirt. The tape is of standard one inch width with 8 tracks, or channels, of data punched along it, and an additional track of sprocket holes, punched at the same time as the data tracks. Three tracks are placed on one side of the sprocket channel and five on the other one as is shown in Fig. 1-10. By the unsymmetrical placement of the sprocket channel, the possibility of incorrect insertion of the tape in the tape-reader is reduced. There can be a maximum of 3 holes in a row. Such a row of holes, representing a decimal digit or other symbol, is called a *character*. A set of characters which represents an instruction (or any complete piece of information) is called a *word*.

The instructions and data are arranged in blocks along the tape. Each block contains the group of instructions and data required for a specific machine movement. A block is terminated by a special End of Block (EB) code. The information within the blocks is punched in a specific format. There are three formats in use : The tab sequential format, the word address format and the fixed block format. For example, in the "tab sequential format", each word in a block (except the last one) is terminated by a special tab code. By counting the number of the tab codes the control can identify a specific instruction in the block. The formats will be widely explained in Chapters 5 and 8.

The information is punched on the tape in a standard code. As a matter of fact, two standard codes are in use, the ISO or ASCII and the EIA standards (No. RS-244 and RS-273). The EIA code is characterized by an odd number of holes in each character, while in the ISO code the number of holes in a character is always an even number. The more popular code is that of the EIA (Electronic Industries Association). It is worthwhile to note that in the latter, the EB code is a single code hole in track 8, and that only in this case track 8 is punched.

The information punched on the tape is inserted into the N/C system by means of a tape-reader. Right after the reading, a parity checking is made to each character. That is, the system checks if the number of holes punched in a character is always an odd number for the EIA code (or an even number in the cases where systems are using the ISO code). A hole which is not clean, resulting in reading of even number of holes in the character for the EIA code and would cause the machine to stop automatically.

The tape-reader reads the characters one after the other until the end of a block. The EB code assigns that the reading of information is terminated and the system has to begin to perform the instructions that have just been read. The N/C system performs the required operation, and sends an instruction to the tape-reader for reading of the next block. In that manner the cutting of the part is proceeding : Reading a block, performing its instructions, and so on, until the termination of the cutting process.

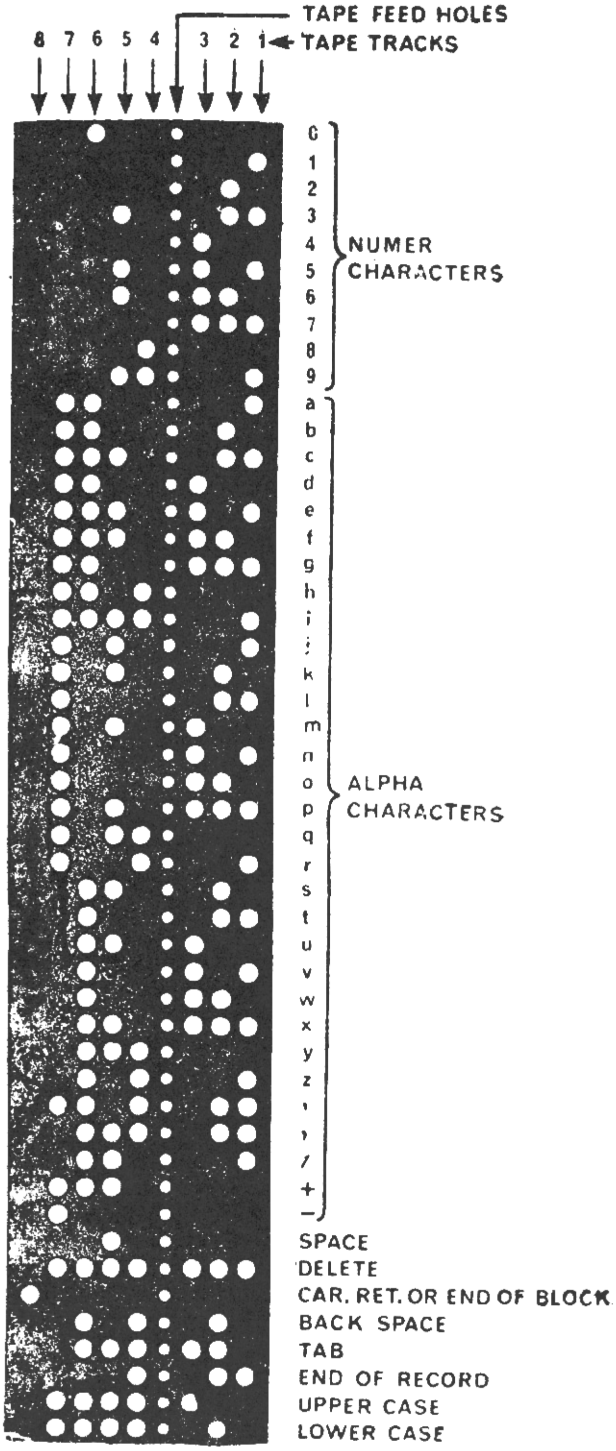


Fig. 1-10. A punched tape.

The rate of reading the tape-information depends on the tape-reader type. A mechanical tape-reader is capable of reading about 30 characters per second. Optical tape-readers have a much higher reading speed on the order of 300 characters per second or more. The mechanical tape-reader is equipped with 8 switches that are closed whenever a hole appears on the tape. The optical tape-reader makes use of 8 light beams and photocells which feed signals to 8 lines whenever a hole is passed through the light beam.

The punched tape is prepared manually or with the aid of a computer.

Manually, the tape is prepared by a Flexowriter or by a Teletypewriter (Fig. 1-11). These machines are electric typewriters with a tape punch and reader. The depression of each key of the keyboard, in addition to typing a character, punches a row on a tape. These machines are operated as any other typewriter, but typing prepares a typed paper sheet and a punched tape simultaneously.

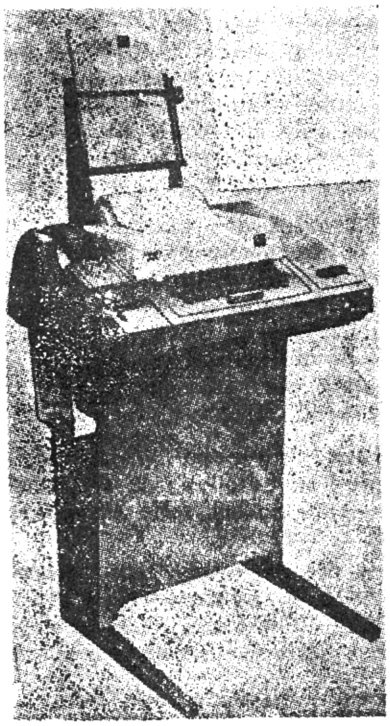


Fig. 1-11. Friden Flexowriter.

Both the Flexowriter and Teletypewriter contain facilities for reproducing a tape. This is done by inserting the original punched tape in the tape reader of the equipment and as the tape reader reads the tape, the tape perforator reproduces a new tape.

An error which is made while punching a tape can be corrected. This is done by manually turning the tape back over the incorrect character and depressing a *Code Delete*, or a *Rub Out* key. This causes eight holes, when the ISO code is in use, to be punched across the tape. In the EIA code the *Code Delete* causes seven holes to be punched in the first seven channels of the tape. The correct character is then punched by depressing the appropriate key on the key-board. The Teletypewriters include features which are not essential for controlling a N/C machine tool. The Flexowriters are more expensive but they are ideally suited for preparing the punched tape and are the most commonly used devices for this purpose.

1.4.2. Magnetic tape

Certain types of numerically controlled machine tools are using digital magnetic tape as a memory device which stores the program of the part. The information may be recorded on the tape explicitly or in a coded form.

Usually the magnetic tape has 7 channels. Recording information in a coded form means that the magnetic pulses on the tape correspond precisely to the holes on the first 7 tracks in the standard perforated tape. Since when using the EIA code, the eighth track is punched only in the EB character (which is noted as a single hole in the eighth track)—only the EB character should be described differently on a 7-channels magnetic tape.

Usually the information on a magnetic tape is not written in a coded form. That is, the pulses used for advancing the axes of motion are produced directly from the tape, where each recorded pulse is an instruction for moving one basic length unit, *e.g.* 0·001 inch or 0·01 mm. Each axis of motion has a separate channel on the magnetic tape. By increasing the density of pulses in a certain channel, the feed along the appropriate axis is increased. By changing the reading speed, the cutting feed can be varied.

The magnetic tape is inserted into a reader, which reads the tape at a constant speed and the tape is advanced with the actual working procedure. The cutting time being longer, the length of the tape will increase.

Compared with the perforated tape method, the DPU of the N/C unit can be elevated, as the need for decoding circuits and interpolator is avoided. Therefore, such systems are called ***non-interpolating***, or ***off-line interpolator systems*** and are less expensive.

On the other hand, a magnetic tape controlled system has the following disadvantages :

(*a*) The magnetic tape has to be produced by a computer. Therfore, it does not seem to be economical in use on a point-to-point system.

(*b*) Errors in programming can be corrected only with difficulty and the use of a computer seems to be essential.

(*c*) Magnetic tape readers are more expensive than punched tape readers.

Due to these disadvantages, the magnetic tape has not found its right place in N/C systems, but recently efforts are being made to develop new systems to increase its use.

1·4·3. Plug-board control

The required data for operating N/C systems may be fed by a plug-board. This board consists of a socket matrix arranged in columns and in rows. Plugging in of any socket connects a row to a column, and feeding the information of the row to the system. The plug-board replaces the perforated tape, where each row is equivalent to a *block* of information on the tape. Each time only one of the rows is energized and the system is performing the instructions of this row. The rows are scanned successively. For each row, one segment of the workpiece is machined and on completing it the system passes on the next row, which contains the data required for the next operation.

The main disadvantages of the plug-board control method compared with punched tape are in the limited number of steps per workpiece. The board comprises a certain number of rows, which is also the number of possible operations on a given workpiece.

Other disadvantages are as follows :

(*a*) Punched tapes may be stored pending further use, while if the present method is used the plugs setup must be preserved, which demands bigger storage space.

(*b*) In the plug-board method, the machine time is wasted while the program is set up, a difficulty obviated by installing twin plug-boards.

On the other hand, the plug-board control has the following advantages :

(*a*) Much lower cost, as the reading and decoding circuits of the DPU are not required and some of the memory units are dispensed with.

(*b*) The system is self-contained, in contrast to its dependence on a Flexowriter in the case of punched tape.

(*c*) Errors in programming are easily corrected.

(*d*) Adjustment of the tool to its initial working point is affected by the plugs of the first row, without need for accurate adjustment of the workpiece (or the tool) itself.

(*e*) Tool compensation can be easily made.

(*f*) Provision for slight adjustment of programme to correct for tool wear is provided.

(*g*) Simplicity of operation and of training of operators.

BIBLIOGRAPHY

1. F.W. WILSON—Numerical Control in Manufacture ; McGraw Hill, 1963.

2. T. MAGER—Einfuhrung i.d. Technik numerisch gesteuerter Werkzeugmaschinen ; Winter'sche Verlagsbuchhandlung, 1963.

3. W. SIMON—Numerische Steuerung von Werkzeug—Maschinen ; Hanser Verlag, 1963.

4. F.V. MAYEREV and Y. CHU—Electronic Digital Integrating Computers ; Iliffe, 1964.

5. O.S. PUCKLE and J.R. ARROWSMITH—Introduction to N/C of Machine Tools ; Chapman and Hall, 1964.

6. G. KOHRING—Grundlagen u. Praxis numerish gesteuerter Werkzeugmaschinen ; Hanser Verlag, 1966.

7. L. BORUCKI and J. DITTMANN—Digitale Messtechnik ; Springer Verlag. 1966.

8. P. VOLK—Antriebstechnik i.d. Metallverarbeitung ; Springer Verlag, 1966.

9. R. GUNSHAUSER-Nicht—numerische Informationsverarbeitung ; Springer Verlag, 1968.

10. G.G. ERTELL—Numerical Control ; Wiley, 1969.

11. N.U. OLESTEN—Numerical Control ; Wiley, 1970.

12. BENDIX, Inc.—N/C Handbook, 1971.

13. HAROLD—Massberg. Stute—Numerische Steuerung i.d. Fertigungs-Technik ; VDI Verlag, 1971.