Unit 5 Numerical Control

Assigned Core Text Reading for this Unit:

5.1 Unit Introduction
5.2 Unit Learning Objectives
5.3 Fundamentals of NC Technology
5.4 Computer Numerical Control
5.5 Distributed Numerical Control
5.6 Applications of NC
5.7 Open and Closed Loop NC
5.8 NC Part Programming
5.9 Unit Review
5.10 Self-Assessment Questions
5.11 Self-Assessment Answers

Section 5.1 Unit Introduction

Numerical control (NC) is a form of programmable automation in which the mechanical actions of a machine tool are precisely controlled by means of a programme of instructions. The programme captures the relative positions of the workhead (e.g. the cutting tool) and workpart (i.e. the object being processed) at all times, and enables these to be brought together, for various processing operations as necessary, or taken apart, upon task completion, as per the instructions in the programme.

KEYPOINT
Numerical control is a form of programmable automation in which the mechanical actions of a machine tool are precisely controlled by means of a data programme.
END KEYPOINT

NC is applied to a wide variety of manufacturing processes such as machine tools (e.g. drilling, milling, turning, bending, punching, etc.), and non-machine tool applications such as assembly, adhesive bonding and inspection. NC machining can involve direct numerical control (DNC) where a number of machines are served by one computer or computer numerical control (CNC) where each machine has its own computer. NC systems were originally developed for the machine tool industry, but they have subsequently been widely adopted across many industrial sectors, making the study of numerical control an important facet of industrial automation.

LEARNING ACTIVITY 5.1
Learn more about the history and subsequent development of numerical control systems at the following web-site: http://en.wikipedia.org/wiki/Numerical_control

END LEARNING ACTIVITY 5.1

This unit outlines the fundamentals of NC, and the different sorts of control that may be achieved, from computer numerical control to distributed numerical control. Specific applications of NC are subsequently examined, as well as their advantages and disadvantages; before we turn to a brief engineering analysis of NC positioning systems. A discussion on NC part programming concludes the unit.

Section 5.2 Unit Learning Objectives

After completing this unit you will be able to:

BULLET LIST
Define the concept of NC
Specify the axis systems used in NC
Outline the difference between absolute and incremental positioning in NC systems
Define computer numerical control (CNC)
Define distributed numerical control (DNC)
Explain the concept of a machining centre
Define three measures of precision for NC positioning systems
Specify the methods to accomplish NC part programming

ENDLIST

Section 5.3 Fundamentals of NC Technology

The basic components of an NC system are illustrated in Figure 5.1 and include:

- Part programme of instructions
- Machine control unit
- Processing equipment
Figure 5.1: Components of NC machining system

KEYPOINT
The basic components of an NC system are the programme of instructions, the machine control unit, and the processing equipment.
END KEYPOINT

The programme of instructions or part programme consists of a detailed set of step-by-step commands that direct the actions of the processing equipment through actuators and sensors. Typical instructions include details of positions where the workhead must move to in relation to the workpart, as well as instructions such as spindle speed, feed rate and cutting tool selection. Part programmes are typically stored on computers and sent directly to the machine controller over a communications cable.

KEYPOINT
The part programme consists of a detailed set of step-by-step commands that direct the actions of the processing equipment.
END KEYPOINT

The machine control unit (MCU) consists of a microcomputer and control hardware for programme storage. It takes the part programme’s set of instructions and executes them by converting each instruction into the mechanical actions of the processing equipment. Related hardware offers feedback control elements to the MCU. MCU software controls system software, calculation algorithms, and translation software that converts the NC part programme into a usable format for the MCU. The MCU in the contemporary
environment is a computer, which distinguishes it from the NC systems of the past that used hardwired elements instead of computers.

**KEYPOINT**
The machine control unit (MCU) converts the part programme into a usable format and executes it in the form of the mechanical actions of the processing equipment.

**END KEYPOINT**

The processing equipment performs the work of the system on the workpart based upon the part programme set of instructions. It accomplishes the processing steps to transform the starting workpiece into a completed part. Some examples of NC processing machine are given in Figure 5.2.

![NC Processing Machines](image)

**Figure 5.2: NC Processing Machines – Lathe and Laser Cutting respectively**

**PROFESSIONAL TRANSFERABLE SKILLS [CRIT]**

**LEARNING ACTIVITY 5.2**

Using the internet or a company with which you are familiar, write a brief report that specifies three machines that use numerical control. State the type of process that each piece of equipment is used for, the product produced, details of the part programme of instructions deployed, the structure and settings of the machine control unit, and the workparts of the processing equipment. Who are the manufacturers and who are their competitors.

**END LEARNING ACTIVITY 5.2**

A NC machine uses a standardised co-ordinate system, which is pre-set by the part programmer. This consists of an axis system by which the position of the workhead relative to the workpart can be specified. Machines are typically designed for two major types of axis system as described in Table 5.1.

<table>
<thead>
<tr>
<th>Axis system type</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flat / prismatic part</td>
<td>Cartesian co-ordinate system with three linear axes (x,y,z), and three rotational axes (a,b,c). In simple operations x- and y-axes typically used to horizontally position workpart, and z-axes for</td>
</tr>
</tbody>
</table>
vertical positioning of cutting tool.

Rotational part | Cartesian co-ordinate system with just two linear axes \((x,z)\), as the workpart rotates and does not use \(y\)-axis.

**KEYPOINT**

Two axis systems for NC may be specified for either flat or prismatic parts; and the axis system used for rotational parts.

**END KEYPOINT**

NC processes may be performed upon specific locations on the workpart (e.g. drilling or welding), or they may be performed while the workpart or tool is moving (e.g. milling or turning), in which case different movement patterns need to be determined. These different movements are accomplished by a motion control system, and are explained further in Table 5.2.

Table 5.2: Movements in the motion control system of NC

<table>
<thead>
<tr>
<th>Movement type</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Point-to-Point</td>
<td>Also known as positioning systems, these move the worktable to a programmed location without regard to the path taken. Thus, the worktable moves directly from point to point as programmed by the system. It is typically used to perform such operations as hole-punching or drilling.</td>
</tr>
<tr>
<td>Continuous path</td>
<td>These are systems capable of continuous simultaneous control of two or more axes, thus providing control of the tool trajectory relative to the workpart. The tool performs the process while the worktable moves through different axes, as necessary. This allows the system to generate angular surfaces, two-dimensional curves, and three-dimensional contours as required on the workpart.</td>
</tr>
</tbody>
</table>

**KEYPOINT**

NC movement patterns can be point-to-point and/or continuous path.

**END KEYPOINT**

For contouring the calculation of intermediate points that define a mathematically-precise or approximated path is important. Interpolation is important in contouring as the paths to be cut by the machine tool may or may not be complex or difficult to pre-define; consequently a number of interpolation methods, which can resolve this problem, are deployed.

**KEYPOINT**

Interpolation is the use of intermediate points that define a mathematically-precise or approximated path to overcome contouring path issues in NC.

**END KEYPOINT**

Positioning of the workhead is an important aspect of motion control; that is, whether positions are defined relative to a pre-defined origin, or relative to the previous location of the tool. The first (using an origin) is called absolute positioning; the latter is called incremental positioning. Although the workhead may move to the same position in both systems, the motion control system
records the move in different ways. This is encapsulated in Figure 5.3, where the tool must move to point (40, 50) in the absolute configuration, whereas the move is specified by the co-ordinates (20, 30) in the incremental system.

Figure 5.3: Absolute versus incremental positioning

KEYPOINT
The positioning of the workhead may be defined as absolute or incremental measurements.
END KEYPOINT

Section 5.4 Computer Numerical Control

CNC is defined as an NC system whose MCU is based on a dedicated microcomputer rather than on a hard-wired controller. Today’s CNC systems boast high-speed processors and large memory configurations, solid-state flash memory, and bus architectures.

KEYPOINT
CNC is defined as an NC system whose MCU is based on a dedicated microcomputer rather than on a hard-wired controller.
END KEYPOINT

LEARNING ACTIVITY 5.3
Investigate more about CNC at the following web-site: http://www.technologystudent.com/cam/camex.htm
Also, the following is a dedicated web-site to all things CNC-related, which contains much useful discussion and shows some of the many applications of CNC systems: [http://www.cncci.com/index.html](http://www.cncci.com/index.html)

END LEARNING ACTIVITY 5.3

The features of CNC are outlined in Table 5.4.

<table>
<thead>
<tr>
<th>Feature</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Multi-programme storage</td>
<td>Traditional hard-wire controllers could only carry-out one programme at a time, and, if they had to be changed, they would require complete re-configuration. Modern CNC controllers have sufficient memory capacity to store multiple programmes, and it is easier to switch from one to another.</td>
</tr>
<tr>
<td>Various forms of programme input</td>
<td>Traditional hard-wire controllers were limited to using punched tape as the programme input medium, whereas modern CNC controllers can use a variety of devices, such as: punched tape, magnetic tape, floppy diskettes, CDs, direct computer communication etc.</td>
</tr>
<tr>
<td>Programme editing at the machine tool</td>
<td>CNC allows the programme to be edited while it is in the MCU, thus allowing for testing and diagnostics to be carried out. The programmed can also be edited for optimisation.</td>
</tr>
<tr>
<td>Fixed cycles and programming subroutines</td>
<td>Commonly-used programme fragments can be stored in the CNC system as macros, which may be called as necessary by the main programme as it runs. This cuts down on programme development cost.</td>
</tr>
<tr>
<td>Interpolation</td>
<td>The interpolation methods outlined above can be run more efficiently on CNC systems, and some—parabolic and cubic interpolations, for example—can only be run on CNC system, owing to their complexity.</td>
</tr>
<tr>
<td>Positioning features for setup</td>
<td>CNC software options exist to make initial positioning of the workhead (see above discussion) easier for the operator.</td>
</tr>
<tr>
<td>Cutter length and size compensation</td>
<td>Traditional NC required care when deploying cutters to ensure that their dimensions matched the path to be cut. In CNC accurate tool paths are ensured by entering tool dimensions into the MCU, which can compensate for these in the automatically computed tool path. Sensors may also be used to assess tool dimensions.</td>
</tr>
<tr>
<td>Acceleration and deceleration calculations</td>
<td>Tool marks can appear on the work surface owing to abrupt changes in the feed rate. CNC systems are designed to smoothly accelerate and decelerate in anticipation of tool path changes, thus removing tool marks.</td>
</tr>
<tr>
<td>Communications interface</td>
<td>CNC systems are linked to other computers and computer-driven devices. This capability allows for the downloading of part programmes from a central data file, the collecting and transference of performance metric data on work rates, cycle times, machine utilisation etc., and the interfacing with peripheral devices, such as robots that load and unload parts.</td>
</tr>
<tr>
<td>Diagnostics</td>
<td>CNC systems possess diagnostic capabilities for ease of troubleshooting, and to allow maintenance personnel to quickly detect malfunctions. They can also send signals of impending malfunctions or diagnose system breakdowns.</td>
</tr>
</tbody>
</table>

The essential element that distinguishes the CNC system from basic NC is the machine control unit (MCU). The MCU consists of five components and subsystems inter-connected by a system bus, which communicates data and signals among the components of the network. The components and subsystems of the MCU are outlined in Table 5.5, as well as the use made of personal computers in CNC systems.
Table 5.5: Components and subsystems of the MCU

<table>
<thead>
<tr>
<th>Element</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Central Processing Unit (CPU)</td>
<td>The brain of the MCU, it manages all other components and subsystems based on software contained in the main memory. Consists of three sections: control section (which retrieves commands and data from memory and generates activation signals to other MCU components); arithmetic-logic unit (ALU) circuitry to perform various calculations, counting, and logical functions as required; and immediate access memory (temporary storage for data being processed by the CPU).</td>
</tr>
<tr>
<td>Memory</td>
<td>Storage capacity for storing programmes and data to operate the CNC system. Consists of two parts: main memory (read-only memory that stores operating system software and machine interface programmes, and random access memory that stores numerical control part programmes); and secondary memory (devices that store large programmes and data files, to be transferred to main memory as required).</td>
</tr>
<tr>
<td>Input/Output interface</td>
<td>Provides communication between components in the CNC system and other systems, and also the operator. It transmits and receives data and signals to and from external devices, such as the operator panel and control readers.</td>
</tr>
<tr>
<td>Controls for Machine Tool Axis and Spindle Speed</td>
<td>Hardware components for controlling position and velocity of each machine axis, as well as rotational speeds of the machine tool spindle.</td>
</tr>
<tr>
<td>Sequence Controls for other Machine Functions</td>
<td>Additional functions accomplished under the part programme control. These include on/off actuations, interlocks, and discrete numerical data.</td>
</tr>
<tr>
<td>Personal computers and the MCU</td>
<td>Personal computers (PCs) are being used in two aspects in CNC systems: Firstly, the PC is used as a separate front-end interface for the MCU; and secondly, the PC contains the motion control board and other hardware required to operate the machine tool. PCs are flexible as they can execute a variety of user software in conjunction to CNC system activities, but there can be issues with set-up times as most PCs need to be retro-fitted to suit CNC system needs.</td>
</tr>
</tbody>
</table>

**KEYPOINT**
The Machine Control Unit consists of five components and subsystems interconnected by a system bus, which communicates data and signals among the components of the network.

**END KEYPOINT**

**Section 5.5 Distributed Numerical Control**

‘Direct’ numerical control involves the control of a number of machine tools by a single computer through direct connection in real time. The programme is transmitted directly to a hardwired MCU (rather than computer) and became known as ‘behind the tape reader’ (BTR) since the BTR replaces the old fashioned paper punch reader. The general configuration of a DNC system consisted of four elements: the central computer; the bulk memory at the central computer site; the controlled machines; and the telecommunications lines to connect the machines to the central computer (see Figure 5.4).
KEYPOINT
Direct Numerical Control involves the control of a number of machine tools by a single mainframe computer through direct connection and in real time.
END KEYPOINT

With the emergence of CNC and the use of computers for the MCR, DNC came to stand for ‘distributed’ numerical control. The configuration of this new DNC is similar to its predecessor, except that the central computer is connected to MCUs, which are themselves computers. This removed the necessity of sending blocks of instructions as in direct numerical control, in favour of transmitting complete part programmes all at once. Typical data flows between the central computer and shop floor machine tools (in both directions) include:

BULLET List
From the central computer to shop floor machine tools: NC part programmes, tool lists, tool set-up instructions, operating instructions, machining cycle times, production schedule information.

From the shop floor machine tools to the central computer: piece counts, actual machining cycle times, tool life statistics, machine utilisation statistics, product quality data.
END LIST
KEYPOINT
Distributed Numerical Control involves the control of a number of machine tools by a series of MCUs, each connected to a central computer.
END KEYPOINT

LEARNING ACTIVITY 5.4
Learn more about direct numerical control and distributed numerical control at the following web-sites:
http://www.mkn.itu.edu.tr/~mkimrak/MAK537E/DNC.pdf
END LEARNING ACTIVITY 5.4

Section 5.6 Applications of NC

NC has many potential applications, which may be divided into machine tool applications, and non-machine tool applications. The former are typically associated with metal-working industries, while the latter may be found across a number of industries applied to a diverse set of operations.

KEYPOINT
Numerical Control (NC) may be applied in machine tool applications and non-machine tool applications.
END KEYPOINT

In machine tool applications, particularly in the metal machining industry, the predominant set of applications that apply NC occur in machine tool control. Machining as a process typically occurs in the metal industry, and is a process that removes excess metal from the surface of a workpart. This process can be performed in different ways, for example by turning, drilling, peripheral milling, and surface grinding. Each of these operations must be carried out at a particular combination of speed, feed, and depth of cut, which are known collectively as the cutting conditions of the operation.

KEYPOINT
Machining is a process that removes excess metal from the surface of a workpart. It can be performed in different ways, for example by turning, drilling, peripheral milling, and surface grinding.
END KEYPOINT

NC processes such as machining are typically performed on specialised equipment, which are designed to handle usually just one type of machining process. Some of these machine tool applications are described further in Table 5.7.
Table 5.7: Common NC machine tools

<table>
<thead>
<tr>
<th>Tool</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>NC lathe</td>
<td>Used for turning, which creates an external cylinder on the workpart. Can be either horizontal or vertical axis in construction. Requires two-axis, continuous path control, either to produce straight cylindrical turning, or contour turning.</td>
</tr>
<tr>
<td>NC boring mill</td>
<td>Used for boring, which is similar to turning except an internal cylinder is created on the workpart. Can be either horizontal or vertical axis in construction. Requires two-axis, continuous path control.</td>
</tr>
<tr>
<td>NC drill press</td>
<td>Used for drilling. Point-to-point control of the drill-bit is accompanied by two-axis control (x-y) of the worktable.</td>
</tr>
<tr>
<td>NC milling machine</td>
<td>Used for milling. Requires continuous path control to perform straight cut or contouring operations.</td>
</tr>
<tr>
<td>NC cylindrical grinder</td>
<td>Used for grinding. Operates in a similar fashion to the NC lathe (see above).</td>
</tr>
</tbody>
</table>

**KEYPOINT**

NC processes such as machining are typically performed on specialised equipment, which are designed to handle usually just one type of machining process; these include: NC lathe, NC boring mill, NC drill press, NC milling machine, and NC cylindrical grinder.

END KEYPOINT

**LEARNING ACTIVITY 5.5**

Visit [www.youtube.com](http://www.youtube.com) and learn more about each of the following machining operations: CNC Turning, CNC Press Break, CNC Laser Cutting, CNC Milling, CNC Adhesive Bonding, CNC Component Insertion

END LEARNING ACTIVITY 5.5

NC technology is appropriate for low-to-medium production of medium-to-high variety product. It is regarded as a ‘flexible’ manufacturing machine since new parts can easily be created by changing the part programme. Certain part characteristics have been identified as most suited to the application of NC; these are outlined in Table 5.8.

Table 5.8: Characteristics suitable for NC

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Batch production</td>
<td>NC is most appropriate for parts produced in small or medium lot sizes.</td>
</tr>
<tr>
<td>Repeat orders</td>
<td>NC is appropriate where batches of the same parts are produced at random or periodic intervals. Part programmes from past batches can be easily retrieved and re-used.</td>
</tr>
<tr>
<td>Complex part geometry</td>
<td>NC is appropriate for parts with complex curved surfaces, and mathematically defined features on parts, such as helixes and circles.</td>
</tr>
<tr>
<td>Removing excess metal</td>
<td>NC is appropriate where much metal needs to be removed from the part. In such cases, the final workpart may only be a fraction of the weight of the original workblock.</td>
</tr>
<tr>
<td>Multiple separate machining operations on part</td>
<td>NC is appropriate for parts with many different types of features that require turning, drilling, milling etc. The number of setups of individual machines is reduced if the setup is just one machining</td>
</tr>
</tbody>
</table>
Expensive parts | NC is appropriate for parts that are of high value. When mistakes in machining would be costly NC helps to reduce scrap and rework.

**KEYPOINT**
Characteristics suitable for NC include: batch production environments; repeat order environments; situations where there is complex part geometries; situations where we must remove excess metal from parts; situations where multiple separate machining operations on the part may be taking place; and where we have expensive parts.

**END KEYPOINT**

NC machine tools have been developed for other processes; these include: punch presses, sheet metal hole punching; sheet metal bending; welding machines for spot and continuous arc welding; thermal cutting machines, such as oxyfuel cutting, laser cutting, and plasma cutting machines; and tube bending machines. Other NC applications are outlined in Table 5.9.

<table>
<thead>
<tr>
<th>Application</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electrical wire wrap machines</td>
<td>Used to wrap and string wires on the back pins of electrical wiring boards to establish connections between components on the front of the board.</td>
</tr>
<tr>
<td>Component insertion machines</td>
<td>Used to position and insert components on an x-y plane. Typical example of its usage is in the circuit board industry, where components are placed and tied to the circuit board as necessary.</td>
</tr>
<tr>
<td>Drafting machines</td>
<td>Used as an output device from CAD/CAM systems, the design of a product is plotted on the drafting machine using a high-speed x-y plotter.</td>
</tr>
<tr>
<td>Co-ordinate measuring machines</td>
<td>Used to inspect or measure the dimensions of a part. Deploys a probe that is operable on three axes and that identifies where contact with the part surface is made. Can be programmed to perform automated inspection in NC.</td>
</tr>
<tr>
<td>Tape laying machines for polymer composites</td>
<td>Used to dispense uncured polymer matrix composite tape. It lays the tape on the surface of a contoured mould, following a back-and-forth and crisscross pattern.</td>
</tr>
<tr>
<td>Filament winding machines for polymer composites</td>
<td>Operates in the same fashion as the tape laying machine above.</td>
</tr>
</tbody>
</table>

**KEYPOINT**
NC has been used for a number of applications; these include electrical wire wrap machines; component insertion machines; drafting machines; co-ordinate measuring machines; tape laying machines for polymer composites; filament winding machines for polymer composites.

**END KEYPOINT**

NC applications have many advantages and disadvantages. Advantages include a reduction in machine idle time, and an improved manufacturing lead time, as well as improved performance in inspection, quality, scrap and rework metrics.
Disadvantages centre on the relatively high cost of the technology, which requires a higher maintenance effort, and higher utilisation to justify investment.

Section 5.7 Open and Closed Loop Systems

Two types of positioning control systems are used in NC systems: open loop, and closed loop. An open-loop system operates without verifying that the actual position achieved in the move is the same as the desired position. Stepper motors are typically used in open loop systems. A closed-loop system uses feedback measurements to confirm that the final position of the worktable is the location specified by the programme. Servo motors utilising optical encoders are typically used in closed loop systems. Open-loop systems are less expensive than closed-loop systems, and are appropriate when the force resisting the actuating motion is minimal. Closed-loop systems are normally specified for machines that perform continuous path operations such as milling or turning, in which there are significant forces resisting the forward motion of the cutting tool. Figure 5.5 illustrates a closed loop axis positioning system controlled by servo motor.

![Closed Loop Control](Image)

Figure 5.5: Closed Loop Control (Source: Groover 2008)

**KEYPOINT**
Two types of positioning control systems are used in NC systems: open loop, and closed loop.

**END KEYPOINT**

Section 5.8 NC Part Programming

NC part programming entails planning and documenting the sequence of processing steps to be performed on an NC machine. Knowledge of machining processes is necessary, as well as geometry and trigonometry. Documentation refers to the input medium used to transfer the created programme to the NC's...
MCU. The input medium has changed throughout the years—from punched cards to punched tape to a range of computing technological breakthroughs, such as magnetic tape, floppy diskettes, data CDs, and direct transmission from the computer itself.

**KEYPOINT**
NC part programming entails planning and documenting the sequence of processing steps to be performed on an NC machine.

**END KEYPOINT**

The methods to accomplish part programming include:

- Manual part programming at the MCU or Computer
- Computer-assisted part programming
- Part programming using CAD/CAM

**KEYPOINT**
The methods to accomplish part programming include manual part programming, computer-assisted part programming, part programming using CAD/CAM.

**END KEYPOINT**

In manual part programming the programmer uses a low-level machine language to prepare the NC code. The coding system is based on binary numbers, and can be readily understood by the MCU; if higher-level languages are used they will still need to be translated into the basic code to be read. NC uses a code called the binary-coded decimal (BCD) system, which uses both binary and decimal number systems; in BCD, the ten digits of the decimal system are coded as a four-digit binary number, and these are added in sequence in the decimal number system. Table 5.11 outlines the operation of the system by showing the translation of binary into decimal numbers in BCD.

<table>
<thead>
<tr>
<th>Binary</th>
<th>Decimal</th>
<th>Binary</th>
<th>Decimal</th>
</tr>
</thead>
<tbody>
<tr>
<td>0000</td>
<td>0</td>
<td>0101</td>
<td>5</td>
</tr>
<tr>
<td>0001</td>
<td>1</td>
<td>0110</td>
<td>6</td>
</tr>
<tr>
<td>0010</td>
<td>2</td>
<td>0111</td>
<td>7</td>
</tr>
<tr>
<td>0011</td>
<td>3</td>
<td>1000</td>
<td>8</td>
</tr>
<tr>
<td>0100</td>
<td>4</td>
<td>1001</td>
<td>9</td>
</tr>
</tbody>
</table>

**KEYPOINT**
In manual part programming the programmer uses a low-level machine language, called the binary-coded decimal system, to prepare the NC code.

**END KEYPOINT**
In addition, the NC coding system must provide for alphabetical characters. Eight binary digits are used to represent all of the characters required for NC part programming; these, in turn, are used to create ‘words’. By forming specific words, the NC programme specifies a detail about an operation, such as the x, y, z position, feed rate, or spindle speed. A collection of words forms a ‘block’, which is one complete NC instruction.

The organisation of the words within a block is called the block format; the most common format is the ‘word address format’ whereby a letter is prefixed to identify the word type, and spaces are used to separate words within a block. The format allows for variations in the word order, and word omissions if necessary. For example, the two drilling commands in word address format to perform the operations illustrated in Figure 5.6 are:

N001 G00 X07000 Y03000 M03  
N002 Y06000

Figure 5.6: Drilling sequence in word address format.

KEYPOINT
In NC code, a collection of words forms a block, which is one complete NC instruction. The organisation of the words within a block is called the block format.

END KEYPOINT

Words in an instruction block are intended to convey all of the commands and data necessary for the machine tool to execute the move defined by the block. Of course, different NC machines will predominantly use different types of words, but the general layout of words is as follows:
BULLETLIST
Sequence number (N-word)

Preparatory word (G-word)

Co-ordinates (X-, Y-, Z-words for linear axes; A-, B-, C-words for rotational axes)

Feed rate (F-word)

Spindle speed (S-word)

Tool selection (T-word)

Miscellaneous command (M-word)

ENDLIST

KEYPOINT
Words in an instruction block convey all of the commands and data necessary for the machine tool to execute the move defined by the block.
END KEYPOINT

EXAMPLE
The following part programme has been written to move the cutting tool of a milling machine around a particular work part. Try to determine what each of the instructions mean and what shape they create in the workpart.

<table>
<thead>
<tr>
<th>NC part program code</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>N001 G21 G90 G92 X-050.0 Y-050.0 Z010.0;</td>
<td>Define origin of axes.</td>
</tr>
<tr>
<td>N002 G00 Z-020.0 S1989 M03;</td>
<td>Rapid to cutter depth, turn spindle on.</td>
</tr>
<tr>
<td>N003 G01 G94 G42 Y0 D05 F398;</td>
<td>Bring tool to starting y-value, start cutter offset.</td>
</tr>
<tr>
<td>N004 G01 X075.0;</td>
<td>Mill lower horizontal edge of part.</td>
</tr>
<tr>
<td>N005 G01 X150.0 Y043.02;</td>
<td>Mill angled edge at 35 degrees.</td>
</tr>
<tr>
<td>N006 G01 Y070.0;</td>
<td>Mill vertical edge at right of part.</td>
</tr>
<tr>
<td>N007 G01 X080.0;</td>
<td>Mill horizontal edge leading to arc.</td>
</tr>
<tr>
<td>N008 G17 G02 X050.0 Y100.0 R030.0;</td>
<td>Circular interpolation around arc.</td>
</tr>
<tr>
<td>N009 G01 Y125.0;</td>
<td>Mill vertical step above arc.</td>
</tr>
<tr>
<td>N010 G01 X0;</td>
<td>Mill top part edge.</td>
</tr>
<tr>
<td>N011 G01 Y0</td>
<td>Mill vertical edge at left of part.</td>
</tr>
<tr>
<td>N012 G40 G00 X-050.0 Y-050.0 Z010.0 M05;</td>
<td>Rapid move to target point, cancel offset, spindle stop.</td>
</tr>
<tr>
<td>N013 M30;</td>
<td>End of program, stop machine.</td>
</tr>
</tbody>
</table>

END EXAMPLE

LEARNING ACTIVITY 5.6
Higher level languages reduce the amount of detail and increase the logical syntax for programmers. A common high level programming language for machine tools is called APT. Search the internet for details of the APT language.
A CAD/CAM system is an interactive computer graphics system with manufacturing and design software installed to integrate design and manufacturing functions. NC systems have been developed on the basis of CAD/CAM systems, which can be discussed here. In this method, portions of the part programme usually performed by the human programmer can be done instead by the CAD/CAM system. The following advantages are associated with NC part programming using CAD/CAM systems:

**BULLET LIST**

- **Accuracy testing**—CAD/CAM systems can simulate part programmes off-line to verify their content.
- **Time/cost analysis**—CAD/CAM systems can provide accurate measurements on the time and cost of a machining operation.
- **Tool selection**—CAD/CAM systems aid in the selection of the correct tool for the operation under analysis.
- **Parameter selection**—CAD/CAM systems can automatically select the correct parameters for the operation at hand, including parameters for speeds and feeds for the work material and operations.

**KEYPOINT**

NC systems have been developed on the basis of CAD/CAM systems, and offer a number of advantages, including: programme accuracy testing, improved time and costing analysis of the operation, improved support for tool selection, and improved support for parameter selection.

**END KEYPOINT**

CAD/CAM systems essentially offer advanced assistance to the human programmer in terms of computer-assisted programming; there we found that the human programmer was expected to define the geometry of the part, and to specify the tool path and operation sequence of the programme. CAD/CAM systems contribute to aid the human programmer in these areas, in ways as outlined in Table 5.12. Figure 5.7 illustrates a CAD/CAM system where the CAD and CAM system are on the same computer and both are in close proximity to the Machine.

<table>
<thead>
<tr>
<th>Function</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Geometry definition</td>
<td>A computer graphics model of the part is created using CAD, and stored as a file in the CAD/CAM database; the model contains all the</td>
</tr>
</tbody>
</table>
geometrical information and material specifications necessary for producing the part. When the NC part programming is to be completed on the part, the file is retrieved from the CAD/CAM database, and is used to construct the appropriate cutter path, thus geometry definition is avoided. Geometrical elements are then labelled for part programming. The key function added by the CAD/CAM system is automatic geometry definition taken straight from the graphics model of the part drawn-up; in other computer-assisted programmes this has to be done separately, and is very complex and time-consuming.

| Tool path generation | Once the programmer selects the tool for the operation, and the CAD/CAM system automatically makes tool offset calculations, tool path definition can occur. Here the CAD/CAM system provides support by helping to generate the tool path to be followed. There are a number of approaches to doing this, based upon the CAD/CAM system being deployed, but the most basic approach involves the use of the interactive graphics system to enter the motion commands one by one, as in computer-assisted part programming. Advanced tool path generation methods may deploy specialised software in the CAD/CAM system that act as subroutines upon which the NC system can call as and when necessary, as part of the machining cycle. These include automatic programming modules for pocket milling, contour turning, facing and shoulder facing, and threading. |

**KEYPOINT**

CAD/CAM systems offer advanced assistance to the human programmer in NC part programming in geometric part definition, and tool path generation.

**END KEYPOINT**

![Figure 5.7: CAD/CAM System](image)

**LEARNING ACTIVITY 5.7**

Use the internet to find suppliers of CAD/CAM solutions for particular machine tools e.g. punch press and milling machine. For the punch press is there any solutions available for a ‘nesting’ requirement?
Numerical control is a form of programmable automation in which the mechanical actions of a machine tool or other equipment are precisely controlled by means of a part programme.

The basic components of an NC system are the part programme of instructions, the machine control unit, and the processing equipment.

The positioning of the workhead may be defined as absolute or incremental. In the absolute system the workhead is defined relative to a pre-defined origin, while in the incremental system the workhead is defined relative to the previous location of the tool.

CNC is defined as an NC system whose MCU is based on a dedicated microcomputer rather than on a hard-wired controller.

Direct Numerical Control involves the control of a number of machine tools by a single mainframe computer through direct connection and in real time.

Distributed Numerical Control involves the control of a number of machine tools by a series of MCUs, each connected to a central computer through direct connection and in real time. Distributed Numerical Control is an advanced and more flexible form of Direct Numerical Control.

Numerical Control (NC) may be applied in machine tool applications and non-machine tool applications including NC lathe, NC boring mill, NC drill press, NC milling machine, and NC cylindrical grinder and electrical wire wrap machines; in component insertion machines; in drafting machines; in co-ordinate measuring machines; in tape laying machines for polymer composites.

Two types of positioning control systems are used in NC systems: open loop, and closed loop.

Three measures of precision for NC positioning systems are control resolution, accuracy, and repeatability.

NC part programming entails planning and documenting the sequence of processing steps to be performed on an NC machine.

The methods to accomplish part programming include manual part programming, computer-assisted part programming, part programming using CAD/CAM.
NC systems have been developed on the basis of CAD/CAM systems, and offer a number of advantages, including: programme accuracy testing, improved time and costing analysis of the operation, improved support for tool selection, and improved support for parameter selection.

CAD/CAM systems offer advanced assistance to the human programmer in NC part programming in geometric part definition, and tool path generation.

Section 5.10 Self-Assessment Questions

What are the basic components of an NC system? Briefly outline each.

Outline the difference between absolute and incremental positioning in NC systems.

What is computer numerical control (CNC)?

What are the five components and sub-systems of the Machine Control Unit (MCU)?

Define Distributed Numerical Control (DNC).

Explain the concept of the machining centre.

What are the characteristics that make NC suitable?

What are the two types of positioning control systems used in NC systems? Outline each briefly.

What are the methods used to accomplish NC part programming?

Section 5.11 Answers to Self-Assessment Questions

The basic components of an NC system are the part programme of instructions, the machine control unit, and the processing equipment. The part programme consists of a detailed set of step-by-step commands that direct the actions of the processing equipment. The machine control unit (MCU) consists of a microcomputer and control hardware for programme storage. It converts the part
programme into a usable format and executes it in the form of the mechanical
actions of the processing equipment. The processing equipment actually
performs the work of the system, once it has been provided with its instructions
by the MCU, based upon the part programme set of instructions.

In the absolute system the workhead is defined relative to a pre-defined origin;
while in the incremental system the workhead is defined relative to the previous
location of the tool.

CNC is defined as an NC system whose MCU is based on a dedicated
microcomputer rather than on a hard-wired controller.

The five components and subsystems of the MCU are: the central processing
unit (CPU); memory; the input/output interface; the controls for machine tool axis
and spindle speed; and the sequence controls for other machine functions.

Distributed Numerical Control involves the control of a number of machine tools
by a series of MCUs, each connected to a central computer through direct
connection and in real time.

A machining centre is a machine tool capable of performing multiple machining
operations on a single workpart in one set-up.

Characteristics suitable for NC include: batch production environments; repeat
order environments; situations where there is complex part geometries; situations
where we must remove excess metal from parts; situations where multiple
separate machining operations on the part may be taking place; and where we
have expensive parts.

Two types of positioning control systems are used in NC systems: open loop,
and closed loop. An open-loop system operates without verifying that the actual
position achieved in the move is the same as the desired position. A closed-loop
system uses feedback measurements to confirm that the final position of the
worktable is the location specified by the programme.

The methods used to accomplish NC part programming include manual part
programming, computer-assisted part programming, part programming using
CAD/CAM, and manual data input.