

# 第十七章 數值控制

## NUMERICAL CONTROL

### 一、Conventional Numerical Control

#### 1.0 NC Definition

NC can be defined as "A form of programmable automation in which the process is controlled by numbers, letters, and symbols.

Defined by *EIA (Electronic Industrial Association)* as "**A system in which actions are controlled by direct insertion of numerical data at some point. The system must automatically interpret at least some portion of this data.**"

利用儲存於紙帶、磁帶、計算機磁碟的數值資料或直接的電腦資料來控制工具機的一種控制方法。早期就有使用打孔的紙帶來演奏鋼琴的例子。

#### 1.1 Application of NC Technology

Drafting	Assembly
Inspection	Sheet Metal Pressworking
Spot Welding	Metal Machining Process

#### 1.2 Historical Background of NC

1949 - The concept of NC was proposed by John C. Parsons at MIT.

- Using a computer to compute the path of a cutting tool and storing the computed cutter positions on punched cards.
- Using a reading device in order to automatically read the punched cards.
- Using a control system that would continuously output the appropriate data to servo-motor, which were attached to lead-screws, in order to drive the cutter over the complex geometry to be machined.

1952 - The first NC machine was successfully demonstrated at MIT.

1954 - The development of APT was begun.

1958 - APT II was released and run on IBM-704 computer.

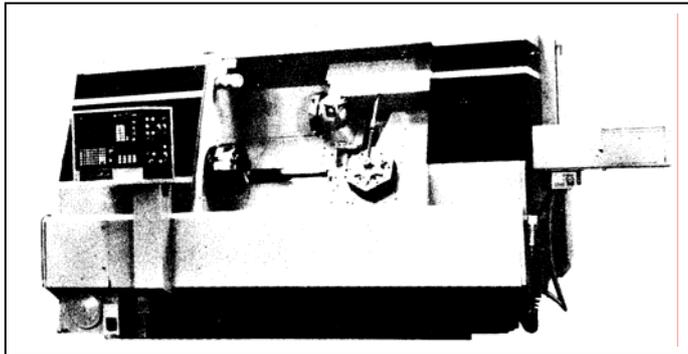
1961 - APT III was released.

- 30 companies of Aerospace Industries Association elected Illinois Institutes of Technology Research Institute to further develop and maintain APT III language.
- APT long-range program was established.
- APT IV was planned.

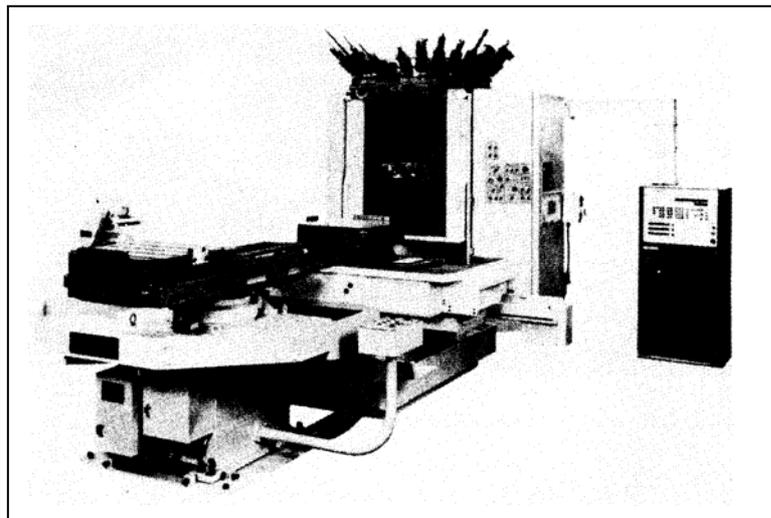
### 1.3 Basic Components of an NC System

- Program of Instructions
- Controller Unit
- Machine Tool or Other Controlled Process

右圖為一數值控制六角車床。



右圖為一具有儲存刀具功能的加工中心 (Machining center)。



#### 1.3.1 Program of Instructions

The program of instructions is the detailed step-by-step set of directions which tell the machine tool what to do.

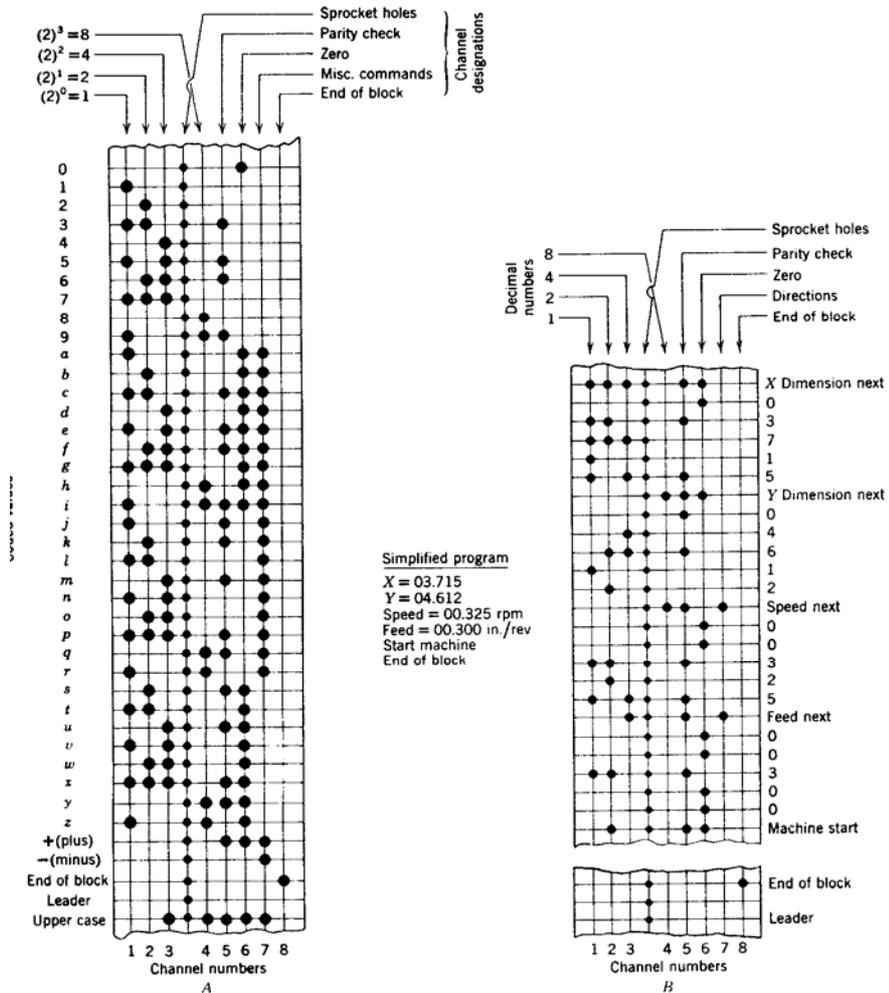
It is coded in numerical or symbolic form on some type of input medium that can be interpreted by the controller unit.

The common input mediums to the NC system are:

- 1 in wide punched tape
- Punched card

- Magnetic tape
- 35mm motion picture film

下圖所示為打孔的紙帶，為二進位字碼十進位系統。



The common input methods to the NC system are:

- Manual entry of instruction data to the controller unit.
- Direct link with computer.

### 1.3.2 Controller Unit

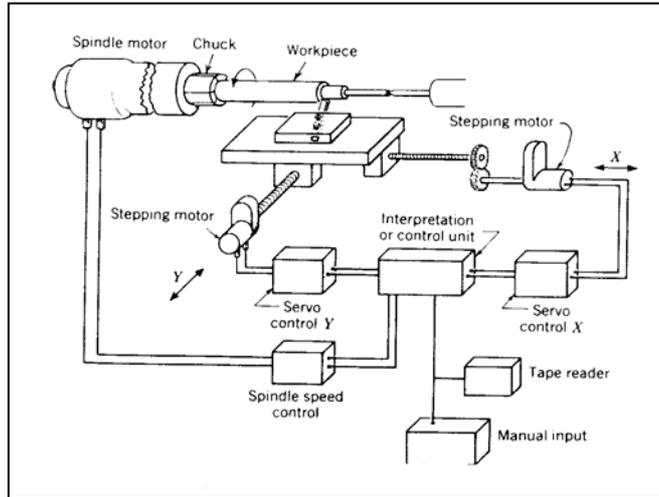
The functions of controller unit are:

- Read/Interpret the program of instructions
- Convert the instruction into the mechanical actions of the machine tool.

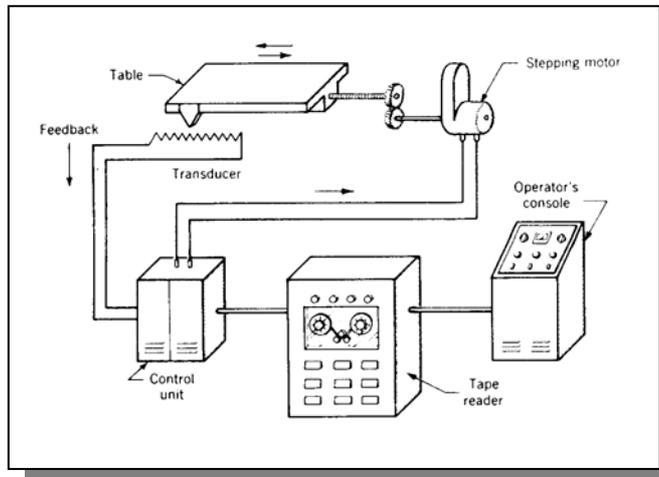
The typical elements of NC controller unit include:

- The tape reader
- Data buffer
- Signal output channels to "servo-motor or other controller" of the machine tool
- Feedback channels from the machine tool
- Sequence controls to coordinate the overall operation of the foregoing elements
- Control panel/console

右圖所示為一雙軸、open-loop control system。



右圖所示為一單軸、closed-loop control system。



### 1.3.3 Machine Tool or Other Controlled Process

To perform machining operations

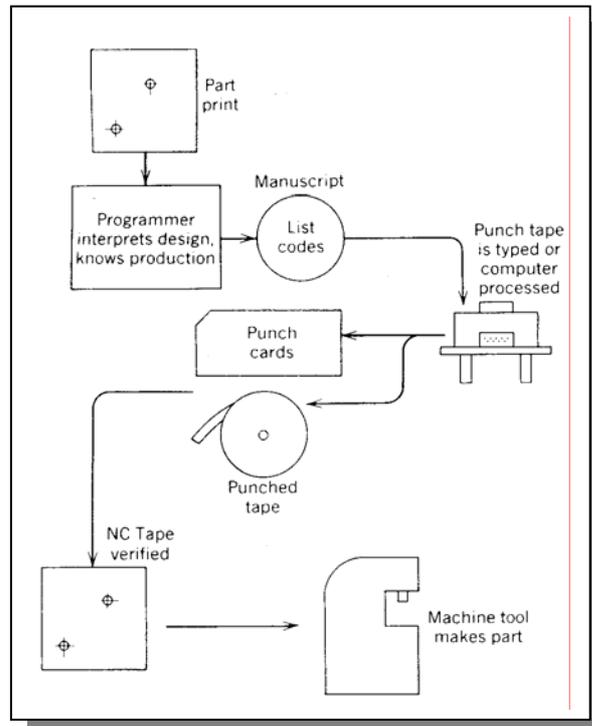
- Worktable
- Spindle
- Motors
- Controls necessary to derive worktable, spindle, and motors.
- Cutting tools
- Work fixtures

- ❑ Other auxiliary equipments needed in the machining operation.

## 1.4 The NC procedure

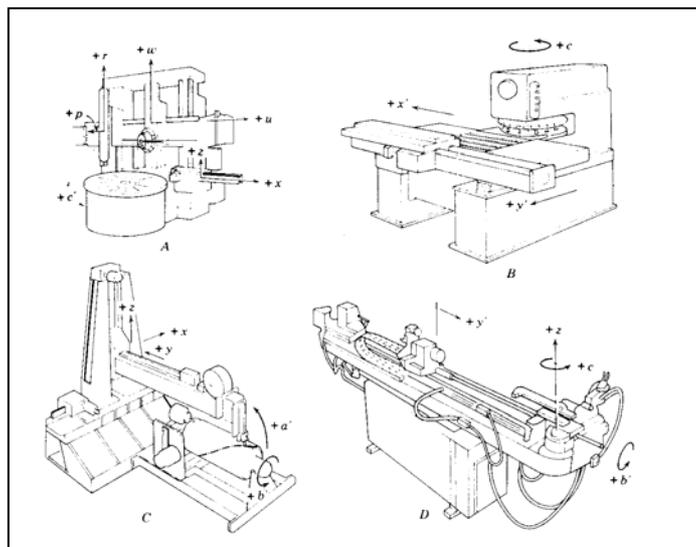
To utilize NC in manufacturing, the following steps must be accomplished.

- ❑ Process planning
  - Preparation of a route sheet (a listing of the sequence of operations which must be performed on the workparts)
- ❑ Part programming and verification
  - Manual part programming
  - Computer assisted part programming
  - Tape preparation (unnecessary)
  - Tape verification (unnecessary)
- ❑ Input part program to NC controller
- ❑ Production

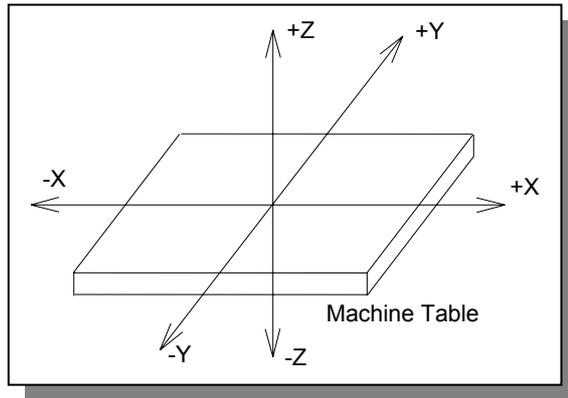


## 1.5 Coordinate System

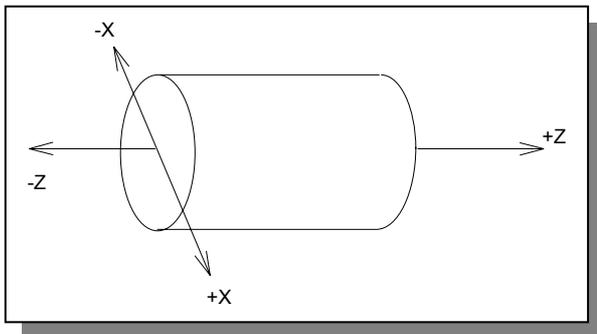
In order to plan the sequence of positions and movements of the cutting tool relative to the workpiece. It is necessary to establish a standard axis system by which the relative position can be defined.



### 1.5.1 Coordinate System for Milling/Drilling Operation



### 1.5.2 Coordinate System for Turning Operation



## 1.6 Machine Motions

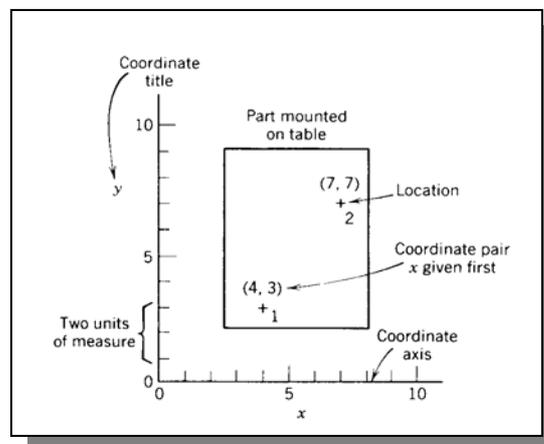
How to define the position of the tool relative to the origin.

Fixed zero and floating zero

**Fixed zero:** The origin is always located at the same position on the machine table.

**Floating zero:** The machine operator can set the zero point at any position on the machine table.

Absolute positioning and incremental positioning



EXAMPLE :

## 1.7 NC Motion Control Systems

Concerning the relative motion between the workpiece and cutting tool.

- Point to Point NC (PTP) (Positioning)
- Straight Cut NC
- Contouring NC (Continuous Path NC)

## 1.8 Applications of NC

NC systems are widely used in industry today, especially in the "metalworking" industry.

- Milling
- Turning
- Boring
- Drilling and other related process
- Grinding
- Sawing

Following are the general characteristics of production jobs in metal machining for which numerical control would be most appropriate:

- Parts are processed frequently and in small lot sizes.
- The part geometry is complex.
- Many operations must be performed on the part in its processing.
- Much metal needs to be removed.
- Engineering design changes are likely.
- Close tolerances must be held on the workpart.
- It is an expensive part where mistakes in processing would be costly.
- The parts require 100% inspection.

## 1.9 Potential Applications of NC

- Pressworking machine tools
- Welding machines
- Inspection machines
- Automatic drafting
- Assembly machines

- Tube bending
- Flame cutting
- Plasma cutting
- Laser beam processes
- Cloth cutting
- Automatic riveting
- Wire-wrap machines
- Automated knitting machines

## 1.10 Economics of NC

### Advantages of NC:

- Reduced nonproductive time
- Reduced fixture
- Reduced manufacturing lead time
- Greater manufacturing flexibility
- Improved quality control
- Reduced inventory
- Reduced floor space requirement

### Disadvantages of NC:

- Higher investment cost
- Higher maintenance cost
- Finding and/or training NC personnel

## 1.11 NC Part Programming

Planning and documenting the sequence of processing steps to be performed on the NC machine.

- Manual part programming

The programmer writes the machining instructions on a special form called a part programmer manuscript. > Tedious task and subject to error

- Computer-assisted part programming

Employing the high speed digital computer to assist in the part programming process.

There are many part programming language systems have been developed to perform automatically most of the calculations which the programmer would otherwise be forced to do.

>>>> Saving times and resulting in a more accurate and more efficient part program.

Part programmer's job:

Defining the workpart geometry

Specifying the operation sequence and tool path

Writing the English-like statements of the APT part program

Computer's job:

Input translation

Arithmetic calculation

Cutter-offset computation

Post-processor

## 二、Extension of Numerical Control

Direct Numerical Control

Computerized Numerical Control

Adaptive Control

Industrial Robots

### 2.0 Definition of Direct Numerical Control

DNC is a manufacturing system in which a number of machines are controlled by a computer through direct-connection and in real time.

Also, defined by EIA as:

DNC is a system connecting a set of NC machines to a common memory for part program or machine program storage with provision for on-demand distribution of data to machines.

The tape reader is omitted.

Involves data connection and processing from the machine tool back to the computer.

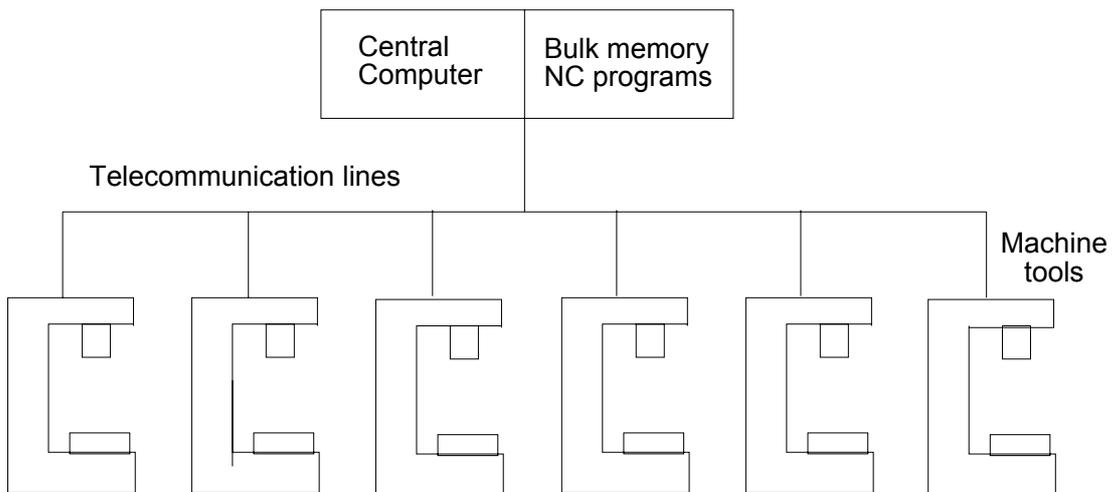
### 2.1 Components of a DNC system

Central computer (and satellite mini/micro computers)

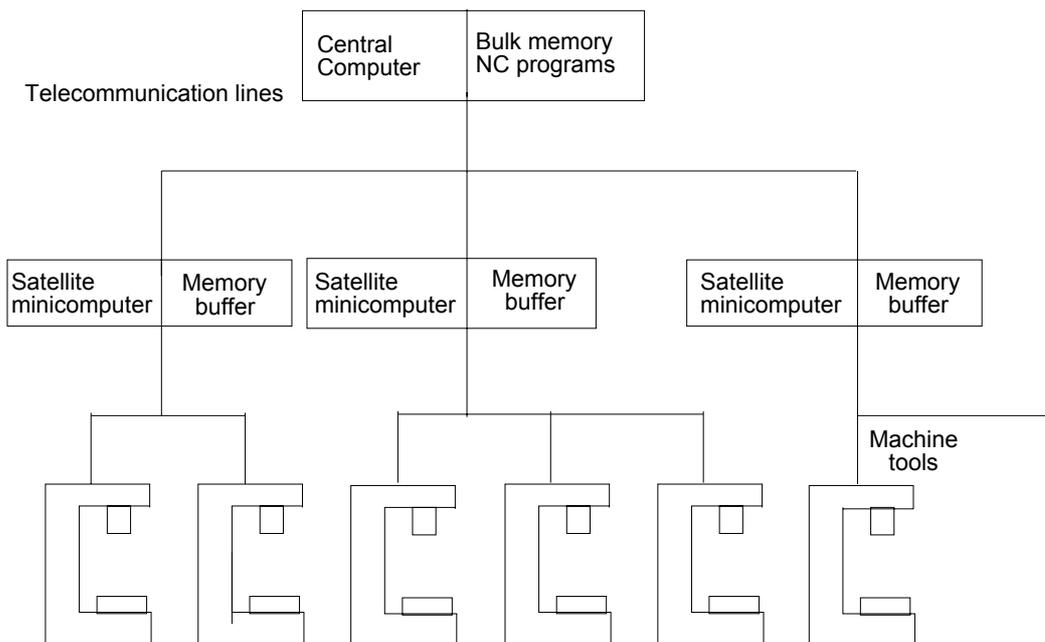
- ❑ Bulk memory to store NC part program
- ❑ Communication lines and interfaces
- ❑ Machine tools
- ❑ Management S/W

Depending on the number of machines and the computational requirements imposed on the computer. The configuration of the DNC system can be divided into:

**(1) DNC system without satellite computer**



**(2) DNC system with satellite computer**



## 2.2 Two Types of DNC

There are two alternative system configurations by which the communication link is established between the control computer and the machine tool.

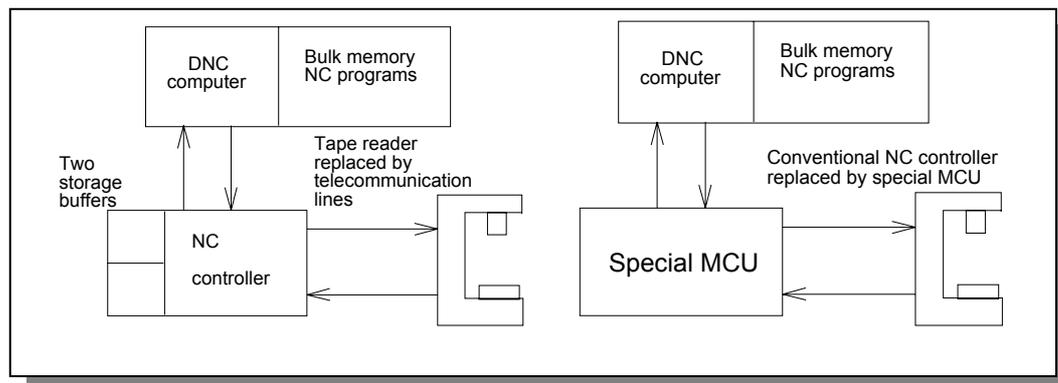
### (1) Behind the Tape Reader (BTR) system:

The computer is linked directly to the regular NC controller unit.

Except for the source of the command instructions, the operation of the system is very similar to conventional NC.

The controller unit uses two temporary storage buffers to receive blocks of instructions from the DNC computer and convert them into machine actions. While one buffer is receiving a block of data, the other is providing control instructions to machine tool.

> Its cost is less



### (2) Special Machine Control Unit:

- Replace the regular controller unit with a special machine control unit.
- The special control unit is designed to facilitate communication between the machine tool and the computer.
- The special MCU configuration achieve a superior balance between accuracy of the interpolation and fast metal removal rates than is generally possible with the BTR system.
- The special MCU is soft-wired. (flexible)

## 2.2 Functions of DNC

The functions which a DNC system is designed to perform:

- NC without punched tape.
- NC part program storage.
- Data collection, processing, and reporting.
- Communication.

### 2.2.1 NC part program storage

The program storage subsystem must be structured to satisfy several purposes:

- The program must be made available for downloading to the NC machine tools.
- The subsystem must allow for new programs to be entered, old programs to be deleted, and existing programs to be edited.
- The DNC software must accomplish the postprocessing function. (The part programs in a DNC system would typically be stored as the CLFILE. The CLFILE must be converted into instructions for a particular machine tool.)
- The storage subsystem must be structured to perform certain data processing and management functions, such as file security, displays of programs, and manipulation of data.

### 2.2.2 Data collection, Processing, and Reporting

The purpose of this functions is to "monitor" production of the factory.

The data concerned are:

- Tool usage
- Machine utilization
- Production piece counts

These data must be processed by the DNC computer, and reports are prepared to provide management with information necessary for running the plant.

### 2.2.3 Communication

A "Communication Network" is required to accomplish the previous functions of DNC. The essential communication links in DNC are between the following components of the system:

- Central computer and machine tools
- Central computer and NC part programmer terminal
- Central computer and bulk memory

Optional communication links may also be extended to following additional systems:

- CAD system
- Shop floor control system
- Corporate data processing computer
- Remote maintenance diagnostics system
- Other computer-automated system in the plant

## 2.3 Advantages of DNC System

- Elimination of punched tapes and tape readers
- Convenient storage of NC part programs in computer files
- Programs stored as CLFILE
- Greater computational capability and flexibility
- Reporting of shop performance
- Establishes the framework for the evolution of the future computer automated factory.

## 3.0 Computer Numerical Control (CNC)

DNC is only one of two approaches in which the computer is used to control the NC machine. Chronologically, DNC came first. The initial DNC systems appeared commercially in the mid-to-late 1960s. Since then the physical size of the digital computer has been reduced at the same time that its computational capabilities have been increased. The result of these improvements has been the development of a new systems concept in NC: CNC.

CNC is an NC system that utilizes a dedicated, stored-program computer to perform some or all of the basic numerical control functions.

### The differences between the DNC and CNC:

- CNC computers control only one machine.
- DNC computers distribute instructional data to, and collect data from, a large number of machines.
- CNC computers are located very near their machine tools.
- DNC computers occupy a location that is typically remote from the machine under their control.
- DNC software is developed not only to control individual pieces of production equipment, but also to serve as part of a management information system in the manufacturing sectors of the firm.
- CNC software is developed to augment the capabilities of a particular machine tool.

### Compared to regular NC:

- CNC offers additional flexibility and computational capability.
- New system options can be incorporated into the CNC controller simply by reprogramming the unit.

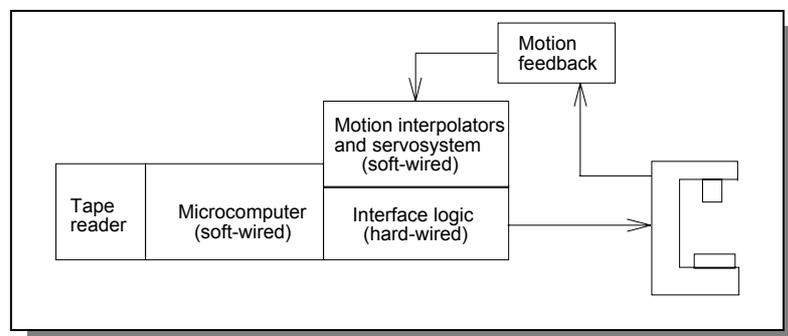
## 3.1 Functions of CNC

- Machine tool control
- In-process compensation
- Improved programming and operating features
- Diagnostics

### 3.1.1 Machine tool control

#### (1) Hybrid CNC

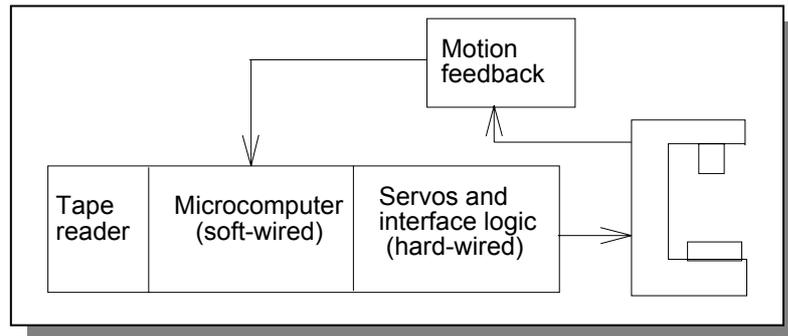
In the hybrid CNC system, the controller consisted of the soft-wired components plus hard-wired logic circuits. The



hard-wired components perform feed rate generation and circular interpolation. The computer performs the remaining control functions plus other duties not normally associated with a conventional hard-wired controller.

## (2) Straight CNC

The straight CNC system uses a computer to perform all the NC functions. The only hard-wired elements are



those required to interface the computer with the machine tool and the operator's console. Interpolation, tool position feedback, and all other functions are performed by computer software.

### 3.1.2 In process compensation

- Adjustments for errors sensed by in-process inspection probes and gauges.
- Re-computation of axis positions when an inspection probe is used to locate a datum reference on a workpart.
- Offset adjustments for tool radius and length.
- Adaptive control adjustments to speed and/or feed.
- Computation of predicted tool life and selection of alternative tooling when indicated.

### 3.1.3 Improved programming and operating features

- Editing of part programs at the machines.
- Graphic display of the tool path to verify the program.
- Various type of interpolation: circular, parabolic, and cubic interpolation.
- Usage of specially written subroutines.
- Manual Data Input(MDI).
- Local storage.

## 3.2 Advantages of CNC

- The part program tape and tape readers are used only once.
- Tape editing at the machine site.
- Metric conversion.
- Greater flexibility.
- User-written programs
- Total manufacturing system.

## 4.0 Adaptive Control Machining Systems

Adaptive control(AC) machining system originated out of research in the early 1960s sponsored by the U.S. Air Force at the Bendix Research Laboratory. The initial AC systems were based on analog control device. Today, AC uses microprocessor-based controls and it is typically integrated with an existing CNC system.

For a machining operation, the term ADAPTIVE CONTROL denotes a control system that measures certain output process variables and use these to control speed and/or feed.

The process variables have been used in AC machining systems:

- Spindle deflection
- Force
- Torque
- Cutting temperature
- Vibration amplitude
- Horse power

**NOTE: The typical measures of performance in machining have been metal removal rate and cost per volume of metal removed.**

### 4.1 Where to Use Adaptive Control

The reasons for using NC(including CNC and DNC) are that NC reduces the nonproductive time in a machining operation. This time savings is achieved by reducing such elements as workpiece handling time, setup of the job, tool changes, and other sources of operator and machine delay. Although NC has a significant effect on downtime, it can do relatively little to reduce the in-process time compared to a conventional machine tool. The most promising answer for reducing the in-process time lies in the use of adaptive control.

AC determines the proper speed and/or feed during machining as a function of variations in such factors as work-material hardness, width or depth of cut, air gap in the part geometry, and so on.

AC is not appropriate for every machining situation. In general, the following characteristics can be used to identify situations where AC can be beneficially applied:

- The in-process time consumes a significant portion of the machining cycle time.
- There are significant sources of variability in the job for which AC can compensate.
- The cost of operating the machine tool is high.
- The typical jobs are ones involving steel, titanium, and high strength alloys. Cast iron and aluminum are also attractive candidates for AC.

## 4.2 Sources of variability in machining

The following are the typical source of variability in machining where adaptive control can be most advantageously applied.

- Variable geometry of cut in the form of changing depth or width of cut.
  - > **Feed rate is adjusted.**
- Variable workpiece hardness and variable machinability.
  - > **Speed or feed us adjusted.**
- Variable workpiece rigidity.
  - > **Feed rate is adjusted.**
- Toolwear (Observed that as the tool begins to dull, the cutting forces increase.)
  - > **Feed rate is adjusted.**
- Air gapping during cutting (No machining is performed and feed-rate maintained )
  - > **Feed rate is adjusted.**

## 4.3 Two types of adaptive control

- Adaptive Control Optimization : ACO
- Adaptive Control Constrain : ACC

### 4.3.1 Adaptive Control Optimization ACO - Represented by Bendix research

An index of performance is specified for the system. This performance index is a measurement of overall process performance, such as production rate, cost per volume of metal removed.

The objective of the adaptive controller is to optimize the index of performance by manipulating speed and/or feed in the operation.

**IP= a function of MRP/TWR**

where MRP= Material Removal Rate

TWR= Tool Wear Rate ( Cannot be measured on-line)

ACO : MAX. IP

**4.3.2 Adaptive Control Constrain : ACC**

Utilizing constrain limits imposed on certain measured process variables.

The objective in this system is to manipulate feed and/or speed so that these measured process variables are maintained at or below their constrain limit values.

**4.4 Operation of an ACC System**

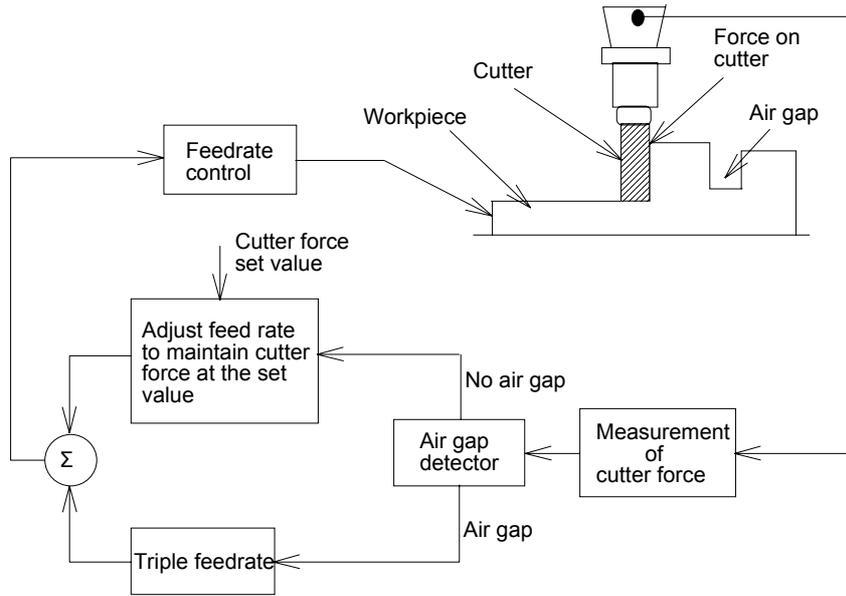
Typical applications of adaptive control machining are in profile or contour milling jobs on an NC machine tool. Feed is used as the controlled variable, and cutter force and horsepower are used as the measured variables.

The reasons to attach an adaptive controller to an NC machine tool are:

- NC machine tools often possess the required servomotors on the table axes to accept automatic control.
- The usual kinds of machining jobs for which NC is used possess the sources of variability that make AC feasible.

The typical hardware components are:

- Sensor mounted on the spindle
  - > cutter deflection(force, air gap)
- Sensor to measure spindle motor current
  - > provide an indication of power consumption
- Control unit/display panel to operate the system
- Interface H/W to connect the AC system to the existing NC or CNC control unit



## 5.0 Robot Definition

A robot is a programmable, multi-function manipulator designed to move material, parts, tools, or special devices through variable programmed motions for the performance of a variety of tasks.

General purpose robots are most likely to be economical and practical in applications with the following characteristics:

- Hazardous working conditions
- The job is repetitive
- The workpart to be moved is heavy

The typical applications performed by the robots are:

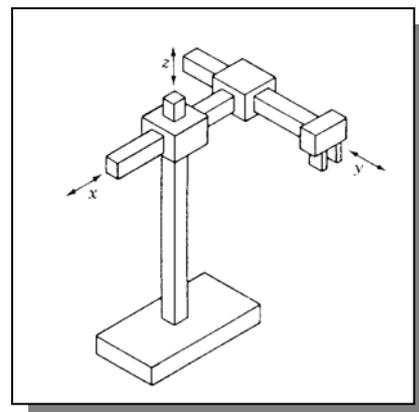
- Parts handling
- Machine loading and unloading
- Spray painting
- Welding
- Assembly

## 5.1 Robot Physical Configuration

Almost all present-day commercially available industrial robots have one of the following four configurations:

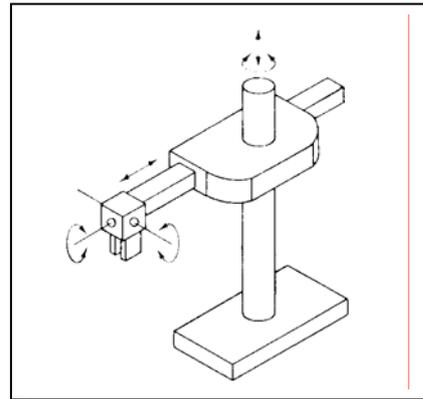
- Polar coordinate configuration

The robot has a rotary base and a pivot that can be used to raise and lower a telescoping arm. One of the most familiar robots, the Unimate Model 2000 series, was designed.



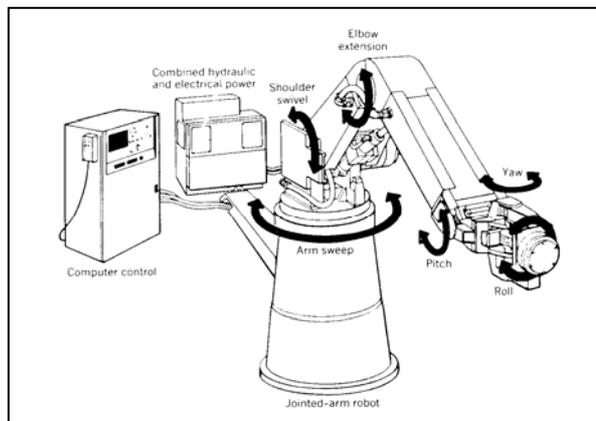
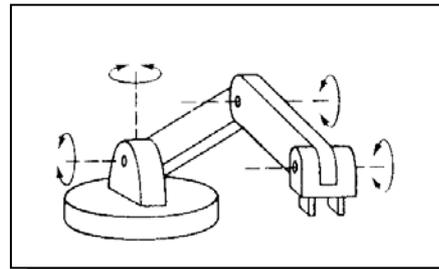
❑ Cylindrical coordinate configuration

The arm consists of several orthogonal slides which allow the arm to be moved up or down and in and out with respect to the body. The Prab Versatran Model FC is an example.



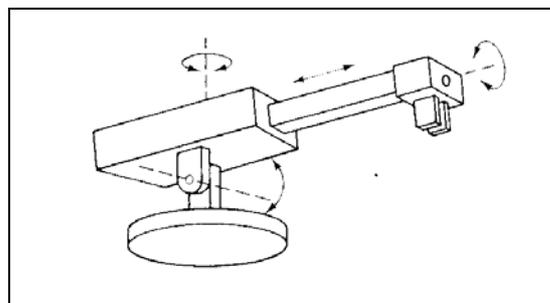
❑ Jointed arm configuration

The jointed arm configuration is similar to the human arm. The arm consists of several straight members connected by joints which are analogous to the human shoulder, elbow, and wrist. The arm is mounted to a base which can be rotated to provide the robot with the capacity to work within a quasi-spherical space. The Cincinnati Milacron T3 model and the Unimate PUMA model are examples.



❑ Cartesian coordinate configuration

The robot consists of three orthogonal slides. By appropriate movements of these slides, the robot is capable of moving its arm to any point within its three dimensional rectangularly shaped workspace.

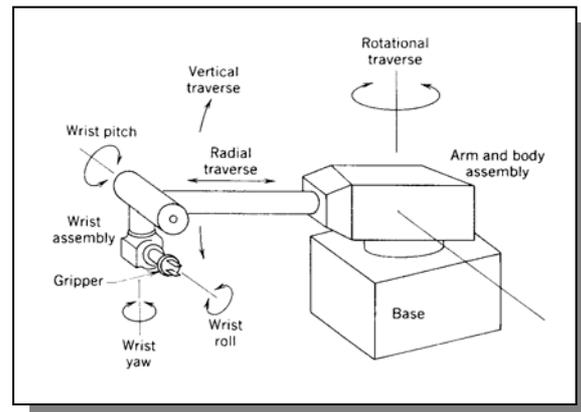


## 5.2 Basic Robot Motions

To do a useful task, the robot arm must be capable of moving the end effector through a sequence of motions and/or positions.

### 5.2.1 Six degrees of freedom

- ❑ Vertical transverse: up-and-down motions of arm, caused by pivoting the entire arm about a horizontal axis or moving the arm along a vertical slide.
- ❑ Radial traverse: extension and retraction of the arm ( in-and-out movement ).



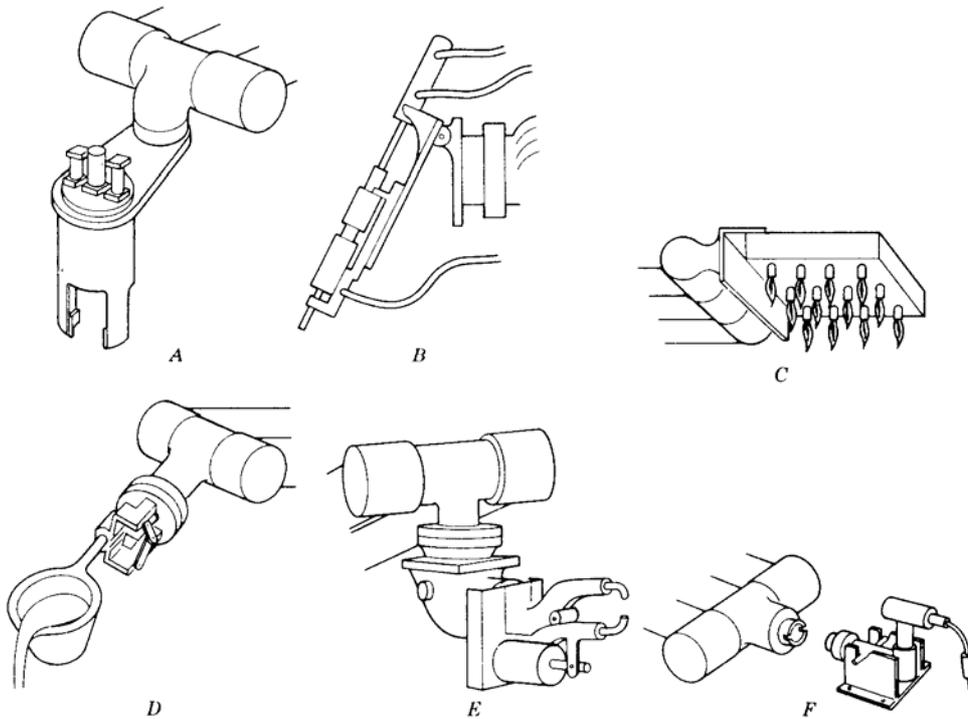
- ❑ Rotational traverse: rotation about the vertical axis ( right or left swivel of the robot arm ).
- ❑ Wrist swivel: rotation of the wrist.
- ❑ Wrist bend: up-or-down movement of the wrist, which also involves a rotational movement.
- ❑ Wrist yaw: right-or-left swivel of the wrist.

### 5.2.2 Motion systems

- ❑ Point to point (PTP)
- ❑ Contouring ( Continuous path )

### 5.3 End Effectors (末端受動器)

末端受動器類似於人的手，有時又稱為夾握器 (Gripper) 或臂端工具 (End-of-arm Tooling)。下圖A用來夾、摺或轉動螺帽；圖B用來焊接螺栓；圖C為火焰噴燈加熱；圖D為傾倒熔融金屬液；圖E為點焊；圖F為工具更換。



### 5.4 Programming the Robot

- Manual method
- Walkthrough method
- Leadthrough method
- Off-line programming

### 5.5 Robotic Sensors

For certain robot applications, the robot take on more humanlike senses and capabilities in order to perform the task in a satisfactory way.

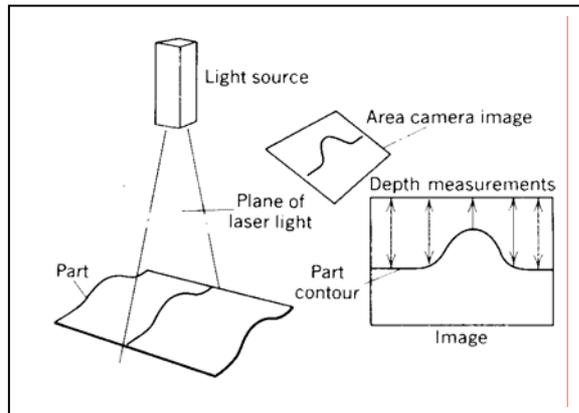
- Vision sensor : Vision capability would enable the robot to carry out the following kinds of operation:
  - Retrieve parts which are randomly oriented on a conveyor.
  - Recognize particular parts which are intermixed with other objects.

Perform visual inspection tasks.

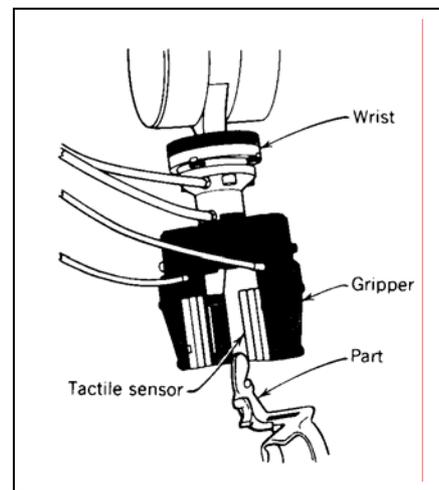
Perform assembly operations which require alignment.

右圖所示為利用三角量測法來定義輪廓的面積攝影機。

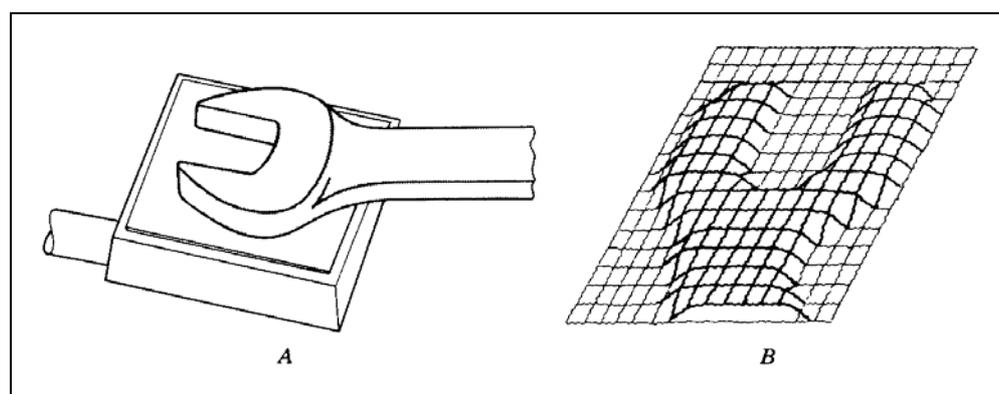
- Tactile (觸覺) and proximity sensors : Tactile sensors provide the robot with the capability to respond to contact forces between itself and other objects within its work volume.



右圖所示為裝有觸覺感測器的夾握器。



下圖A為觸覺感測器、圖B為感測器所顯示的扳手頭端外形。



- Voice sensors

## 5.6 Other Technical Features

- Work volume
- Precision of movement
- Speed of movement
- Weight-carrying capacity
- Type of drive system

### 5.6.1 Work volume

The work volume is the spatial region within which the end of the robot's wrist can be manipulated.

The work volume of an industrial robot is determined by its physical configuration, size, and the limits of its arm and joint manipulations.

### 5.6.2 Precision of movement

We describe the precision of movement as consisting of three attributes:

- Spatial resolution : The smallest increment of motion at the wrist end that can be controlled by the robot. This is determined by the robot's control resolution
- Accuracy : The accuracy of the robot refers to its capability to position its end at a given target point within its work volume.
- Repeatability : This refers to the robot's ability to position its wrist end back to a point in space that was previously taught.

### 5.6.3 Type of drive system

- Hydraulic
- Electric motor
- Pneumatic