NEHRU COLLEGE OF ENGINEERING AND RESEARCH CENTRE
(NAAC Accredited)
(Approved by AICTE, Affiliated to APJ Abdul Kalam Technological University, Kerala)

DEPARTMENT OF MECHATRONICS ENGINEERING

COURSE MATERIALS

MR 308 DIGITAL MANUFACTURING

VISION OF THE INSTITUTION
To mould true citizens who are millennium leaders and catalysts of change through excellence in education.
MISSION OF THE INSTITUTION
NCERC is committed to transform itself into a center of excellence in Learning and Research in Engineering and Frontier Technology and to impart quality education to mould technically competent citizens with moral integrity, social commitment and ethical values. We intend to facilitate our students to assimilate the latest technological know-how and to imbibe discipline, culture and spiritually, and to mould them in to technological giants, dedicated research scientists and intellectual leaders of the country who can spread the beams of light and happiness among the poor and the underprivileged.

ABOUT DEPARTMENT

- Established in: 2013
- Course offered: B.Tech Mechatronics Engineering
- Approved by AICTE New Delhi and Accredited by NAAC
- Affiliated to the University of Dr. A P J Abdul Kalam Technological University.

DEPARTMENT VISION

To develop professionally ethical and socially responsible Mechatronics engineers to serve the humanity through quality professional education.

DEPARTMENT MISSION

1) The department is committed to impart the right blend of knowledge and quality education to create professionally ethical and socially responsible graduates.

2) The department is committed to impart the awareness to meet the current challenges in technology.

3) Establish state-of-the-art laboratories to promote practical knowledge of mechatronics to meet the needs of the society

PROGRAMME EDUCATIONAL OBJECTIVES

I. Graduates shall have the ability to work in multidisciplinary environment with good professional and commitment.

II. Graduates shall have the ability to solve the complex engineering problems by applying electrical, mechanical, electronics and computer knowledge and engage in lifelong learning in their profession.

III. Graduates shall have the ability to lead and contribute in a team with entrepreneur skills, professional, social and ethical responsibilities.

IV. Graduates shall have ability to acquire scientific and engineering fundamentals necessary for higher studies and research.

PROGRAM OUTCOME (PO'S)

Engineering Graduates will be able to:

PO 1. Engineering knowledge: Apply the knowledge of mathematics, science, engineering fundamentals, and an engineering specialization to the solution of complex engineering problems.

PO 2. Problem analysis: Identify, formulate, review research literature, and analyze complex engineering problems reaching substantiated conclusions using first principles of mathematics, natural sciences, and engineering sciences.

PO 3. Design/development of solutions: Design solutions for complex engineering problems and design system components or processes that meet the specified needs with appropriate consideration for the public health and safety, and the cultural, societal, and environmental considerations.

PO 4. Conduct investigations of complex problems: Use research-based knowledge and research methods including design of experiments, analysis and interpretation of data, and synthesis of the information to provide valid conclusions.

PO 5. Modern tool usage: Create, select, and apply appropriate techniques, resources, and modern engineering and IT tools including prediction and modeling to complex engineering activities with an understanding of the limitations.

PO 6. The engineer and society: Apply reasoning informed by the contextual knowledge to assess societal, health, safety, legal and cultural issues and the consequent responsibilities relevant to the professional engineering practice.

PO 7. Environment and sustainability: Understand the impact of the professional engineering solutions in societal and environmental contexts, and demonstrate the knowledge of, and need for sustainable development.

PO 8. Ethics: Apply ethical principles and commit to professional ethics and responsibilities and norms of the engineering practice.

PO 9. Individual and team work: Function effectively as an individual, and as a member or leader in diverse teams, and in multidisciplinary settings.

PO 10. Communication: Communicate effectively on complex engineering activities with the engineering community and with society at large, such as, being able to comprehend and write effective reports and design documentation, make effective presentations, and give and receive clear instructions.

PO 11. Project management and finance: Demonstrate knowledge and understanding of the engineering and management principles and apply these to one's own work, as a member and leader in a team, to manage projects and in multidisciplinary environments.

PO 12. Life-long learning: Recognize the need for, and have the preparation and ability to engage in independent and life-long learning in the broadest context of technological change.

PROGRAM SPECIFIC OUTCOME(PSO'S)

PSO 1: Design and develop Mechatronics systems to solve the complex engineering problem by integrating electronics, mechanical and control systems.

PSO 2: Apply the engineering knowledge to conduct investigations of complex engineering problem related to instrumentation, control, automation, robotics and provide solutions.

COURSE OUTCOME

After the completion of the course the student will be able to

CO 1	**Develop** the knowledge in CIM and Numerical control machines
CO 2	**Understand** and familiarize in NC part programming
CO 3	**Understand** various controls in computer integrated manufacturing
CO 4	**Analyze** various sensors used in manufacturing and automation
CO 5	**Understand** various quality control and condition monitoring in manufacturing
CO 6	**Analyze** different techniques used in planning, data collection and automatic identification methods

CO VS PO'S AND PSO'S MAPPING

CO	PO1	PO 2	PO3	PO 4	PO5	PO6	PO7	PO8	PO9	PO10	PO11	PO12	PS0 1	PSO 2
CO 1	3		3		2	-	-	-	-	-	-	3	3	3
CO 2	3	3	3	3	2	-	-	-	-	-	-	2	2	2
CO 3	3		3		2	-	-	-	-	-	-	2	2	2
CO 4	3	2	3		-	-	-	-	-	-	-	2	3	3
CO 5	3				-	-	-	-	-	-	-	3	3	3
CO 6	3	2	2		2	-	-	-	-	-	-	2	2	2

Note: H-Highly correlated=3, M-Medium correlated=2, L-Less correlated=1

SYLLABUS

Course code	Course Name	L-T-P - Credits	Year of Introduction
MR308	Digital Manufacturing	3-0-0 -3	2016

Prerequisite : NIL

Course Objectives

- To impart knowledge in FMS and shop floor control.
- To give knowledge in CNC machines and their programming.
- To enlighten on the working principles of various sensors in digital manufacturing.

Syllabus

Introduction to Computer Integrated Manufacturing- - classification - open loop and closed loop systems - special tool holders- Automatic tool changers. NC part programming - part programming examples. Controls in CIM- material handling in CIM- AGV- Vehicle guidance- vehicle management and safety automated storage systems- ASRS components and operations- features of ASRS- Quality control Condition monitoring of manufacturing systems – Role of sensors in manufacturing automation-operation principles of different sensors in Robotics and manufacturing – pneumatic- Light sensors– encoder- resolver- potentiometers- range- proximity – Temperature sensors -Pressure sensors –position sensors- displacement and velocity sensors. – sensors for monitoring force- vibration and noise. Acoustics emission sensors-principles and applications- concept of tool wear and its monitoring-MRP-MRPII-Shop floor control –Factory data collection systems – Automatic identification methods – Bar code technology- magnetic strips- automated data collection system – Agile manufacturing-flexible manufacturing.

Expected outcome

The students will

i. Understand the concept of FMS and shop floor control.
ii. Get knowledge on the construction and working of sensors used in robotics and digital manufacturing.
iii. Get knowledge in automatic identification methods.

Text Books:

1. Sabrie Salomon, Sensors and Control Systems in Manufacturing, McGraw Hill Int. Ed., 1994.
2. Mikell P. Groover, Automation Production System and Computer Integrated Manufacturing, Prentice Hall of India Ltd., 2001
3. Patranabis .D, Sensors and Transducers, Wheeler publishers, 1994.
4. S.R.Deb, Robotics technology and flexible automation, Tata McGraw Hill publishing Co. Ltd., 1994.

References:

1. Richard D. Klafter, Robotic Engineering, Prentice Hall of India Pvt., Ltd., 2001.
2. Julian W. Gardner, Micro Sensor MEMS and Smart Devices, John Wiley & Sons, 2001
3. Randy Frank, Understanding Smart Sensors, Artech house, USA, 1996

Course Plan

Module	Contents	Hours	Sem. Exam Marks
I	Introduction to Computer Integrated Manufacturing- fundamentals of numerical control and Computer Numerical Control- advantages of NC system - classification of NC system - open loop and closed loop systems - special tool	7	15%
	holders- Automatic tool changers – Digital inspection		
II	NC part programming - manual programming - part programming examples- point to point programming and contour programming- computer aided programming concepts- post processor- program languages- APT- programming - part programming examples.	7	15%
FIRST INTERNAL EXAMINATION			
III	Controls in CIM- material handling in CIM- AGV- Vehicle guidance- vehicle management and safety automated storage systems- ASRS components and operations- features of ASRS-	7	15%
IV	Introduction – Role of sensors in manufacturing automation- operation principles of different sensors in Robotics and manufacturing – pneumatic- Light sensors– encoder- resolver- potentiometers- range- proximity- – Temperature sensors - Pressure sensors –position sensors- displacement and velocity sensors.	7	15%
SECOND INTERNAL EXAMINATION			
V	Quality control Condition monitoring of manufacturing systems-principles –sensors for monitoring force- vibration and noise. Acoustics emission sensors-principles and applications- concept of tool wear and its monitoring	7	20%
VI	MRP-MRPII-Shop floor control –Factory data collection systems – Automatic identification methods – Bar code technology- magnetic strips- automated data collection system – Agile manufacturing-flexible manufacturing	7	20%
END SEMESTER EXAM			

QUESTION BANK

MODULE I				
Q:NO:	**QUESTIONS**	**CO**	**KL**	**PAGE NO:**
1	What is numerical control?	CO1	K2	13
2	What are the basic components of NC system?	CO1	K2	14
3	What is right hand rule in NC and where it is used?	CO1	K2	15
4	What is point to point and continuous path control in a motion control system?	CO1	K2	15
5	How is CNC distinguished from conventional NC?	CO1	K2	21
6	What is distributed numerical control(DNC) ?	CO1	K2	28
7	What is machining center?	CO1	K2	25
8	What are three advantages of implementing NC technology	CO1	K2	40
9	Explain NC coordinate system in detail.	CO1	K2	15
10	What are features of CNC?	CO1	K3	22
11	With neat sketch explain in detail about machine control unit for CNC?	CO1	K2	24
12	List out the software used in CNC?	CO1	K3	27
MODULE II				

1	What is the difference between manual part programing and computer assisted part programming?	CO2	K2	43
2	What is the post processing in computer assisted programming?	CO2	K2	45
3	What is the manual data input of the NC part program?	CO2	K2	52
4	Explain NC part programming using CAD/CAM?	CO2	K2	54
5	Explain common G words used in manual part program.	CO2	K2	51
6	List out any five M words and their functions.	CO2	K3	52
7	Write one example of manual part program with neat fig.	CO2	K4	58
8	Write one example of program using APT with neat fig.	CO2	K4	64
MODULE III				
1	Provide a definition of material handling	CO3	K2	79
2	Name the four major categories of material handling equipment.	CO3	K2	83
3	What is included within the term unitizing equipment?	CO3	K2	85
4	What is unit load principle?	CO3	K3	84
5	Give some examples of industrial truck used in material handling.	CO3	K2	84
6	What is an automated guided vehicle system?	CO3	K3	86
7	Name the three categories of AGV.	CO3	K2	86

8	What is a conveyor?	CO3	K2	84
9	What are the categories of automated storage systems?	CO3	K2	93
10	Identify the three application of AS/RS.	CO3	K2	101
	MODULE IV			
1	What are benefits of sensors?	CO4	K2	103
2	Explain light sensors in detail.	CO4	K1	108
3	What are the applications of light sensors?	CO4	K2	111
4	What you mean by encoders? Explain in detail.	CO4	K2	113
5	Write a short note on resolver.	CO4	K1	116
6	Explain the working of a potentiometer with fig.	CO4	K2	118
7	How does temperature sensor work.	CO4	K3	122
8	Explain most common type of pressure sensors.	CO4	K3	129
9	Explain LVDT with neat fig.	CO4	K2	136
10	Explain displacement and velocity sensors with fig.	CO4	K2	146
	MODULE V			
1	What are the methods of condition monitoring?	CO5	K2	149
2	Explain the types of condition monitoring system.	CO5	K2	151
3	Explain vibration monitoring system with fig.	CO5	K3	156
4	Explain working of acoustic emission sensor.	CO5	K2	159
5	How to determine tool wear?	CO5	K3	161

6	What are measurement parameters for tool wearing?	CO5	K2	162
MODULE VI				
1	Define MRP	CO6	K2	165
2	Compare MRP and MRP II	CO6	K2	167
3	What are three phases of shop floor control?	CO6	K2	168
4	Explain automatic identification methods.	CO6	K2	174
5	Explain barcode technology.	CO6	K2	174
6	Write a short note of FMS?	CO6	K2	179
7	Differentiate agile manufacturing and FMS.	CO6	K2	175

APPENDIX 1

CONTENT BEYOND THE SYLLABUS

S:NO;	TOPIC	PAGE NO:
1	CONDITION MONITORING FOR MACHINERIES	150
2	LEAN PRODUCTION	175
3	CELLULAR MANUFACTURING	88

MODULE 1

Fundamentals of numerical control

Numerical control (NC) is a form of programmable automation in which the mechanical actions of a machine tool or other equipment are controlled by a program containing coded alphanumeric data. The alphanumerical data represent relative positions between a workhead and a workpart as well as other instructions needed to operate the machine. The workhead is a cutting tool or other processing apparatus, and the workpart is the object being processed, When the current job is completed. the program of instructions can be changed to process a new job. The capability to change the program makes NC suitable for low and medium production. It is much easier to write new programs than to make major alterations of the processing equipment.

Numerical control can be applied to a wide variety of processes. The applications divide into two categories; (Il machine tool applications, such as drilling, milling, turning, and other metal working; and (2) non machine tool applications such as assembly, drafting, and inspection. The common operating feature of *NC* in all of these applications is control of the workhead movement relative to the work part.

FUNDAMENTALS OF NC TECHNOLOGY

a. Basic Components of an NC System

b. NC Coordinate Systems

c. Motion Control Systems

To introduce NC technology, we First define the basic components of an NC system. This is followed by a description of NC coordinate systems in common use and types of motion controls used in NC.

BASIC COMPONENTS OF AN NC SYSTEM

An NC system consists of three basic components: (1) a program of instructions, (2) a machine control unit, and (3) processing equipment. The general relationship among the three components is illustrated in Figure 6.1.

The *program of instructions* is the detailed step by step commands that direct the actions of the processing equipment. In machine tool applications, the program of instructions is called a *part program*, and the person who prepares the program is called a *part programmer*. In these applications, the individual commands refer to positions of a cutting tool relative to the worktable on which the workpart is fixtured. Additional instructions are usually included, such as spindle speed, feed rate, cutting tool selection, and other functions. The program is coded on a suitable medium for submission to the machine control unit. For many years, the common medium was 1-inch wide punched tape, using a standard format that could be interpreted by the machine control unit. Today, punched tape has largely been replaced by newer storage technologies in modern machine shops. These technologies include magnetic tape, diskettes, and electronic transfer of part programs from a computer.

In modern NC technology, the *machine control unit* (MCU) consists or a microcomputer and related control hardware that stores the program of instructions and executes it by converting each command into mechanical actions of the processing equipment, one command at a time. The related hardware of the Mel) includes components to interface with the processing equipment and reedbuck control elements. The MCU also includes one *or* more reading devices lor entering part programs into memory. Software residing in the MCU also includes control system software. calculation algorithms. and translation software to convert the NC part program into a usable format for the MCU, Because the MCU is a computer, the term *computer numerical control (CNC)* is used to distinguish this type of NC from its technological predecessors that wen: based entirely on hard-Wired electronics. Today, virtually all new MCUs are based on computer technology; hence. when we refer to NC in this chapter and elsewhere, we mean CNC

The third basic component of an NC system is the *processing equipment* that performs actual productive work. It accomplishes the processing steps to transform the starting workpiece into a completed part .Its operation is directed by the MCU, which in turn is driven by instruction, contained in the part program. In the most common example of NC machining, the processing equipment consists of the worktable and spindle as well as the motors and controls to drive them

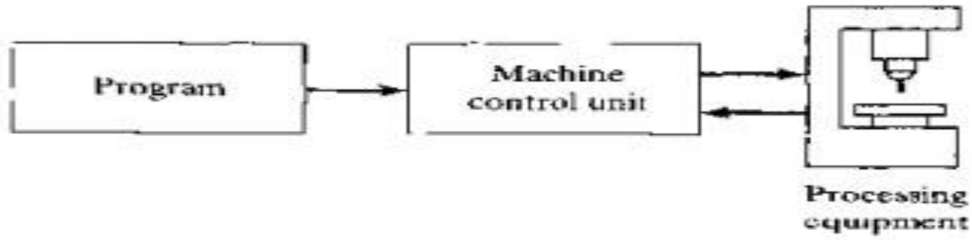


Figure 6.1 Basic components of an NC system.

NC Coordinate Systems

To program the NC processing equipment, a part programmer must defined a standard axis system must by which the position of the workhead relative to the workpart can be specified. There are two axis systems used in NC, one for flat and prismatic workparts and the other for rotational parts. Both axis systems are based on the Cartesian coordinate system.

The axis system for flat and prismatic parts consists of the three linear axes *(x,* y, *z)* in the Cartesian coordinate system, plus three rotational axes *(a, b, c),* as shown in Figure 6.2(a). In most machine tool applications, the x and y axes are used to move and position the worktable to which the part is attached, and the z-axis is used to control the vertical position of the cutting tool. Such a positioning scheme is adequate for simple NC applications such as drilling and punching of flat sheet metal. Programming of these machine tools consists of little more than specifying a sequence of *xy* coordinates.

The *a, b,* and c rotational axes specify angular positions about the *x, y* and z axes respectively, To distinguish positive from negative angles, the *righthand rule* is used. Using the right hand with the thumb pointing in the positive linear axis direction *(+x, +y,* or *+z),* the fingers of the hand are curled in the positive rotational direction. The rotational axes can be used for one or both of the following: (1) orientation of the workpart to present different surfaces for machining or (2) orientation of the tool or workhead at some angle relative to the part. These additional axes permit machining of complex workpart geometries.

Machine tools with rotational axis capability generally have either four or five axes: three linear axes plus one or two rotational axes. Most NC machine tool systems do not require all six axes.

The coordinate axes for a rotational NC system are illustrated in Figure 6.2(b). These systems are associated with NC lathes and turning centers. Although the work rotates, this is not one of the controlled axes on most of these turning machines. Consequently, the y axis is not used. The path of the cutting tool relative to the rotating workpiece is defined in the x-z plane, where the x axis is the radial location of the tool, and the z axis is parallel to the axis of rotation of the part.

The part programmer must decide where the origin of the coordinate axis system should be located. This decision is usually based on programming convenience. For example, the origin might be located at one of the corners of the part. If the workpart is sym

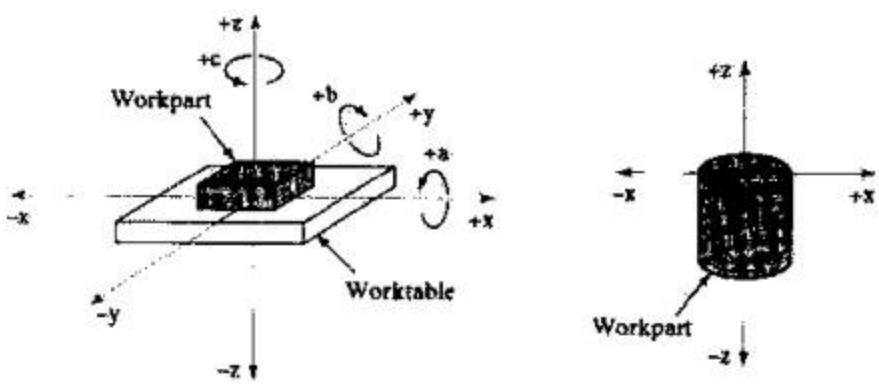


Figure 6.2 Coordinate systems used in NC: (a) for flat and prismatic work and (b) for rotational work. (On most turning machines, the z-axis is horizontal rather than vertical as we have shown it.)

metrical, the zero point might be most conveniently defined at the center of symmetry. wherever the location this zero point is communicated to the machine tool operator. At the beginning of the job, the operator must move the cutting tool under manual control to some *target point* on the worktable, where the tool can be easily and accurately positioned. The target point has been previously referenced to the origin of the coordinate axis system by the part programmer. When the tool has been accurately positioned at the target point, the operator indicates to the MCU where the origin is located for subsequent tool movements

Motion Control Systems

Some NC processes are performed at discrete locations on the workpart (e.g., drilling and spot welding). Others are carried out while the workhead is moving (e.g., turning and continuous arc welding). If the workhead is moving, it may be required to follow a straight line path or a circular or other curvilinear path. These different types of movement are accomplished by the motion control system, whose features are explained below.

Point to Point Versus Continuous Path Control. Motion control systems for NC can be divided into two types: (1) point to point and (2) continuous path. *Point to point systems* also called *positioning systems*, move the worktable to a programmed location without regard for the path taken to get to that location. Once the move has been completed, some processing action is accomplished by the workhead at the location. such as drilling or punching a hole. Thus, the program consists of a series of point locations at which operations are performed, as depicted in Figure 6.3.

Continuous path systems generally refer to systems that are capable of continuous simultaneous control of two or more axes. This provides control of the tool trajectory relative to the workpart. In this case, the tool performs the process while the worktable is moving, thus enabling the system to generate angular surfaces, two dimensional curves, or three dimensional contours in the workpart. This control mode is required in many milling and turning operations. A simple two dimensional profile milling operation is shown in Figure 6.4 to illustrate continuous path control. When continuous path control is utilized to move the tool parallel to only one of the major axes of the machine tool worktable, this is called *straight cut NC*. When continuous path control is used for simultaneous control of two or more axes in machining operations, the term *contouring* is used.

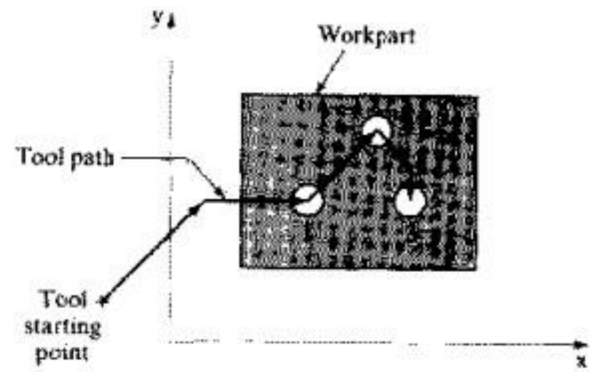


Figure 6.3 Point-to-point (positioning) control in NC. At each x-y position, table movement stops to perform the hole-drilling operation.

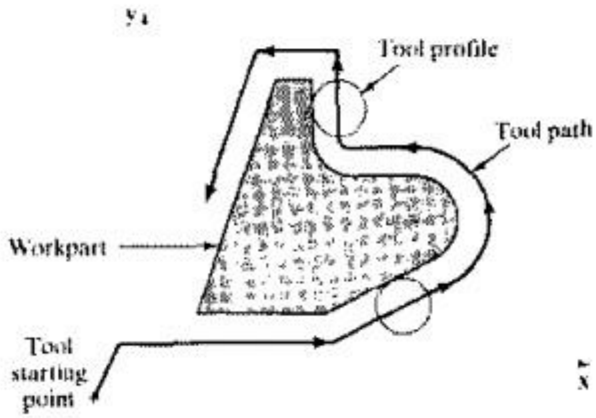


Figure 6.4 Continuous path (contouring) control in NC (x-y plane only). Note that cutting tool path must be offset from the part outline by a distance equal to its radius.

Interpolation Methods. One of the important aspects of contouring is interpolation. The paths that a contouring type NC system is required to generate often consist of circular arcs and other smooth nonlinear shapes. Some of these shapes can be defined mathematically by relatively simple geometric formulas (e.g., the equation for a circle is $X^2 + y^2 = R^2$•where R = the radius of the circle and the center of the circle is at the origin), whereas others cannot be mathematically defined except by approximation. In any case, a fundamental problem in generating these shapes using NC equipment is that they are continuous, whereas NC is digital. To cut along a circular path, the circle must be divided into a series of straight line segments that approximate the curve. The tool is commanded to machine each line segment in succession so that the machined surface closely matches the desired shape. The maximum error between the nominal (desired) surface and the actual (machined) surface can be controlled by the lengths of the individual line segments, as explained in Figure 6.5.

If the programmer were required to specify the endpoints for each of the line segments, the programming task would be extremely arduous and fraught with errors. Also, the part program would be extremely long because of the large number of points. To ease the burden, interpolation routines have been developed that calculate the intermediate points to be followed by the cutter to generate a particular mathematically defined or approximated path.

A number of interpolation methods are available to deal with the various problems encountered in generating a smooth continuous path in contouring. They include: (1) linear interpolation, (2) circular interpolation, (3) helical interpolation, (4) parabolic interpolation, and (5) cubic interpolation. Each of these procedures, briefly described in Table 6.1, permits the programmer to generate machine instructions for linear or curvilinear paths using relatively few input parameters. The interpolation module in the MCU performs the calculations and directs the tool along the path. In CNC systems, the interpolator is generally accomplished by software. Linear and circular interpolators are almost always included in modem CNC systems, whereas helical interpolation is a common option. Parabolic and cubic interpolations are less common; they are only needed by machine shops that must produce complex surface contours.

Absolute Versus Incremental Positioning. Another aspect of motion control is concerned with whether positions are defined relative to the origin of the coordinate system

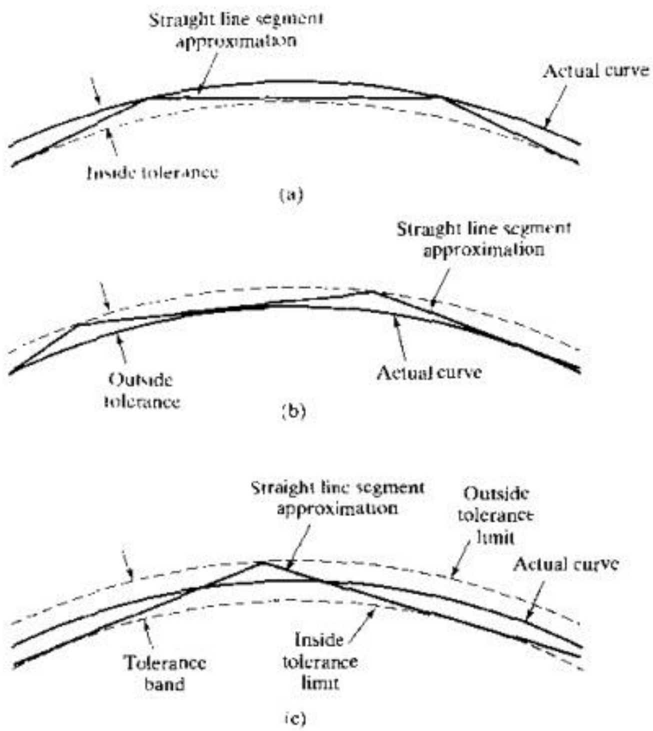


Figure 6.5 Approximation of a curved path in NC by a series of straight line segments. The accuracy of the approximation is controlled by the maximum deviation (called the tolerance) between the nominal (desired) curve and the straight line segments that are machined by the NC system. In (a) the tolerance is defined on only the inside of the nominal curve. In (b) the tolerance is defined on only the outside of the desired curve. In (c) the tolerance is defined on both the inside and outside of the desired curve.

Figure 6.5 Approximation of a curved path in NC by a series of straight line segments. The accuracy of the approximation is controlled by the maximum deviation (called the tolerance) between the nominal (desired) curve and the straight line segments that are machined by the NC system. In (a) the tolerance is defined on only the inside of the nominal curve. In (b) the tolerance is defined on only the outside of the desired curve. In (c) the tolerance is defined on both the inside and outside of the desired curve.

Linear interpolation. This is the most basic and is used when a straight line path is to be generated in continuous path NC. Two axis and three axis linear interpolation routines are sometimes distinguished in practice, but conceptually they are the same. The programmar specifies the beginning point and end point of the straight line and the feed rate to be used along the straight line. The interpolator computes the feed rates for each of the two (or three) axes to achieve the specified feed rate.

Circular interpolation. This method permits programming of a circular arc by specifying the following parameters: (1) the coordinates of the starting point, (2) the coordinates of the endpoint, (3) either the center or radius of the arc, and (4) the direction of the cutter along the *arc*. The genarated tool path consists of a series of small straight line segments calculated by the interpolation module. The cutter is directed to move along each line segment one by one to generate the smooth circular path. A limitation of circular interpolation is that the plane in which the circular arc exists must be a plane defined by two *axes* of the NC system (x *y, x* Z, or *y* Z)

Helical interpolation. This method combines the circular interpolation scheme for two axes described above with linear movement of a third axis. This permits the definition of a helical path in three-dimensional space. Applications include the machining of large internal threads, either straight or tapered.

Parabolic and *cubic interpolations.* These routines provide approximations of free form curves using higher order equations. They generally require considerable computational power and are not as common as linear and circular interpolation. Most applications are in the aerospace and automotive industries for free form designs that cannot accurately and conveniently be approximated by combining linear and circular interpolations.

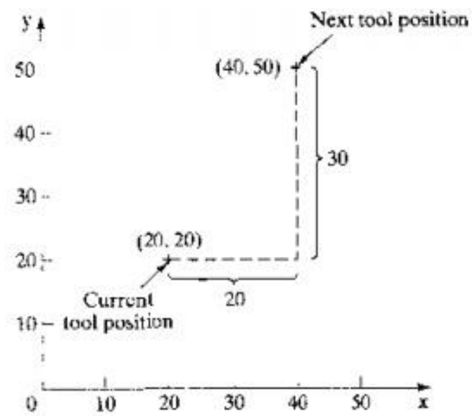


Figure 6.6 Absolute versus incremental positioning. The workhead is presently at point (20, 20) and is to be moved to point (40, 50). In absolute positioning, the move is specified by $x = 40$, $y = 50$; whereas in incremental positioning, the move is specified by $x = 20$, $y = 30$.

or relative to the previous location of the tool. The two cases are called absolute positioning and incremental positioning. In *absolute positioning,* the workhead locations are always defined with respect to the origin of the axis system. In *incremental positioning,* the next workhead position is defined relative to the present location. The difference is illustrated in Figure 6.6.

COMPUTER NUMERICAL CONTROL

Since the introduction of NC in 1952, there have been dramatic advances in digital computer technology. The physical size and cost of 11digital computer have been significantly reduced at the same time that its computational capabilities have been substantially increased. It was logical for the makers of NC equipment to incorporate these advances in computer technology into their products, starting first with large mainframe computers in the 1960s, followed by minicomputers in the 1970s, and microcomputers in the 1980s (Historical Note 6.2). Today, NC means computer numerical control. *Computer numerical control* (CNC) is defined as an NC system whose *MeV* is based on a dedicated microcomputer rather than on a hardwired controller.

Features of CNC

Computer NC systems include additional features beyond what is feasible with conventional hardwired NC. These features, many of which are standard on most CNC *MCVs* whereas others are optional, include rhc following'

Storage of more than one part program. With improvements in computer storage technology. newer *CNC* controllers have sufficient capacity to store multiple programs. Controller manufacturers generally offer one or more memory expansions as options to the MCU.

Various forms of program input. Whereas conventional (hardwired) MCUs are limited to punched tape as the input medium for entering part programs. CNC controllers generally possess multiple data entry capabilities, such as punched tape (if the machine shop still uses punched tape), magnetic tape. floppy diskette. RS232 communications with external computers, and manual data input (operator entry of program).

Program editing at the machine tool. CNC permits a part program to be edited while it resides in the *MCV* computer memory. Hence, the process of testing and correcting a program can be done entirely at the machine sire, rather than returning to the programming office for corrections. In addition to part programm corrections. editing also permits optimizing cutting conditions in the machining cycle to be optimized. After the programme has been corrected and optimized,the revised version can be stored on punched tape or other media for future use

Fixed cycles and programming subroutines. The increased memory capacity and the ability to programme control computer provide the opportunity to store frequently used machining cycles as *macros* that can be called by the part program. Instead of writing the full instructions for the particular cycle into every program, a call statement is included in the part program to indicate that the macro cycle should be executed. These cycles often require that certain parameters be defined; for example. a bolt hole circle, in which the diameter of the bolt circle, the spacing of the bolt holes, and other parameters must be specified.

Interpolation. Some of the interpolation schemes described in Table 6.1 are normally executed only on a CNC system because of the computational requirements. Linear and circular interpolation arc sometimes hardwired into the control unit, but helical, parabolic, and cubic interpolations are usually executed in a stored program algorithm.

Positioning features for setup. Setting up the machine tool for a given work part involves installing and aligning a fixture on the machine tool table. This must be accomplished so that the machine axes are established with respect to the workpart, The alignment task can be facilitated using certain features made possible by software options in a CNC system. *Position set* is one of these features. With position set , the operator is not required to locate the fixture on the machine table with extreme accuracy. Instead, the machine tool axes are referenced to the location of the fixture by using a target point or set of target points on the work or fixture.

Cutter length and size compensation. **In** older style controls, cutter dimensions had 10 be set very precisely to agree with the tool path defined in the part program. Alternative methods for ensuring accurate tool path definition have been incorporated into CNC controls. One method involves manually entering the actual 1001dimensions into the MCU. These actual dimensions may differ from those originally programmed Compensations arc then automatically made in the computed tool path. Another method involves use of a tool length sensor built into the machine. In this technique. the cutter is mounted in the spindle and the sensor measures its length. This measured value is then used to correct the programmed tool path.

Acceleration and deceleration calculations, This feature is applicable when the cutter moves at high feed rates. It is designed to avoid tool marks on the work surface that would be generated due to machine tool dynamics when the cutter path changes abruptly. Instead, the feed rate is smoothly decelerated in anticipation of a tool path change and then accelerated back up to the programmed feed rate after the direction change.

Communications interface. With the trend toward interfacing and networking in plants today, most modem CNC con/rollers are equipped with a standard RS232 or other communications interface to allow the machine to be linked to other computers and computer driven devices. This is useful for various applications, such as: (1) downloading part programs from a central data file as in distributed NC; (2) collecting operational data such as workpiece counts, cycle times, and machine utilization; and interfacing with peripheral equipment. such as robots that load and unload parts.

Diagnostics. Many modern CNC systems possess an online diagnostics capability that monitors certain aspects of the machine tool to detect malfunctions or signs of impending malfunctions or to diagnose system breakdowns. Some of the common features of a CNC diagnostics system are listed in Table

The Machine Control Unit for CNC

The MCU is the hardware that distinguishes CNC from conventional NC. The general configuration of the MCU in a CNC system is illustrated in Figure 6.7. The *MCU* consists of the following components and subsystems: (I) central processing unit, (2) memory (3) I/O interface. (4) controls for machine tool axes and spindle speed. and (5) sequence controls for other machine tool functions. These subsystems are interconnected by means of a system bus. as indicated in the figure,

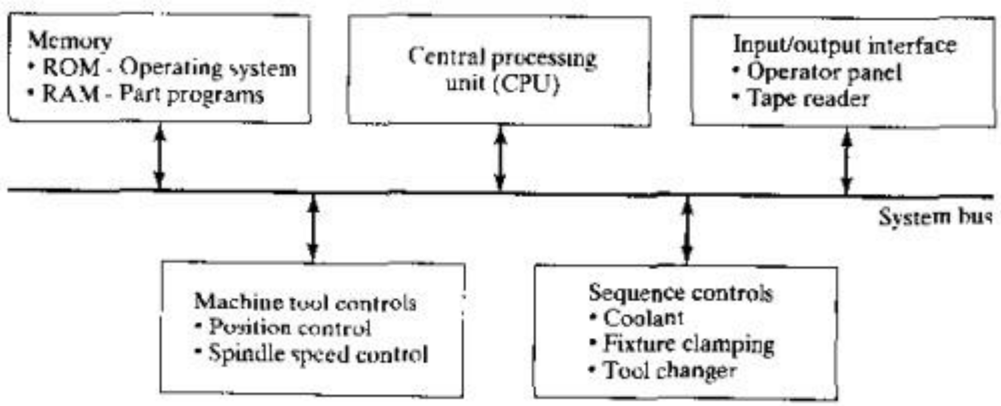


Figure 6.7 Configuration of CNC machine control unit.

Central Processing Unit. The central processing unit (CPU) is the brain of the *MCU.* It manages the other components in the MCU based on software contained in main memory. The CPU can be divided into three sections: (1) control section, (2) arithmetic logic unit, and (3) immediate access memory. The *control section* retrieves commands and data from memory and generates signals to activate other components in the MCU. In short it sequences. Coordinates and regulates all of the activities of the MCU computer. The *arithmetic logic unit* (ALU) consists of the circuitry to perform various calculations (addition, subtraction, multiplication), counting. and logical functions required by software residing in memory. The *immediate access memory* provides a temporary storage for data being processed by the CPu. It is connected to main memory by means of the system data bus.

Memory. The immediate access memory in the CPU is not intended for storing CNC software, A much greater storage capacity is required for the various programs and data needed to operate the CNC system. As with most other computer systems, CNC memory can be divided into two categories: (I) main memory and (2) secondary memory. *Main memory* (also known as *primary storage)* consists of ROM (read only memory) and RAM (random access memory) devices. Operating system software and machine interface programs (Section 6.2.3) are generally stored in ROM. These programs are usually installed by the manufacturer of the MCU. Numerical control part programs are stored in RAM devices. Current programs in RAM can he erased and replaced by new programs as jobs are changed.

High capacity *secondary memory* (also called *auxiliary storage* or *secondary storage)* devices are used to store large programs and data files, which are transferred to main memory as needed. Common among the secondary memory devices are floppy diskettes and hard disks. Floppy diskettes are portable and have replaced much of the punched paper tape traditionally used 10 store part programs. Hard disks are high capacity storage devices that are permanently installed in the CNC machine control unit. CNC secondary memory is used to store part programs, macros, and other software.

Input/Output Interface. The *I/O* interface provides communication between the various components of the CNC system, other computer systems. and the machine operator. As its name suggests, the *i/o* interface transmits and receives data and signals to and [rom external devices, several of which are indicated in Figure 6.7. The *operator control panel* is the basic interface by which the machine operator communicates to the CNC system. This is used to enter commands relating to part program editing, MCU operating mode (e.g .. program control vs. manual control),speeds and feeds, cutting fluid pump *on/off,* and similar functions. Either an alphanumeric keypad or keyboard is usually included in the operator control panel. The i/o interface also includes a *display* (CRT or LED) for communication of data and information from the *MCU* to the machine operator. The display is used to indicate current status of the program as it is being executed and to warn the operator of any malfunctions in the CNC system.

Also included in the i/o interface are one or more means of entering the part program into storage. As indicated previously, NC part programs are stored in a variety of ways, including punched tape. magnetic tape, and floppy disks. Programs can also be entered manually by the machine operator or stored at a central computer site and transmitted via *local area network* (LAN) to the CNC system, Whichever means is employed by the plant, a suitable device must be included in the i/O interface to allow input of the program into MCU memory.

Controls for Machine Tool Axes and Spindle Speed. These are hardware components that control the position and velocity (feed rate) of each machine axis as well as the rotational speed of the machine tool spindle. The control signals generated by MCU must be converted to a form and power level suited to the particular position control systems used to drive the machine axes. Positioning systems can be classified as open-loop or closed-loop, and different hardware components are required in each case. A more-detailed discussion of these hardware elements is presented in Section 6.6, together with an analysis of how they operate together to achieve position and feed rate control. For our purposes here, it is sufficient to indicate that some of the hardware components are resident in the MCU.

Depending on the type of machine tool, the spindle is used to drive either (1) the workpiece or (2) a rotating cutter. Turning exemplifies the first case, whereas milling and drilling exemplify the second. Spindle speed is a programmed parameter for most CNC machine tools. Spindle speed control components in the MCU usually consist of a drive control circuit and a feedback sensor interface. The particular hardware components depend on the type of spindle drive.

Sequence Controls for Other Machine Tool Functions. In addition to control of table position. feed rate. and spindle speed, several additional functions arc accomplished under pan program control. These auxiliary functions arc generally on/off (binary] actuations. interlocks. and discrete numerical data. A sampling of these functions is presented in Table 0.3. To avoid overloading the CPU, a programmable logic controller (Chapter H) is sometimes used to manage the i/0 interface for these auxiliary functions

Personal Computers and the MCU. In growing numbers, personal computers (PCs) are being used in the factory to implement process control and CNC is no exception. The basic configurations are being applied (1) the PC is used as a separate front- end interface for the MCU, and (2) the PC contains the motion control board and other hardware required to operate the machine tool. In the second case, the CNC control board fits into a standard slot of the P'C. In either configuration, the advantage of using a PC for CNC is its flexibility to execute a variety of user software in addition

TABLE 6.3 Examples of CNC Auxiliary Functions Often Implemented by a Programmable Logic Controller in the MCU

CNC Auxiliary Function	Type or Classification
Coolant control	On/off output from MCU to pump
Tool changer and tool storage unit	Discrete numerical data (possible values limited to capacity of tool storage unit)
Fixture clamping device	On/off output from MCU to clamp actuator
Emergency warning or stop	On/off input to MCU from sensor; on/off output to display and alarm
Robot for part loading/unloading	Interlock to sequence loading and unloading operation; I/O signals between MCU and robot
Timers	Continuous
Counters (e.g., piece counts)	Discrete numerical data (possible values limited to number of parts that can be produced in a given time period, such as a shift)

to and concurrently with controlling the machine tool operation. The user software might include programs for shop floor control. statistical process control, solid modelling ,cutting tool management, and other computer aided manufacturing software. Other benefits include improved case of use compared with conventional CNC and ease of networking the PCs, Possible disadvantages include (1) lost time to retrofit the PC for CNC. particularly when installing the CNC motion controls inside the PC

CNC Software

The computer in CNC operates by means of software. There are three types of software programs used in CNC systems: (I) operating system software, (2) machine interface software, and (3) application software.

The principal function of the *operating system software* is to interpret the NC part programs and generate the corresponding control signals to drive the machine tool axes. It is installed by the controller manufacturer and is stored in ROM in the MCU. The operating system software consists of the following: (1) an *editor,* which permits the machine operator to input and edit NC part programs and perform other file management functions: (2) a *control program,* which decodes the part program instructions, performs interpolation and acceleration/deceleration calculations, *and* accomplishes other related functions to produce the coordinate control signals for each axis and (3) an *executive program,* which manages the execution of the CNC software as well as the i/o operations of the MCU. The operating system software also includes the diagnostics routines that are available in the CNC system (Table 6.2).

The *machine interface software* is used to operate the communication link between the CPU and the machine tool to accomplish the CNC auxiliary functions (Table 6.3).As previously indicated, the I/O signals associated with the auxiliary functions arc sometimes implemented by means of a programmable logic controller interfaced to the MCU, and so the machine interface software is often written in the form of ladder logic diagrams

Finally, the *application software* consists of the NC part programs that are written for machining (or other) applications in the user's plant.

Direct Numerical Control

The first attempt to use a digital computer to drive the NC machine tool was DNC This was in the late 19605 before the advent of CNC. A; initially implemented. DNC involved the control or a number of machine tools by a single (mainframe) computer through direct connection and in real time. Instead of using a punched tape reader to enter the part program into the MCU, the program was transmitted to the MCU directly from the computer, one block of instructions at a time. This mode of operation was referred to by the name *behind the tape reader* (BTR). The one computer provided instruction blocks to the machine tool on demand; when a machine needed control commands, they were communicated to it immediately. As each block was executed by the machine, the next block was transmitted. As far as the machine tool was concerned, the operation was no different from that of a conventional NC controller. In theory, DNC relieved the NC system of its least reliable components: the punched tape and tape reader.

The general configuration of a one system is depicted in Figure 6.8. The system consisted of four components: (1) central computer, (2) bulk memory at the central computer site, (3) set of controlled machines, and (4) telecommunications lines to connect the machines to the central computer. In operation, the computer caned the required part program from bulk memory and sent it (one block at a time) to the designated machine tool. This procedure was replicated for all machine toots under direct control of the computer. One commercially available ONC system during the 1970s claimed to be capable of controlling up to 256 machines.

In addition to transmitting data to the machines, the central computer also received data back from the machines to indicate operating performance in the shop (e.g., number of machining cycle completed, machine utilization, and breakdowns). A central objective of one was to achieve two way communication between the machines and the central computer.

Advantages claimed for DNC in the early 19708 included: (1) high reliability of a central computer compared with individual hardwired MCUs; (2) elimination of the tape and tape reader, which were unreliable and errorprone; (3) control of multiple machines by one cornputer;(4) improved computational capability for circular interpolation; (5) part programs stored magnetically in bulk memory in a central location; and (6) computer located in an environmentally agreeable location. However, these advantages were not enough to persuade a conservative manufacturing community to pay the high investment cost for a ONC system, and some of the claimed advantages proved to be overly optimistic.

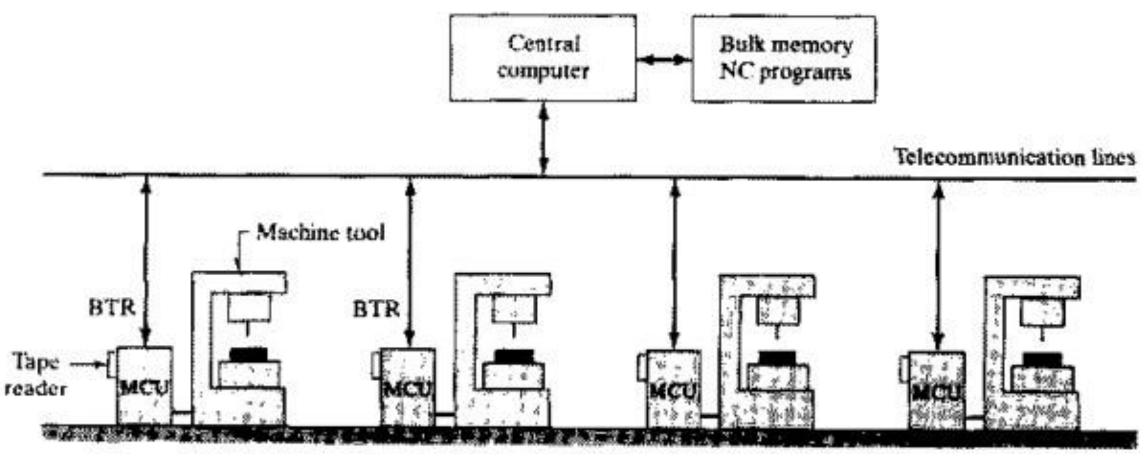


Figure 6.8 General configuration of a DNC system. Connection to MCU is behind the tape reader. Key: BTR = behind the tape reader, MCU = machine control unit.

For example, elimination of tape readers was unrealistic because of the need for an alternative way to load part programs in case the central computer went down. The installations of DNC were limited lathe aerospace industry. which had been involved in N(' technology since the beginning and possessed a larger number of NC machines. The.s~ machines were often dispersed throughout large factories, and DNC represented an efficient way to distribute part programs to the machines

Distributed Numerical Control

As the number of CNC machine installations grew during the 1970s and 19805, DNC emerged called distributed computer system, or *distributed numerical control* (DNC). The configuration of the new DNC is very similar to that shown In Figure 6.8 except that the central computer is connected to MCUs, which are themselves computers. This permits complete part programs to be sent to the machine tools. rather than one block at a time. It also permits easier and less costly installation of the overall system, because the individual CNC machines can be put into service and the distributed I\'C can be added later. Redundant computers improve system reliability compared with the original DNC. The new DNC permits two - way communication of data between the shop floor and the central computer. which was one of the important features included in the old DNC. However. improvements in data collection devices as well as advances in computer and communications technologies have expanded the range and flexibility of the information that can be gathered and disseminated. Some of the data and information sets included in the two-way communication flow are itemized in Table 6.4. This flow of information in DNC is similar to the information flow in shop floor control.

Distributed NC systems can take on a variety of physical configurations, depending on the number of machine tools included, job complexity, security requirements, and equipment availability and preferences. There are several ways to configure a ONC system. We illustrate two types in Figure 6.9: (a) switching network and (b) LAN. Each type has several possible variations.

Thc switching network is the simplest DNC system to configure. It uses a data switching box to make a connection from the central computer to a given CNC machine for downloading part programs or uploading data. Transmission of programs to the MCU is accomplished through a RS232C connection, (Virtually all commercial MCUs include the RS232C or compatible device as standard equipment today.) Use of a switching box limits the number of machines that can be included in the ONC system. The limit depends on

TABLE 6.4 Flow of Data and Information Between Central Computer and Machine Tools in DNC

Data and Information Downloaded from the Central Computer to Machine Tools and Shop Floor	*Data and Information Loaded from the Machine Tools and Shop Floor to the Central Computer*
NC part programs List of tools needed for job Machine tool setup instructions Machine operator instructions Machining cycle time for part program Data about when program was last used Production schedule information	Piece counts Actual machining cycle times Tool life statistics Machine uptime and downtime statistics, from which machine utilization and reliability can be assessed Product quality data

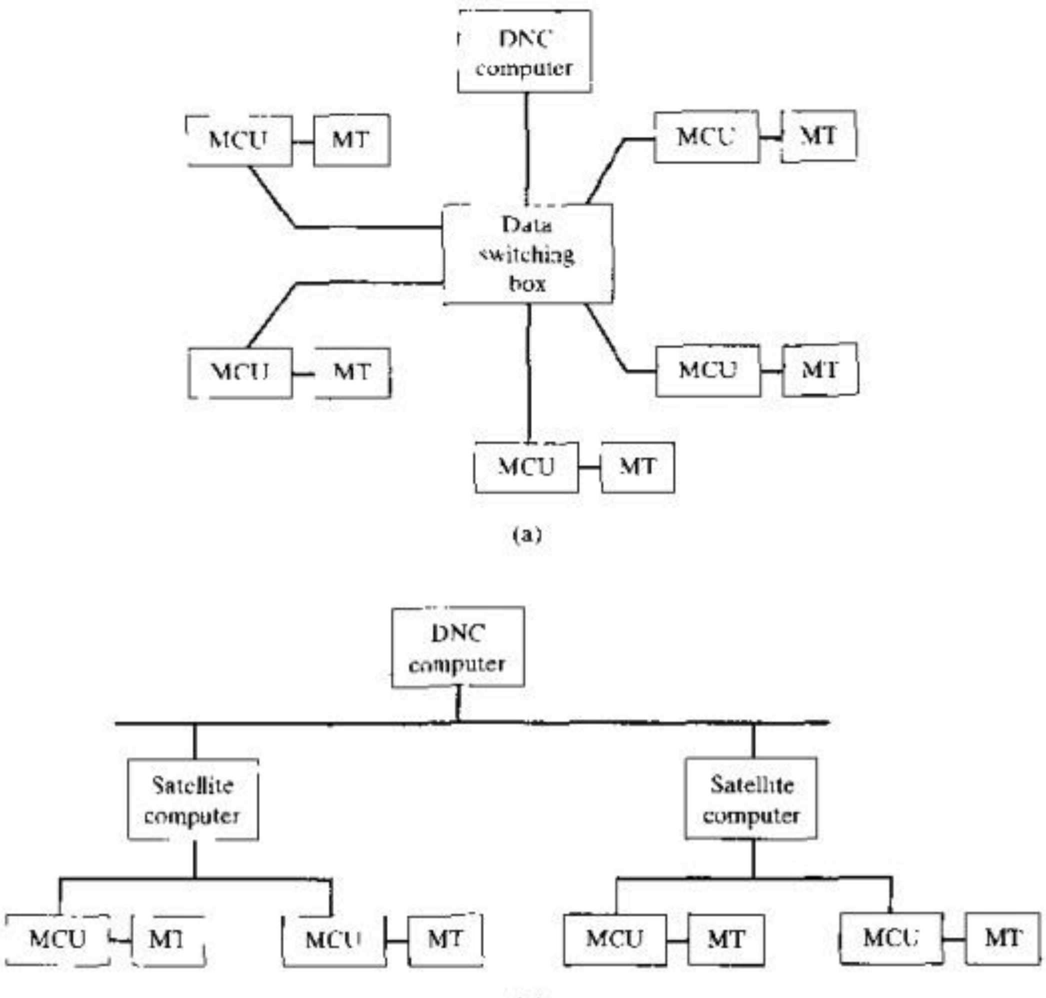


Figure 6.9 Two configurations of DNC: (a) switching network and (b) LAN. Key: MCU = machine control unit, MT = machine tool.

factors such as part program complexity, frequency of service required to each machine. and capabilities of the central computer. The number of machines in the DNC system can be increased by employing a serial link RS232C multiplexer.

Local area networks have been used for DNC since the early I980s. Various network structures are used m DNC systems, among which is the centralized structure illustrated in Figure 6.9(b). In this arrangement. the computer system is organized as a hierarchy, with the central [host} computer coordinating several satellite computers that are each responsible for a number of CNC machines. Alternative LAN structures are possible,each with its relative advantages and disadvantages. Local area networks in different sections and departments of a plant arc often interconnected in plant wide and corporate-wide networks.

APPLICATIONS OF NC

The operating principle of NC has many applications. There are many industrial operations in which the position of a workhead must be controlled relative to a part or product being processed. The applications divide into two categories: (1) machine tool applications and (2) nonmachine tool applications. Machine tool applications are those usually associated with the metalworking industry. Nonmachine tool applications comprise a diverse group of operations in other industries. It should he noted that the applications are not always identified by the name "numerical control"; this term is used principally in the machine tool industry

Machine Tool Applications

The most common applications of NC are in machine tool control. Machining was the first application of NC and it is still one of the most important commercially. In this section, we discuss NC machine tool applications with emphasis on metal machining processes.

Machining Operations and NC Machine Tools. *Machining* is a manufacturing process in which the geometry of the work is produced by removing excess material (Section 2.2.1), By controlling the relative motion between a cutting tool and the workpiece, the desired geometry is created. Machining is considered one of the most versatile processes because it can be used to create a wide variety of shapes and surface finishes. It can be performed at relatively high production rates to yield highly accurate parts at relatively low cost.

There are four common types of machining operations: (a) turning, (b) drilling,*(c)* milling, and (d) grinding. The four operations arc shown in Figure 6.10. Each of the machining operations is carried out at a certain combination of speed, feed, and depth of cut, collectively called the *cutting canditions* for the operation. The terminology varies somewhat for grinding,These cutting conditions are illustrated in Figure 6.10 for (a) turning,

(b) drilling. and (c) milling. Consider milling. The *cutting speed* is the velocity of the tool (milling cutter) relative to the work, measured in meters per minute (feet per minute). This is usually programmed into the machine as a spindle rotation speed (revolutions per minute). Cutting speed can be converted into spindle rotation speed by means of the following equation:

$$N = \frac{v}{\pi D} \qquad (6.1)$$

where N = spindle rotation speed (rev/min), v = cutting speed (m/min, ft/min), and D = milling cutter diameter (m, ft). In milling, the *feed* usually means the size of the chip formed by each tooth in the milling cutter, often referred to as the *chip load* per tooth. This must normally be programmed into the NC machine as the feed rate (the travel rate of the machine tool table). Therefore, feed must be converted to feed rate as follows:

$$f_r = N\, n_t f \qquad (6.2)$$

where *fr* = feed rate (mm/min, in/min)N = rotational speed (rev/min),n_t = number of teeth on the milling cutter. and *f* = feed (mm/tooth,in/tooth]. For a turning operation, feed is defined as the lateral movement of the cutting tool per revolution of the workpiece, so the units are milli meters per revolution (inches per revolution). *Depth of cut* is the distance the tool penetrates below the original surface of the work (mm, in). These are the parameters that must be controlled during the operation of an NC machine through motion or position commands in the part program

Each of the four machining processes is traditionally carried out on a machine tool designed to perform that process. Turning is performed on a lathe, drilling is done on a drill

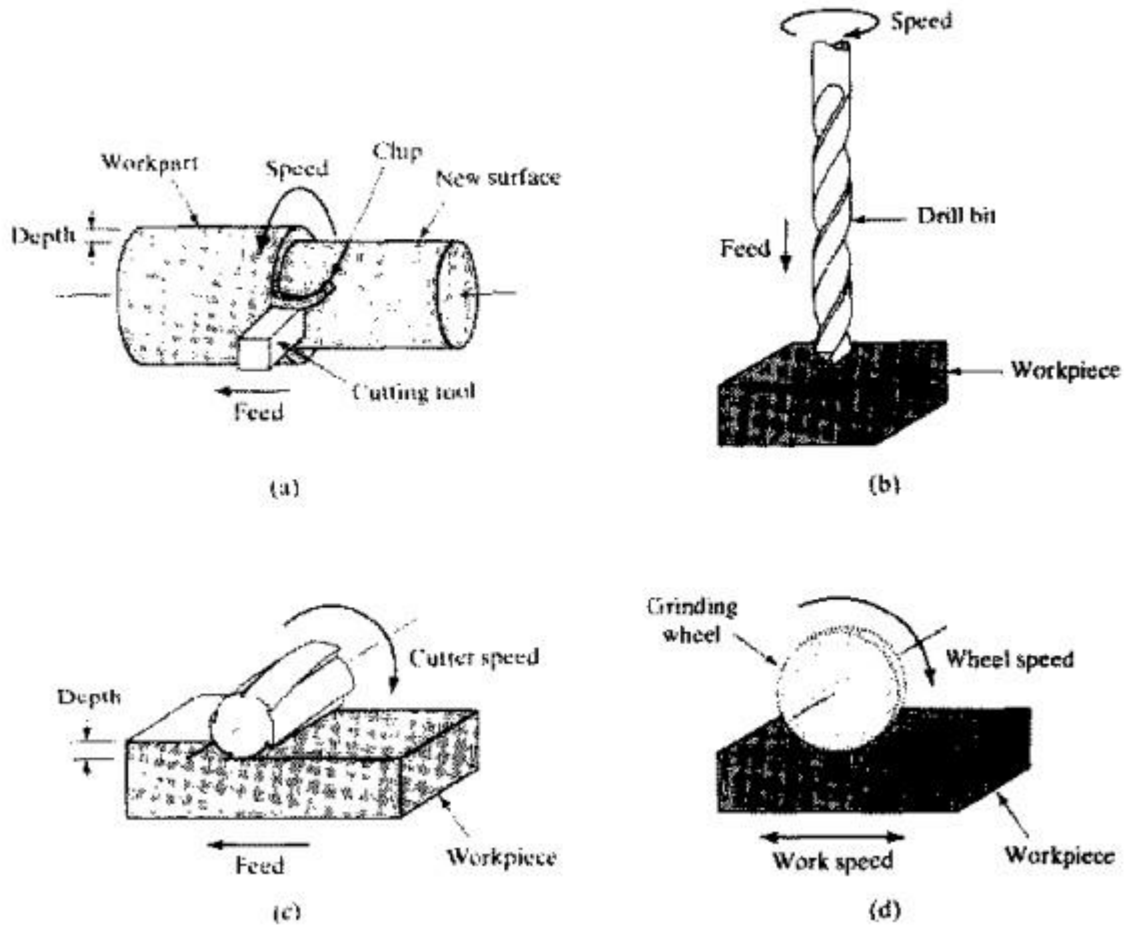


Figure 6.10 The four common machining operations: (a) turning, (b) drilling, (c) peripheral milling, and (d) surface grinding.

press, milling on a milling machine, and so on. The common NC machine tools are listed in the tollcw.ng along with their typical features:

NC lathe, either horizontal or vertical axis. Turning requires two-axis, continuous path control, either to produce a straight cylindrical geometry [called straight turning) or to create a profile (contour turning).

NC boring mill, horizontal and vertical spindle. Boring is similar to turning. except that an internal cylinder is created instead of an external cylinder. The operation requires continuous path, two-axis control.

NC drill press. These machines use point to point control of the workhead (spindle containing the drill bit) and two axis *(x-y)* control of the worktable. Some NC drill presses have turrets containing six or eight drill bits. The turret position is programmed under NC control, thus allowing different drill bits to be applied to the same workpart during the machine cycle without requiring the machine operator to manually change the tool.

NC milling machine. Milling machines require continuous path control to perform straight cut or contouring operations. Figure 6.11 illustrates the features of a four-axis milling machine.

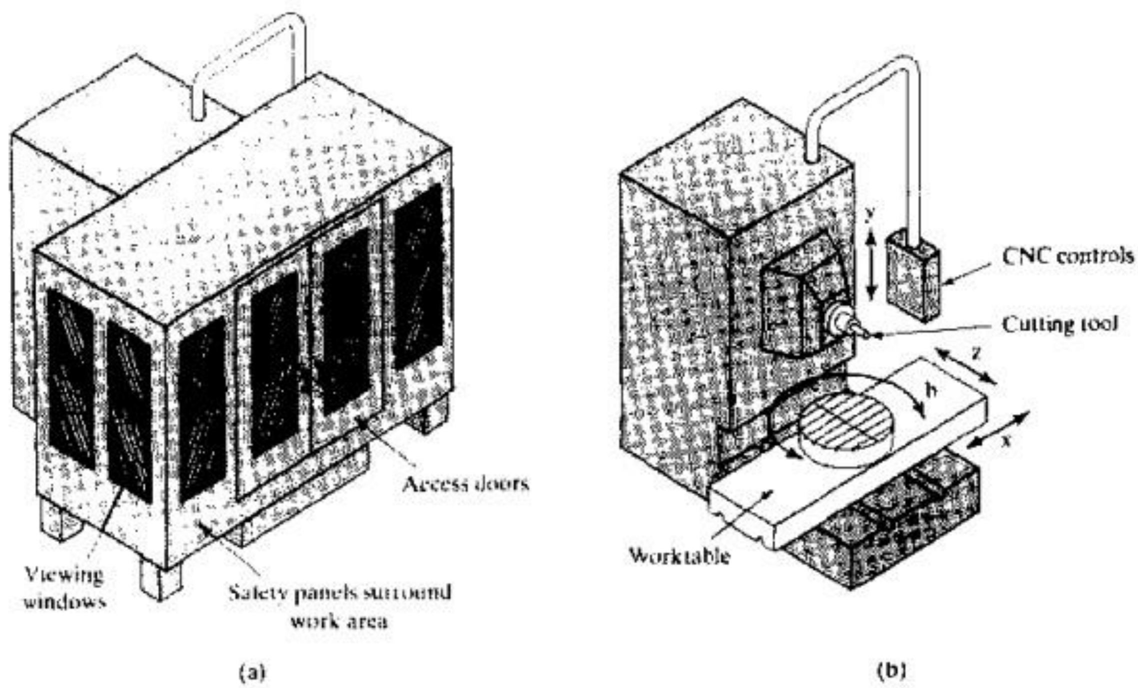


Figure 6.11 (a) Four-axis CNC horizontal milling machine with safety panels installed and (b) with safety panels removed to show typical axis configuration for the horizontal spindle.

- *NC cylindrical grinder.* This machine operates like a turning machine, except that the tool is a grinding wheel. It has continuous path two-axis control, similar to an NC lathe.

Numerical control has had a profound influence on the design and operation of machine tool. One of the effects has been that the proportion of time spent by the machine cutting metal is significantly greater than with manually operated machines. This causes certain components such as the spindle, drive gears, and feed screws to wear more rapidly. These components must be designed to last longer on NC machines. Second, the addition of the electronic control unit has increased the cost of the machine, therefore requiring higher equipment utilization. Instead of running the machine during only one shift, which is usually the convention with manually operated machines, NC machines are often operated during two or even three shifts to obtain the required economic payback. Third, the increasing cost of labor has altered the relative roles of the human operator and the machine tool. Consider the role of the operator. Instead of being the highly skilled worker who controlled every aspect of part production, the tasks of the NC machine operator *have* been reduced to part loading and unloading, tool changing, chip clearing, and the like Owing to these reduced responsibilities, one operator can often run two or three automatic machines.

The functions of the machine tool have also changed. NC machines are designed to be highly automatic and capable of combining several operations in one setup that formerly required several different machines. They are also designed to reduce the time consumed by the noncutting elements in the operation cycle, such as changing tools and loading and unloading the workpart. These changes are best exemplified by a new type of machine

that did not exist prior to the advent and development of NC: machining centers. A *machining center* is a machine tool capable of performing multiple machining operations on a single workpiece in one setup. The operations involve rotating cutters, such as milling and drilling, and the feature that enables more than one operation to be performed in one setup is automatic tool-changing. We discuss machining centers and related machine tools in our coverage of single station manufacturing cells (Section 14.3.3).

NC Application Characteristics. In general, NC technology is appropriate for low-to-medium production of medium-to-high variety product. Using the terminology of Section 2.3.1, the product is low-to-medium Q, medium-to-high P. Over many years of machine shop practice, certain part characteristics have come to be identified as being most suited to the application of NC. These characteristics are the following:

1. *Batch production.* NC is most appropriate for parts produced in small or medium lot sizes (batch sizes ranging from as low as one unit up to several hundred units). Dedicated automation would be uneconomical for these quantities because of the high fixed cost. Manual production would require many separate machine setups and would result in higher labor cost longer lead time. and higher scrap rate.

2. *Repeat enters.* Batches of the same parts are produced at random or periodic intervals. Once the NC part program has been prepared, parts can he economically produced in subsequent batches using the same part program.

3. Complex parr geometry. The part geometry includes complex curved surfaces such as those found on airfoils and turbine blades. Mathematically defined surfaces such as circles and helixes can also be accomplished with NC. Some of these geometries would he difficult if not impossible to achieve accurately using conventional machine tools.

4. *Much metal needs to be removed from the workpart.* This condition is often associated with a complex part geometry, The volume and weight of the final machined part is a relatively small fraction of the starting *block.* Such parts are common in the aircraft industry to fabricate large structural sections with low weights.

5. *Many separate machining operation on the part,* This applies to parts consisting of many machined features requiring different cutting tools, such as drilled and or tapped hole, slots. flats. and so on. If these operations were machined by a series of manual operations. many setups would be needed. The number of setups can usually be reduced significantly using NC.

6. *The part is expensive.* This factor is often a consequence of one or more of preceding factor3, 4. and 5. It can also result from using a high cost starting work material When the part is expensive. and mistakes in processing would be costly. the use of NC helps to reduce rework and scrap losses

These characteristics are summarized in Table 6.5, which is organized as a checklist for potential NC users to evaluate their operations in terms of NC applicability. The more check marks falling in the "YES" column, the more likely that NC will be successful. Although the list pertains to machining, the characteristics are adaptable to other production applications.

NC for Other Metalworking Processes. In addition to the machining process, NC machine tools have also been developed for other metal working processes. These machines include the following:

TABLE 6.5 Checklist to Determine Applicability of NC in Machine Shop Operations

Production Characteristic	*NO (few or no applications)*	*YES (many applications)*
1. Batch production in small or medium lot sizes		
2. Repeat orders at random or periodic intervals		
3. Complex part geometry		
4. Much metal needs to be removed from the part		
5. Many separate machining operations on the part		
6. The part is expensive		
Total check marks in each column		

- *Punch: presses* for sheet metal hole punching. The twoaxis NC operation is similar to that of a drill press except that holes are produced by punching rather than by drilling.
- *Presses* for sheet metal bending. Instead of cutting sheet metal, these systems bend sheet metal according to programmed commands.
- *Welding machines.* Both spot welding and continuous arc welding machines are available with automatic controls based on NC.
- *Thermal cutting machines,* su<.:has oxyfuel cutting, laser cutting, and plasma arc cutting. The stock is usually flat; thus, twoaxis control is adequate. Some laser cutting machines can cut holes in preformed sheet metal stock, requiring four or five axis control.

- *Tube bending machines. Automatic* tube bending machines are programmed to control the location (along the length of the tube stock) and the angle of the bend. Important applications include frames for bicycles and motorcycles.

Other NC Applications

The operating principle of NC has a host of other applications besides machine tool control. However, the applications are not always referred to by the term "numerical control." Some of these machines with NCtype controls that position a workhead relative to an object being processed are the following:

- *Electrical wire wrap machines.* These machines, pioneered by Gardner Denver Corporation, have been 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. The program of coordinate positions that define the back panel connections is determined from design data and fed to the wire wrap machine. This type of equipment has been used by computer firms and other companies in the electronics industry.

- *Component insertion machines.* This equipment is used to position and insert components on an *x-y* plane, usually a flat board or panel. The program specifies the x- and y-axis positions in the plane. where the components are to be located. Component insertion machines find extensive applications for inserting electronic components into pointed circuit boards. Machines are available for either through-hole or surface mount applications as well as similar Insertion-type mechanical assembly operations.

- *Drafting machines. Automated* drafting machines serve as one of the output devices for a CAD/CAM [computer aided design/computer aided manufacturing) system. The design of a product and its components are developed on the CAD/CAM system. Design iterations arc developed on the graphics monitor rather than on a mechanical drafting board. When the design is sufficiently finalized for presentation, the output is plotted on the drafting machine, basically a high speed *x-y* plotter.

- *Coordinate measuring machine.*

  A coordinate measuring machine (CMM) is an inspection machine used for measuring or checking dimensions of a part. The CMM has a probe that can be manipulated In three axes and Identifies when contact IS made against a pan surface. The location of the probe tip is determined by the CMM control unit. thereby indicating some dimension on the part. Many coordinate measuring machines are programmed to perform automated inspections under NC.

- *Tap laying machines for polymer composites.* The workhead of this machine is a dispenser of uncured polymer matrix composite tape. The machine is programmed to lay the tape onto the surface of a contoured mold, following a back-and-forth and crisscross pattern to build up a required thickness. The result is a multilayered panel of the same shape as the mold.
- *Filament winding machines for polymer composites*. This is similar to the preceding except that a filament is dipped in uncured polymer and wrapped around a rotating pattern of roughly cylindrical shape

Additional applications of NC include cloth cutting, knitting, and riveting.

Advantages and Disadvantages of NC

When the production application satisfies the characteristics in Table 6.5, NC yields many benefits and advantages over manual production methods. These benefits and advantages translate into economic savings for the user company. However, NC is a more sophisticated technology than conventional production methods, and there are drawbacks and costs that must be considered to apply the technology effectively. In this section, we examine the advantages and disadvantages of NC.

Advantages of NC. The advantages generally attributed to NC, with emphasis on machine tool applications, are the following:

- *Non-productive time is reduced.* NC cannot optimize the metal cutting process itself, hut it does increase the proportion of time the machine is cutting metal. Reduction in noncutting time is achieved through fewer setups, less setup time, reduced workpiece handling time, and automatic tool changes on some NC machines. This advantage translates into labor cost savings and lower elapsed times to produce parts.

- *Greater accuracy and repeatability*. Compared with manual production methods, NC reduces or eliminates variations that arc due to operator skill differences, fatigue, and other factors attributed to inherent human variabilities. Parts are made closer to nominal dimensions, and there is less dimensional variation among parts in the batch.
- *Lower scrap rates*. Because greater accuracy and repeatability are achieved, and because human errors are reduced during production, more parts are produced within tolerance. As a consequence, a lower scrap allowance can be planned into the production schedule. so fewer parts arc made in each batch with the result that production time IS saved.

- *Inspection requirements are reduced*. Less inspection is needed when NC is used because parts produced from the same NC part program are virtually identical. Once the program has been verified, there is no need for the high level of sampling inspection that IS required when parts are produced by conventional manual methods. Except for tool wear and equipment malfunctions, NC produces exact replicates of the part each cycle
- *More complex part geometries are possible.* t\C technology has extended the range of possible part geometries beyond what is practical with manual machining methods. This is an advantage in product design in several ways: (1) More functional features can he designed into a single part. thus reducing the total number of parts in the product and the associated cost of assembly: (2) mathematically defined surfaces can be fabricated with high precision; and (3) the space is expanded within which the designer's Imagination com wander to create new part and product geometries.
- *Engineering changes can be accommodated more gracefully*. Instead of making alterations in a complex fixture so that the part can be machined to the engineering change. revisions are made in the NC part program to accomplish the change
- *Simpler fixtures are needed.* NC requires simpler fixtures because accurate positioning the tool is accomplished by the NC machine tool. Tool positioning does not have to be designed into the jig.

- *Shorter manufacturing lead times.* Jobs can be set up more quickly and fewer setups arc required per part when NC is used. This results in shorter elapsed time between order release and completion.

- *Reduced parts inventory*. Because fewer setups are required and job changeovers are easier and faster. NC permits production of parts in smaller lot sizes. The economic lot size is lower in NC than in conventional batch production. Average parts inventory is therefore reduced.

- *Less floor space is required*. This results from the fact that fewer NC machines are required to perform the same amount of work compared to the number of conventional machine tools needed. Reduced parts inventory also contributes to lower floor space requirements.

- *Operator skill-level requirements (Ire reduced*. The skill requirements for operating an NC machine arc generally less than those required to operate a conventional machine tool. Tending an NC machine tool usually consists only of loading and unloading parts and periodically changing tools. The machining cycle is carried out under program control. Performing a comparable machining cycle on a conventional machine requires much more participation by the operator, and a higher level of training and skill are needed.

Disadvantages of *NC.* On the opposing side, there are certain commitments to NC technology that must be made by the machine shop that installs NC equipment; and these commitments, most of which involve additional cost to the company, might be seen as disadvantages. The disadvantages of NC include the following

- Higher investment cost
- Higher maintenance cost
- Part programming
- Higher utilization of equipment

MODULE 2

NC PART PROGRAMMING

NC part programming consists of planning and documenting the sequence of processing steps 10 be performed on an NC machine. The part programmer must have a knowledge of machining (or other processing technology for which the NC machine is designed) as well as geometry and trigonometry. The documentation portion of par! programming involves the input medium used to transmit the program of instructions to the NC machine control unit (MCU). The traditional input medium dating back to the first NC machines in the 1950s is inch wide punched rape, More recently the use of magnetic tape and floppy disks have been growing in popularity as storage technologies for NC The advantage of these input media is their much higher data density.

Part programming can he accomplished using a variety of procedures ranging from highly manual to highly automated methods. The methods are: (1) manual part programming, (2) computer assisted part programming, (3) part programming using CAD/CAM. and (4) manual data input. These part programming techniques are described in this section. Let us begin our presentation by explaining the NC coding system used to convoy the part program to the machine tool

NC Coding System

The program of instructions is communicated to the machine tool using a coding system based on binary numbers. This NC coding system is the low-level machine language that can be understood by the MCU. when higher level languages are used. such as A[Yf (Section 6.5.4), the statements in the program are converted to this basic code. In the present section, we discuss how instructions are written in this NC code to control the relative positions of the tool and workpiece and to *accomplish* the other functions of the machine tool.

$$(0 \times 2^3) + (1 \times 2^2) + (0 \times 2^1) + (1 \times 2^0) = (0 \times 8) + (1 \times 4) + (0 \times 2) + (1 \times 1)$$
$$- 4 + 1 = 5$$

Conversion of the 10 digits in the decimal number system into binary numbers is shown in Table 6,6. Four binary digits are required to represent the ten single digit numbers in decimal. Of course, the numerical data required in NC includes large decimal values; for example, the coordinate position r = 1250 rpm. To encode the decimal value 1250 in the binary number system requires a total of 11 digits:

10011100010. Another problem with the binary number system is the coding of decimal fractions, for example, feed = 0.085 mm/rev.

To deal with these problems in NC, a combination of the binary and decimal number systems has been adopted, called the *binary coded decimal* (BCD) system. In this coding scheme, each of the ten digits (09) in the decimal system is coded as a four digit binary number, and these binary numbers are added in sequence as in the decimal number system. For example, the decimal value 1250 would be coded in BCD as follows:

Number sequence	*Binary number*	*Decimal value*
First	0001	1000
Second	0010	200
Third	0101	50
Fourth	0000	0
Sum		1250

TABLE 6.7 Standard EIA and ISO (ASCII) Codes for Numerical Control Programming, Originally Designed for Punched Tape

EIA Code									*Character or Interpretation*	*ISO Code (ASCII)*								
8	7	6	5	4		3	2	1		8	7	6	5	4		3	2	1
		O			o				0			O	O		o			
					o			O	1	O		O	O		o			O
					o		O		2	O		O	O		o		O	
			O		o		O	O	3			O	O		o		O	O
					o	O			4	O		O	O		o	O		
			O		o	O		O	5			O	O		o	O		O
			O		o	O	O		6			O	O		o	O	O	
					o	O	O	O	7	O		O	O		o	O	O	O
				O	o				8	O		O	O	O	o			
			O	O	o			O	9	O	O	O	o			O		
	O	O			o			O	A		O				o			O
	O	O			o		O		B		O				o		O	
	O	O	O		o		O	O	C	O	O				o		O	O
	O	O			o	O			D		O				o	O		
	O	O	O		o	O		O	E	O	O				o	O		O
	O	O	O		o	O	O		F	O	O				o	O	O	
	O	O			o	O	O	O	G		O				o	O	O	O
	O	O		O	o				H		O			O	o			
	O	O	O	O	o			O	I	O	O			O	o			O
	O		O		o			O	J	O	O			O	o		O	
	O		O		o		O		K		O			O	o		O	O
	O				o		O	O	L	O	O			O	o	O		
	O		O		o	O			M		O			O	o	O		O
	O				o	O		O	N		O			O	o	O	O	
	O				o	O	O		O	O	O			O	o	O	O	O
	O		O		o	O	O	O	P		O		O		o			
	O		O	O	o				Q	O	O		O		o			O
	O			O	o			O	R	O	O		O		o		O	
		O	O		o		O		S		O		O		o	O	O	
		O			o	O	O		T	O	O		O		o	O		
		O	O		o	O			U		O		O		o	O		O
		O			o	O		O	V		O		O		o	O	O	
		O			o	O	O		W	O	O		O		o	O	O	O
		O	O		o	O	O	O	X	O	O		O	O	o			
		O	O	O	o				Y		O		O	O	o			O
		O		O	o			O	Z		O		O	O	o		O	
		O	O	O	o	O	O		Tab					O	o			O
O					o				End-of-Block					O	o		O	
			O		o				Space	O		O			o			
	O	O	O		o				Positive sign (+)			O		O	o		O	O
	O				o				Negative sign (−)			O		O	o	O		O
	O	O		O	o		O	O	Period (decimal point) (.)			O		O	o	O	O	
		O	O	O	o		O	O	Comma (,)	O		O		O	o	O		

Note: Column numbers identify columns on the punched tape; O's represent holes in the tape.

EIA and ISO Coding Standards. In addition to numerical values, the NC coding system must also provide for alphabetical characters and other symbols. Eight binary dig. its are used to represent all of the characters required for NC part programming. There are two standard coding systems currently used in NC: (1) the Electronics Industry Association (EIA) and (2) the International Standards Organization (ISO). The Electronics Industry Association system is known as EIA RS244R The ISO code was originally developed as the American Standard Code for Information Interchange (ASCII) and has been adopted by ISO as its NC standard. The complete listings of EIA and ISO (ASCII) codes for NC are shown in Table 6.7. Many NC controllers are capable of reading either code,

TABLE 6.6 Comparison of Binary and Decimal Numbers

Binary	Decimal	Binary	Decimal
0000	0	0101	5
0001	1	0110	6
0010	2	0111	7
0011	3	1000	8
0100	4	1001	9

Both EIA and ISO coding schemes were developed when punched tape was the predominant medium fur storing NC part programs. Although punched tape has been largely superseded by more modern media. it is still widely used in industry. if only for backup storage. To ensure the correctness of the punched tape. the eight binary digits in the EIA and ISO codes include a *paru» check*. Here's how the parity check work, explained here

for the EIA code. In the EIA system, the tape reader is instructed to count an odd num-

ber of holes across the width of the tape. Whenever the particular number or symbol being punched requires an even number of holes. an extra hole is punched in column 5, hence making the total an odd number. For example, the decimal numbers is coded by means of holes in columns 1 and 3. Since this is an even number of holes, a parity hole would be: added. The decimal 7 requires an odd number of holes (in columns 1, 2, and 3),so no parity hole is needed. The parity check helps 10 ensure that the tape punch mechanism has perforated a complete hole in all required positions. If the tape reader counts an even number of holes. then a signal is issued that a parity error has occurred.

The difference between the EIA and ISO systems is that the parity check in the ISO code i~ an even number of holes, called an *even parity*. The EIA system uses an *odd parity*. whereas the parity hole is in the fifthdigit position in the 'EIA coding system, it is in the eighth position in the ISO system. These differences can be seen in Table 6.7

How instructions Are *Formed.* A binary digit is called a *bit.* In punched tape, the values 0 or 1 are represented by the absence or presence of a hole in a certain row and column position (rows run across the tape columns run lengthwise along the tape). Out of one row of bits a character is formed. A *character* is a combination of bits representing a numerical digit (09), an alphabetical letter (AZ),or a symbol (Table 6.7). Out of a sequence of characters, a word is formed. A *wont* specifies a detail about the operation, such as x position, y position, feed rate, or spindle speed. Out of a collection of words, a block is formed. A *block* is one complete NC instruction. It specifies the destination for the move, the speed and feed of the cutting operation. and other commands that determine explicitly what the machine tool will do. For example, an instruction block for a two axis NC milling machine would likely include the *x* and coordinates to which the machine table should be moved, the type of motion to be performed (linear or circular interpolation), the rotational speed of the milling cutler, and the feed rate at which the milling operation should be performed. Instruction blocks arc separated by an end of block (LOB) symbol (a hole in column 8 in the EIA standard or holes in columns 2 and 4 in the ISO standard. as in Table 6.7).

The essential information in a part program is conveyed to the MCU by means of words that specify coordinates, feeds and speeds, tooling, and other commands necessary to operate the machine tool. Given the variety of machine tool types and the many different companies that build NC machine tools and MCUs, it is no surprise that several different formats have been developed over the years to specify words within an instruction block. These are often referred to as *tape formats,* because they were developed for punched tapes, More generally, they are known as *block formats.* At least five block formats have been developed [8]; these are briefly described in Table 6.8, with two lines of code for the drilling sequence shown in Figure 6.12

The word address format with TAB separation and variable word order has been standardized by EIA as RS·274. It is the block format used on all modern controllers and is the format we will discuss here. It is usually referred to simply as the word address format even though it has been enhanced by tab separation and variable word order. Com. man letter prefixes used in the word address format are defined in Table 6.9.

Words in an instruction block are intended to convey all of the commands and data needed for the machine tool to execute the move defined in the block. The words required for one machine tool type may differ from those required for a different type; for example. turning requires a different set of commands than milling. The words in a block are usually given in the following order (although the word address format allows variations in the order):

TABLE 6.8 Five Block Formats Used in NC Programming

Block Format (Tape Format)	*Example for Figure 6.12*
Fixed sequential format. This format was used on many of the first commercially available NC machines. Each instruction block contains five words specified in only numerical data and in a very fixed order.	00100070000300003 00200070000600003
Fixed sequential format with TAB ignored. This is the same as the fixed sequential format except that TAB codes are used to separate the words for easier reading by humans.	001 00 07000 03000 03 002 00 07000 06000 03
Tab sequential format. This is the same as the preceding format except that words with the same value as in the preceding block can be omitted in the sequence.	001 00 07000 03000 03 002 00 06000
Word address format. This format uses a letter prefix to identify the type of word. See Table 6.9 for definition of prefixes. Repeated words can be omitted. The words run together, which makes the code difficult to read (for humans).	N001G00X07000Y03000M03 N002Y06000
Word address format with TAB separation and variable word order. This is the same format as the previous, except that words are separated by TABs, and the words in the block can be listed in any order. See Table 6.9 for definition of letter prefixes.	N001 G00 X07000 Y03000 M03 N002 Y06000

Note: Examples indicate point-to-point moves to two hole locations in Figure 6.12.

Words in an instruction block are intended to convey all of the commands and data needed for the machine tool to execute the move defined in the block. The words required for one machine tool type may differ from those required for a different type; for example. turning requires a different set of commands than milling. The words in a block are usually given in the following order (although the word address format allows variations in the order):

- sequence number (N-word)
- preparatory word (G-word); see Table 6.10 for definition of G-words
- coordinates (X-, Y-, Z-words for linear axes, A-, B-, C-words for rotational axes)
- feed rate (F-word)

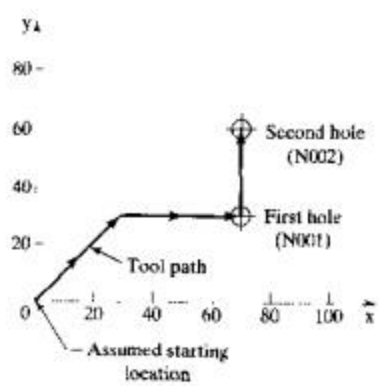


Figure 6.12 Example drilling sequence for block formats described in Table 6.8. Dimensions are in millimeters.

TABLE 6.9 Common Word Prefixes Used in Word Address Format

Word Prefix	Example	Function
N	N01	Sequence number; identifies block of instruction. From one to four digits can be used.
G	G21	Preparatory word; prepares controller for instructions given in the block. See Table 6.10. There may be more than one G-word in a block. (Example specifies that numerical values are in millimeters.)
X, Y, Z	X75.0	Coordinate data for three linear axes. Can be specified in either inches or millimeters. (Example defines *x*-axis value as 75 mm.)
U, W	U25.0	Coordinate data for incremental moves in turning in the *x*- and *z*-directions, respectively. (Example specifies an incremental move of 25 mm in the *x*-direction.)
A, B, C	A90.0	Coordinate data for three rotational axes. A is the rotational axis about *x*-axis; B rotates about *y*-axis; and C rotates about *z*-axis. Specified in degrees of rotation. (Example defines 90° of rotation about *x*-axis.)
R	R100.0	Radius of arc; used in circular interpolation. (Example defines radius = 100 mm for circular interpolation.) The R-code can also be used to enter cutter radius data for defining the tool path offset distance from the part edge.
I, J, K	I32 J67	Coordinate values of arc center, corresponding to *x*-, *y*-, and *z*-axes, respectively; used in circular interpolation. (Example defines center of arc for circular interpolation to be at $x = 32$ mm and $y = 67$ mm.)
F	G94 F40	Feed rate per minute or per revolution in either inches or millimeters, as specified by G-words in Table 6.10. (Example specifies feed rate = 40 mm/min in milling or drilling operation.)
S	S0800	Spindle rotation speed in revolutions per minute, expressed in four digits. For some machines, spindle rotation speed is expressed as a percentage of maximum speed available on machine, expressed in two digits.
T	T14	Tool selection, used for machine tools with automatic tool changers or tool turrets. (Example specifies that the cutting tool to be used in the present instruction block is in position 14 in the tool drum.)
D	D05	Tool diameter word used in contouring moves for offsetting the tool from the workpart by a distance stored in the indicated register, usually the distance is the cutter radius. (Example indicates that the radius offset distance is stored in offset register number 05 in the controller.)
P	P05 R15.0	Used to store cutter radius data in offset register number 05. (Example indicates that a cutter radius value of 15.0 mm is to be stored in offset register 05.
M	M03	Miscellaneous command. See Table 6.11. (Example commands the machine to start spindle rotation in clockwise direction.)

Note: Dimensional values in the examples are specified in millimeters.

- spindle speed (S-word)
- tool selection (T-word)
- miscellaneous command (M-word); see Table 6.11 for definition of M-words
- end-of-block (EOB symbol)

G-words and Mwords require some elaboration. Gwords are called preparatory words. They consist of two numerical digits (following the "G" prefix in the word address for mat) that prepare the MCU for the instructions and data contained in the block. For example, G02 prepares the controller for clockwise circular interpolation, so that the subsequent data in the block can be properly interpreted for this type of move. In some cases, more than one Gword is needed to prepare the MCU for the move. Most of the common Gwords are presented in Table 6.10.While Gwords have been standardized in the machine tool industrv, there arc sometimes deviations for particular machines. For instance, there are several differences between milling and turning type machines; these are identified in Table 6.10.

TABLE 6.10 Common G-words (Preparatory Word)

G-word	Function
G00	Point-to-point movement (rapid traverse) between previous point and endpoint defined in current block. Block must include *x-y-z* coordinates of end position.
G01	Linear interpolation movement. Block must include *x-y-z* coordinates of end position. Feed rate must also be specified.
G02	Circular interpolation, clockwise. Block must include either arc radius or arc center; coordinates of end position must also be specified.
G03	Circular interpolation, counterclockwise. Block must include either arc radius or arc center; coordinates of end position must also be specified.
G04	Dwell for a specified time.
G10	Input of cutter offset data, followed by a P-code and an R-code.
G17	Selection of *x-y* plane in milling.
G18	Selection of *x-z* plane in milling.
G19	Selection of *y-z* plane in milling.
G20	Input values specified in inches.
G21	Input values specified in millimeters.
G28	Return to reference point.
G32	Thread cutting in turning.
G40	Cancel offset compensation for cutter radius (nose radius in turning).
G41	Cutter offset compensation, left of part surface. Cutter radius (nose radius in turning) must be specified in block.
G42	Cutter offset compensation, right of part surface. Cutter radius (nose radius in turning) must be specified in block.
G50	Specify location of coordinate axis system origin relative to starting location of cutting tool. Used in some lathes. Milling and drilling machines use G92.
G90	Programming in absolute coordinates.
G91	Programming in incremental coordinates.
G92	Specify location of coordinate axis system origin relative to starting location of cutting tool. Used in milling and drilling machines and some lathes. Other lathes use G50.
G94	Specify feed per minute in milling and drilling.
G95	Specify feed per revolution in milling and drilling.
G98	Specify feed per minute in turning.
G99	Specify feed per revolution in turning.

Note: Some G-words apply to milling and/or drilling only, whereas others apply to turning only.

TABLE 6.11 Common M-words Used in Word Address Format

M-word	Function
M00	Program stop; used in middle of program. Operator must restart machine.
M01	Optional program stop; active only when optional stop button on control panel has been depressed.
M02	End of program. Machine stop.
M03	Start spindle in clockwise direction for milling machine (forward for turning machine).
M04	Start spindle in counterclockwise direction for milling machine (reverse for turning machine).
M05	Spindle stop.
M06	Execute tool change, either manually or automatically. If manually, operator must restart machine. Does not include selection of tool, which is done by T-word if automatic, by operator if manual.
M07	Turn cutting fluid on flood.
M08	Turn cutting fluid on mist.
M09	Turn cutting fluid off.
M10	Automatic clamping of fixture, machine slides, etc.
M11	Automatic unclamping.
M13	Start spindle in clockwise direction for milling machine (forward for turning machine) and turn on cutting fluid.
M14	Start spindle in counterclockwise direction for milling machine (reverse for turning machine) and turn on cutting fluid.
M17	Spindle and cutting fluid off.
M19	Turn spindle off at oriented position.
M30	End of program. Machine stop. Rewind tape (on tape-controlled machines).

M-words are used to specify miscellaneous or auxiliary functions that an: available on the machine tool. Examples include starting the spindle rotation, stopping the spindle for a tool change, and turning the cutting fluid on or off. Of course, the particular machine tool must possess the function that is being called. Many of the common M-words are explained in Table 6.11. Miscellaneous commands are normally placed at the end of the block.

Manual Part Programming

In manual part programming, the programmer prepares the NC code using the low-level machine language previously described. The program is either written by hand on a fonn from which a punched tape or other storage media is subsequently coded, or it is entered directly into a computer equipped with NC part programming software, which writes the program onto the storage media. In any case. the part program is a block by block listing of the machining instructions for the given job, formatted for the particular machine tool to be used.

Manual part programming can be used for both point to point and contouring jobs. It is most suited for point to point machining operations such as drilling. It can also be used for simple contouring jobs, such as milling and turning when only two axes are in valved. However, for complex three dimensional machining operations, there is an advantage in using computer assisted part programming

Instructions in Word Address Format. Instructions in word address format consist of a series of words, each identified by a prefix label. **In** our coverage, statement, are illustrated with dimensions given in milli meters. The values are expressed in four digits including one decimal place. For example. X020.0 means x = 20,0 rnrn. It should be noted that many CNC machines use formats that differ from ours, and so the instruction manual for each particular machine tool must be consulted to determine its own proper format. Our format is designed to convey principles and for easy reading.

Tn preparing the NC part program, the part programmer must initially define the origin of the coordinate axes and then reference the succeeding motion commands to this axis system. This is accomplished in the first statement of the part program. The directions of the X, y, and/or a axes are predetermined by the machine tool configuration, but the origin of the coordinate system can be located at any desired position. The part programmer defines this position relative to some part feature that can be readily recognized by the machine operator. The operator is instructed to move the tool to this position at the beginning of the job. With the tool in position, the G92 code is used by the programmer to define the origin as follows:

G92 XOY050,0 ZOIO.0

where the x,y, and z values specify the coordinates of the tool location in the coordinate system; in effect, this defines the location of the origin. In some CNC lathes and turning centers, the code G50 is used instead of G92. Our x, y, and z values are specified in millimeters, and this would have to be explicitly stated. Thus, a more complete instruction block would be the following:

G21 G92 XO YOSO,O ZOlO.O

where the G21 code indicates that the subsequent coordinate values are in millimeters.

Motions are programmed by the codes 000, GOL 002, and G03. GOOis used for a point to point rapid traverse movement of the tool to the coordinates specified in the command; for example

G00 X050.0Y086.5ZI00.0

specifies a rapid traverse motion from the current location to the location defined b) the coordinates r = 50.0 mm, *y* = 86.5 mm, and z = 100.0 mm. This command would be appropriate for NC drilling machines in which a rapid move is desired to the next hole location. with no specification on the tool path. The velocity with which the move is achieved in rapid traverse mode is set by parameters in the MCV and is not specified numerically in the instruction block. The GOO code is not intended for contouring operations,

Linear interpolation is accomplished by the 001 code. This is used when it is desired for the tool to execute a contour cutting operation along a straight line path. For example, the command

GOI G94 X050.0 Y086.5 Z100.0 F40 5800

specifies that the G01 is to move in a straight line from its current position to the location defined by x = *50.0mm,y 0*= 86.5 mm and *z 100* mm at a feed rate of 40 mm/min and spindle speed of 800 rev/*min.*

The G02 and G03 codes are used for circular interpolation, clockwise and counterclockwise, respectively. As indicated in Table 6.1, circular interpolation on a milling machine is limited to one of three planes, *xy*, xz, or yz. The distinction between clockwise and counterclockwise is established by viewing the plane from the front view, Selection of the desired plane is accomplished by entering one of the codes,G17, G IS, or 019, respectively. Thus, the instruction

G02 G17 X088.0 Y040.0 R028.0 F30

moves the tool along a clockwise circular trajectory in the *x y* plane to the final coordinates defined by *x* = 88 nun and *y* = 40 mm at a feed rate of 30 mm/min. The radius of the circular arc is 28 mm. The path taken by the cutter from an assumed starting point *(x* = 40, *Y* = 60) is illustrated in Figure 6.13

In a point-to-point motion statement (GOO), it is usually desirable to position the tool so that its center is located at the specified coordinates. This is appropriate for operations such as drilling, in which a hole is to be positioned at the coordinates indicated in the statement. But in contouring motions, it is almost always desirable that the path followed by the center of the tool be separated from the actual surface of the part by a distance equal to the cutter radius. This is shown in Figure 6.14 for profile milling the outside edges of a rectangular part in two dimensions. For a threedimensional surface, the shape of the end of the cutter would also have to be considered in the offset computation. This tool path compensation is called the *cutter offset*, and the calculation of the correct coordinates of the endpoints of each move can be time consuming and tedious for the part programmer. Modern CNC machine tool controllers perform these cutter offset calculations automatically when the programmer uses the G40, G41, and G42 codes. The 040 code is used to cancel the cutter offset compensation. The *041* and G42 codes invoke the cutter offset compensation of the tool path on the left or righthand side of the part, respectively. The left and righthand sides are defined according to the tool path direction. To illustrate, in the rectangular part

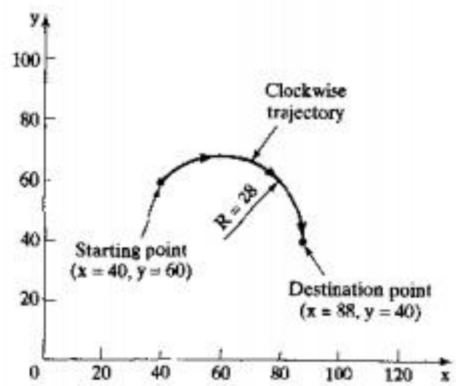


Figure 6.13 Tool path in circular interpolation for the statement: G02 G17 X088.0 Y040.0 R028.0. Units are millimeters.

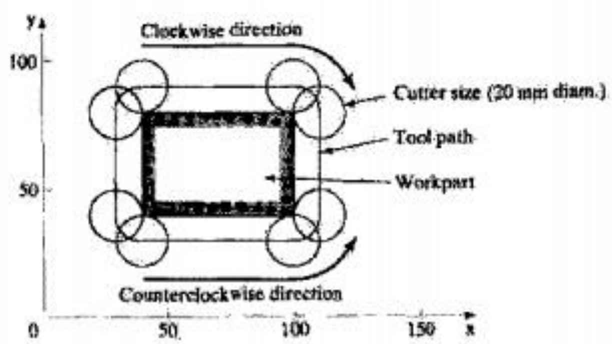


Figure 6.14 Cutter offset for a simple rectangular part. The tool path is separated from the part perimeter by a distance equal to the cutter radius. To invoke cutter offset compensation, the G41 code is used to follow the clockwise path, which keeps the tool on the left-hand side of the part. G42 is used to follow the counterclockwise path, which keeps the tool on the right-hand side of the part.

in Figure 6.14, a clockwise tool path around the part would always position the tool on the left hand side of the edge being cut, so a 041 code would be used to compute the cutter offset compensation. By contrast, a counterclockwise tool path would keep the tool on he righthand side of the part, so G42 would be used. Accordingly, the instruction for profile milling the bottom edge of the part, assuming that the cutter begins along the bottom left comer, would read:

G42 X I00.0 Y04O.O D05

where D05 refers to the cutter radius value stored in MCU memory. Certain registers are reserved in the control unit for these cutter offset values. The Dcode references the value contained in the identified register. D05 indicates that the radius offset distance is stored in the number 5 offset register in the controller. This data can be entered into the controller in either of two ways: (1) as manual input or (2) as an instruction in the part program. Manual input is more flexible because the tooling used to machine the part may change from one setup to the next. At the time the job is run, the operator knows which tool will be used. and the data can be loaded into the proper register as one of the steps in the getup. When the offset data is entered as a part program instruction, the statement has the form:

GIO P05 RlO.O

where G 10 is a preparatory w ord indicating that cutter offset data will be entered; P05 indicates that the data will be entered into offset register number 05; and RIO,() is the radius value here l0.0 mm.

Some Part Programming Examples. To demonstrate manual part programming, we present two examples using the sample part shown in Figure 6.1S.The first example is a pointtopoint program to drill the three holes in the part. The second example is a twoaxis contouring program to accomplish profile milling around the periphery of the part.

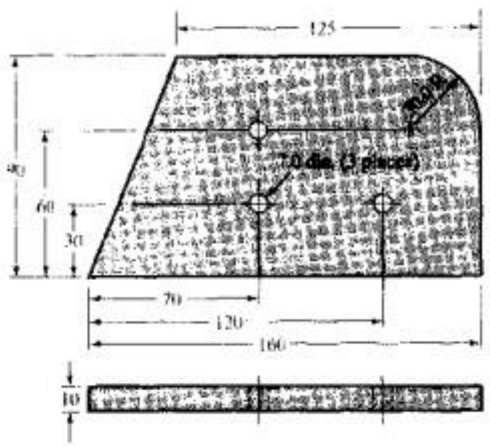


Figure 6.15 Sample part to illustrate NC part programming. Dimensions are in millimeters. General tolerance = ±0.1 mm. Work material is a machinable grade of aluminum.

This example presents the NC part program in word address format for drilling the three holes in the sample part shown in Figure 6.15. We assume that the outside edges of the starting workpart have been rough cut (by jig sawing) and are s1Jgbtly oversized for subsequent profile milling. The three holes to be drilled in thi:; example will be used to locate and fixture the part for profile milling in the following example. For the present drilling sequence, the part is gripped in place so that its top surface is 40 mm above the surface of the machine tool table to provide ample clearance beneath the part for hole drilling. We will define the *X. y and* zaxes as shown in Figure 6.16.A 7.omm diameter drill Corresponding to the specified hole size, has been chucked in the CNC drill press. The drill will be operated at a feed of 0.05 mm/rev and a spindle speed of 1000 rev/min (corresponding to a surface speed of about 0.37 m/sec, which is slow for the aluminum work material). At the beginning of the job, the drill point will be positioned at a target point located *at* $x = 0, y = 50$, and $z = +10$ (axis units are millimeters). The program begins with the tool positioned at this target point.

NC Part Program Code	Comments
N001 G21 G90 G92 X0 Y-050.0 Z010.0;	Define origin of axes.
N002 G00 X070.0 Y030.0;	Rapid move to first hole location.
N003 G01 G95 Z-15.0 F0.05 S1000 M03;	Drill first hole.
N004 G01 Z010.0;	Retract drill from hole.
N005 G00 Y060.0;	Rapid move to second hole location.
N006 G01 G95 Z-15.0 F0.05;	Drill second hole.
N007 G01 Z010.0;	Retract drill from hole.

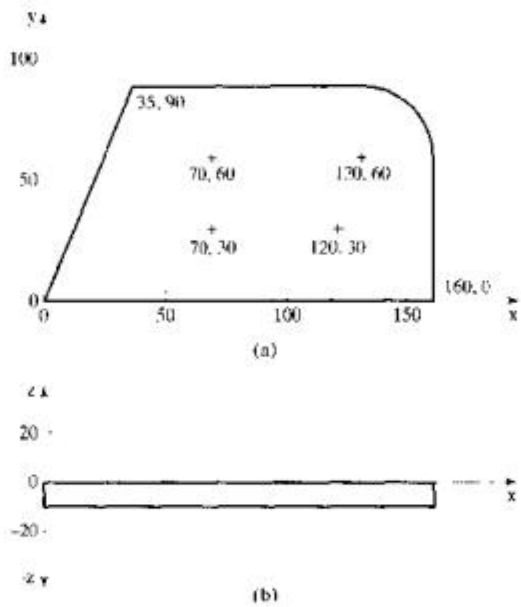


Figure 6.16 Sample part aligned relative to (a) x- and y-axes, and (b) z-axis. Coordinates are given for significant part features in (a).

N008 G00 X120.0 Y030.0;	Rapid move to third hole location.
N009 G01 G95 Z-15.0 F0.05;	Drill third hole.
N010 G01 Z010.0;	Retract drill from hole.
N011 G00 X0 Y-050.0 M05;	Rapid move to target point.
N012 M30;	End of program, stop machine.

EXAMPLE 6.2 Two Axis Milling

The three holes drilled in the previous example can be used for locating and holding the workpart to completely mill the outside edges without re fixturing The axis coordinates are shown in Figure 6,16 (same coordinates as in the previous drilling sequence). The part is fixtured so that its top surface is 40 mm above the surface of the machine tool table. Thus, the orgine of the axis system will be 40 mm above the table surface. A 20mm diameter end mill with four teeth will be used. The cutter has a side tooth engagement length of 40 mm. Throughout the machining sequence, the bottom tip of the cutler will be positioned 25 mm below the part top surface. which corresponds to Z = 25 mrn. Since the part is 10 mm thick, this z position will allow the side cutting edges of the milling cutter to cut the full thickness of the part during profile milling. The cutter will be operated at a spindle speed = 1000 rev/min (which corresponds to a surface speed of about 1.0 m/sec) and a feed rate = 50 mm/min (which cor responds 10 0.20 rnm/tooth). The tool path to be followed by the culler is shown

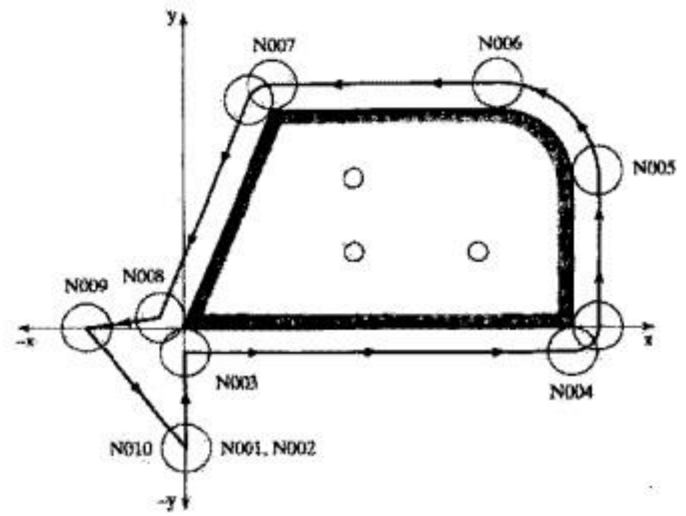


Figure 6.17 Cutter path for profile milling outside perimeter of sample part.

in Figure 6.17, with numbering that corresponds to the sequence number in the program. Cutter diameter data has been manually entered into offset register 05. At the beginning of the job, the cutter will be positioned so that its center tip is at a target point located at x = O. Y = 50, and *t;* = +10. The program begins with the tool positioned at this location.

NC Part Program Code	Comments
N001 G21 G90 G92 X0 Y-050.0 Z010.0;	Define origin of axes.
N002 G00 Z-025.0 S1000 M03;	Rapid to cutter depth, turn spindle on.
N003 G01 G94 G42 Y0 D05 F40;	Engage part, start cutter offset.
N004 G01 X160.0;	Mill lower part edge.
N005 G01 Y060.0;	Mill right straight edge.
N006 G17 G03 X130.0 Y090.0 R030.0;	Circular interpolation around arc.
N007 G01 X035.0;	Mill upper part edge.
N008 G01 X0 Y0;	Mill left part edge.
N009 G40 G00 X-040.0 M05;	Rapid exit from part. cancel offset.
N010 G00 X0 Y-050.0;	Rapid move to target point.
N011 M30;	End of program, stop machine.

Computer Assisted part Programming

Manual part programming can be time consuming, tedious. and subject to errors for parts possessing complex geometries or requiring many machining operations .In these cases, and even for simpler jobs, it is advantageous to use computer-assisted part programming. A number of NC part programming language systems have been developed to accomplish many of the calculations that the programmer would otherwise have to do. This saves time and results in a more-accurate and efficient part program. In computer-assisted part programming. the various tasks are divided between the human part programmer and the computer.

In computer-assisted part programming, the machining instructions are written in English like statements that are subsequently translated by the computer into the low-level machine code that can be interpreted and executed by the machine tool controller When using one of the part programming languages. the two main tasks of the programmer are: (1) defining the geometry of the workpart and (2) specifying the tool path and operation-sequence

Defining the Part Geometry. No matter how complicated the workpart may appear, it is composed of basic geometric elements and mathematically defined surfaces. Consider our sample part in Figure 6.18. Although its appearance is somewhat irregular, the outline of the part consists of intersecting straight lines and a partial circle. The hole locations in the part can be defined in terms of the x and y coordinates of their centers. Near*ly* any component that can be conceived by a designer can be described by points, straight lines, planes, circles, cylinders, and other mathematically defined surfaces. It is the part programmer's task to identify and enumerate the geometric elements of which the part is comprised, Each element must be defined in terms of its dimensions and location relative to

other elements. A few examples will be instructive here to show how geometric elements arc defined. We will use our sample part to illustrate, with labels of geometry elements added as shown in Figure 6.18.

Let us begin with. the simplest geometric element, a point, The simplest way to define a *point* is by means of its coordinates; for example,

P4 = POINT /35,90,0

where the point is identified by a symbol (P4), and its coordinates are given in the order

x, *y*, *z* in millimeters (*x* = 35 mm, *y* = 90 mm, and *z* = 0). A *line* can be defined by two points, as in the following:

L1 = LINE/PI, P2

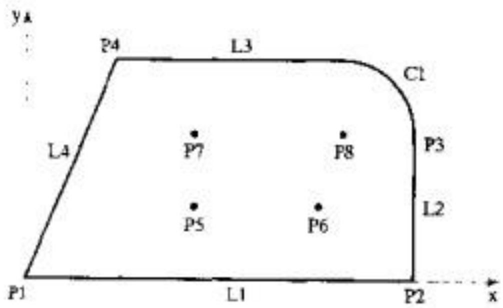


Figure 6.18 Sample part with geometry elements (points, lines, and circle) labeled for computer-assisted part programming.

where L1 is the line defined in the statement, and PI and P2 are two previously defined points. And finally, a *circle* can be defined by its center location and radius:

Cl = CIRCLE/CENTERP8,RADIUS,30

where Cl is the newly defined circle. with center at previously defined point *PR* and radius = 30 mm. Our examples are based on the APT language, which offers many alternative ways to define points, lines. circles, and other geometric elements.

Specifying Tool Path and Operation Sequence. After the part geometry has been defined, the part programmer must next specify the tool path that the cutter will follow to machine the part. The tool path consists of a sequence of connected line and arc segments, using the previously defined geometry elements to guide the cutter. For example, suppose we are machining the outline of our sample part in Figure 6.18 in a profile milling operation (contouring). We have just finished cutting along surface in a counterclockwise direction around the part, and the tool is presently located at the intersection of surfaces L1 and L2. The following APT statement could be used to command the tool to make a left turn from Ll unto L2 and to cut along L2:

GOLFT/L2,TANTO,CI

The tool proceeds along surface L2 until it is tangent to (TANTO) circle C1. This is a continuous path motion command. Pointtopoint commands tend to be simpler: for example, the following statement directs the tool to go to a previously defined point P0

GOTOPO

A variety of contouring and pointtopoint motion commands are available in the APT language

Other Functions. **In** addition to defining part geometry and specifying tool path, the programmer must also accomplish various other programming functions, such as:

- naming the program
- identifying the machine tool on which the job will be performed
- specifying cutting speeds and feed rates
- designating the cutter size (cutter radius, tool length, etc.)
- specifying tolerances in circular interpolation

Computer Tasks in Computer Assisted Part Programming. The computer's role in computer assisted part programming consists of the following tasks, performed more or less in the sequence noted: (1) input translation, (2) arithmetic and cutter offset computations. (3) editing, and (4) postprocessing, The first three tasks are carried out under the supervision of the language processing program. For example, the APT language uses a processor designed to interpret and process the words, symbols, and numbers written in APT. Other languages require their own processors. The fourth task, post-processing, re

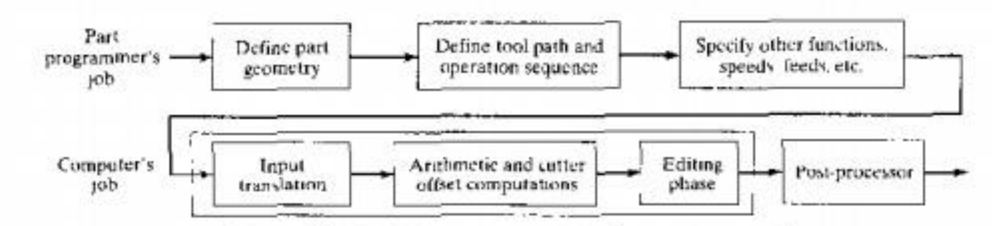


Figure 6.19 Tasks in computer-assisted part programming.

quires a separate computer program "I he sequence and relationship of the tasks of the part programmer and the computer are portrayed in Figure 6.19.

The part programmer enters the program using APT or some other highlevel part programming language. The *input translation* module converts the coded instructions contained in the program into computer usable form preparatory to further processing. In APT, input translation accomplishes the following tasks: (1) syntax check of the input woe to identify errors in format, punctuation. spelling, and statement sequence; 12) assigning a sequence number 10 each APT statement in the program; (3) converting geometry elements into a suitable form for computer processing; and (4) generating an intermediate file called PROFTL that is utilized in subsequent arithmetic calculations.

The *arithmetic module* consists of a set of subroutines to perform the mathematical computations required to define the part surface and generate the tool path. including compensation for cutter offset. The individual subroutines are called by the various statements used in the part programming language, The arithmetic computations are performed on the PROFIL file. The arithmetic module frees the programmer from the time consuming and error prone geometry and trigonometry calculations to concentrate on issues related to workpart processing. The output of this module is a file called CLFILE, which stands for "cutter location file." As its name suggests. this file consists mainly of tool path data.

In *editing*. the CLFILE is edited. and a new file is generated called CLDATA. When printed, CLDATA provides readable data on cutter locations and machine tool operating commands. The machine 1001commands can be converted to specific instructions during postprocessing. Some of the editing of CLFILE involves processing of special functions associated with the part programming language. For example, in APT. one of the special functions is a COpy command, which provides for copying a tool path sequence that has been generated in the preceding computations and translating the sequence to a new location. Another APT instruction processed in the editing phase is lRACUT. which stands for "transform cutter locations." This instruction allows a tool path sequence to be transformed from one coordinate system to another, based on matrix manipulation. Other editing functions are concerned with constructing tool paths for machines having rotational axes, such as four and fiveaxis machining centers. The output of the editing phase is a part program in a format that can be postprocessed for the given machine tool on which the job will be accomplished

NC machine tool systems are different. They have different features and capabilities. Highlevel part programming languages, such as APT, are generally not intended for only one machine tool type. They arc designed to be genera] purpose. Accordingly, the final task of the computer in computerassisted part programming is *postprocessing*, in which the CUller location data and machining commands in the CLDATA file arc converted into lowlevel code that can be interpreted by the NC controller for a specific machine tool. The output of postprocessing is a part program consisting of Gcodes, *x, y, and z coordinates. S, F,M. and other functions in word address format. The postprocessor is separate from the highlevel part programming language. A unique postprocessor must be written for each machine tool system.*

Part Programming with APT

In this section, we present some of the basic principles and vocabulary of the APT language. APT is an acronym that stands for Automatically Programmed Tooling. It is a three dimensional NC part programming system that was developed in the late 19508 and early 60s (Historical Note 6.3). Today it remains an important and widely used language in the United States and around the world. APT is also important because many of the concepts incorporated into it termed the basis for other subsequently developed languages. APT was originally intended as a contouring language. but modern versions can be used for both point to point and contouring operations in up to five axes. Our discussion will be limited to the three linear axes, x, *y,* and *z. APT* can be used for a variety of machining operations.

Our coverage will concentrate on drilling (point to point) and milling (contouring) operations. There are more than 500 words in the APT vocabulary. Only a small (but important) fraction of the total lexicon will be covered here. The Appendix to this chapter lists some of these important APT words.

Historical Note 6.3 APT: Automatically Programmed Tool [2]. [16]. [18].

The reader must remember that the work described in this historical note was started in the 1950s,a lime when digital computer technology was in its infancy, and so were the associated computer programming languages and methods. The APT project was a pioneering effort, not only io the development of NC technology, but also in computer programming concepts, computer graphics, and computer aided design (CAD).

It was recognized early in the NC development research at MIT that part programming would be a time consuming task in the application of the new technology, and that there were opportunities to reduce the programming time by delegating portions of the task to a general purpose computer. In June 1951, even before the first experimental NC machine was operating, a study was undertaken to explore how the digital computer might be used as a programming aid. The result of this study was a recommendation that a set of computer programs be developed to perform the mathematical computations that otherwise would have to be accomplished by the part programmer. In hindsight, the drawback of this approach was that, while it automated certain steps in the part programming task, the basic manual programming procedure was preserved

The significant breakthrough in computer assisted part programming was the development of the automatically programmed 1001 system (APT) during the years 19561959. It was the brainchild of mathematician Douglas Ross, who worked in the MIT Servomechanisms Lab at the time. Ross envisioned a part programming system in which (1) the user would prepare instructions for operating the machine tool using English like words, (2) the digital computer would translate these instructions into a language that the computer could understand and process. (3) the computer would carry out the arithmetic and geometric calculations needed to execute the instructions. and (4) the computer would further process (postprocess) the instruction that they could be interpreted by the machine tool controller. He further recognized that the programming system should be expandable for applications beyond those considered in the immediate research (milling applications).

Around this time, the Aircraft Industries Association (AlA, renamed the Aerospace Industries Association in 1959) was attempting to deal with NC part programming issues through its Subcommittee on Numerical Control (SNC). Ross was invited 10 attend a meeting of the SNC in January 1957 to present his views on computer assisted part programming. The result 01 this meeting was that Rosa's work at MIT was established as a focal point for NC programming within the AlA, A project was initiated in Apri11957to develop a two dimensional version of APT, with nine alrcrafr companies plus IBM Corporation participating in the joint effort MIT as project coordinator. The 2D APT system was ready for field evaluation at plant, of participating companies in April 1958.Testing, debugging, am] refining the programming system took approximately three years. During which time the AlA assumed responsibility for further APT development. In 1961, the Illinois Institute of Technology Research lnstitution; (lITRl) was selected by the *AlA* to become the agency responsible for long range maintenance and upgrading of AlA In 1962,IITRI announced completion of APTIII. a commercial version 01APT for three dimensional part programming. In 1974,APT was accepted as the U.S standard for programming NC metal cutting machine tools. In 1978,it was accepted by the ISO as the international standard.

One of the initial problems with APT when it was released in the early 1960swas that a very large computer was required 10execute it, thereby limiting the number of companies that could use it Several part programming languages based directly on APT were developed to address this problem. Two of the more important APT based languages were ADAPT and EXAPT. ADAPT (Adaptation of APT) was developed by IBM under Air Force contract to include many of the features of APT bUI required a much smaller computer. ADAPT can be used for both pointtopoint and contouring jobs. EXAPT (EXtended subset of APT) was anoTher NC part programming language based on APT. EXAPT was developed in Germany around 1964in three versions',(1) EXAPT I was designed for pointtopoint applications, such as drilling and straight milling; (2) EXAPT 11was developed for turning operations; and

(3) EXAPT III was capable of limited contouring for milling.

APT is not only a language; it is also the computer program that processes the APT statements to calculate the corresponding cutter positions and generate the machine tool control commands. To program in APT. the part geometry must first be defined. Then the tool is directed to various point locations and along surfaces of the workpart to accomplish the required machining operations. The viewpoint of the programmer is that the workpiece remains stationary and the tool is instructed to move relative to the part. To complete the program, speeds and feeds must be specified, tools must be called, tolerances must be given for circular interpolation, and so forth. Thus, there are four basic types of statements in the APT language:

Geometry statements, also called *definition statements*, are used to define the geometry elements that comprise the part.

Motion commands are used to specify the tool path.

Post-processor statements control the machine tool operation, for example, to specify speeds and feeds, set tolerance values for circular interpolation, and actuate other capabilities of the machine tool.

Auxiliary statements, a group of miscellaneous statements used to name the part program, insert comments in the program and accomplish similar functions.

These statements arc constructed of APT vocabulary words, symbols. and numbers, all arranged using appropriate punctuation. APT vocabulary words consist of six or fewer characters. 1 he characters are almost always letters of the alphabet. Only a very few APT vocabulary words contain numerical digitsso few in fact that we will not encounter any of them in our treatment of APT in this chapter. Most APT statements include a slash *(I)* as part of the punctuation. APT vocabulary words that immediately precede the slash arc called *major words.* whereas those that follow the slash are called *minor words.*

Geometry Statements. The geometry of the part must be defined to identify the surfaces and features that are to be machined. Accordingly, the points, lines, and surfaces must be defined in the program prior to specifying the motion statements. The general form of an APT geometry statement is the following:

SYMBOL = GEOMETRY TYPE/descriptive data (6.3)

An example of such a statement is

P1 = POINT/20.0, 40.0, 60.0

An APT geometry statement consists of three sections. The first is the symbol used to identify the geometry element. A symbol can be any combination of six or fewer alphabetical and numerical characters, at least one of which must be alphabetical. Also, the symbol cannot be an APT vocabulary word. Some examples are presented in Table 6.12 to illustrate what is permissible as a symbol and what is not. The second section of the APT geometry statement is an APT major word that identifies the type of geometry element. Examples are POINT, LINE, CIRCLE, and PLANE. The third section of the APT geometry statement provides the descriptive data that define the element precisely, completely, and uniquely. These data may include numerical values to specify dimensional and position data, previously defined geometry dements, and APT minor words.

Punctuation in an APT geometry statement is indicated in Eq. (6.3). The definition statement is written as an equation, the symbol being equated to the geometry element type, followed by a slash with descriptive data to the right of the slash. Commas are used to separate the words and numerical values in the descriptive data.

There is a variety of ways lu spectry the various geometry elements. The Appendix to this chapter presents a sampling of statements for defining the geometry elements we

TABLE 6.12 Examples of Permissible and Impermissible Symbols in APT Geometry Statements

Symbol	Permissible or Not, and Why
P1	Permissible
PZL	Permissible
ABCDEF	Permissible
PABCDEF	Not permissible, too many characters
123456	Not permissible, all numerical characters
POINT	Not permissible, APT vocabulary word
P1.5	Not permissible, only alphabetic and numerical characters are allowed

will be using in our treatment of APT: points. lines, planes, and circles. The reader may benefit from a few examples:

Points.

PI =POINT/20.0,40.0,60.0

where the descriptive data following the slash indicate the x,*y* and z coordinates. The specification can be done in either inches or millimeters (metric). We use metric values in our examples. As an alternative, a point can be defined as the intersection of two mter secrmg lines, as in the following

P2 = POINT/INTOF, L1. L2

where the APT word INTOF in the descriptive data stands for "intersection of." Other methods of defining points are given in the Appendix under POINT

Lines. A line defined in APT is considered to be of infinite length in both directions. Also, APT treats a line as a vertical plane that is perpendicular to the x-y plane. The easyast way to specify a line is by two points through which it passes:

L3 = LINE/P3. P4

In some situations, the part programmer may find it more convenient to define a new line as being parallel to another line that has been previously defined; for example,

L4 = LlNEIP5, PARLEL, L3

where PARLEL is APT's way of spelling "parallel" The statement indicate, line l4 passes through point PS and is parallel to line L3.

Planes. A plane can be defined by specifying three points through which the plane passed as in the following'

PLl = PLANE/Pl.P2,P3

Of course. the three points must he noncollinear. A plane can also be defined as being parallel to another plane that has been previously defined; for instance,

PL2 = PLANE!P2, PARLEL, PLl

which states that plane PL2 passes through point P2 and is parallel to plane PLI. In APT, a plane extends indefinitely.

Circles. In APT, a circle is considered to be a cylindrical surface that is perpendicular to the xy plane and extends to infinity in the z direction. The easiest way to define a circle by its center and radius. as in the following

Cl = CIRCLE/CENTER,Pl,RADIUS,25.0

By convention. the circle is located in the .e.y plane. An alternative way of defining a circle is to specify thus it passes through three points; for example,

C2 = CIRCLE/P4,P5, P6

where the three points must not he collinear There are many other ways to define a circle, several of which are listed in the Appendix under CIRCLE

Certain ground rule must he obeyed when formulating APT geometry statements.

Following are four important APT rules:

Coordinate data must be specified in the order x, then *y*, then *z*, because the statement

PI = POINT/20.5,40,O,60.0

is interpreted to mean *x* = 20.5 *mm* ,*y* = 40.0 mm. and z = 60.0 mm Any symbols used as descriptive data must have been previously defined; for example. In the statement

P2 = POINT/INTOF,Ll,L2

the two lines L1 and L2 must have been previously defined. In setting up the list of geometry statements, the APT programmer must be sure to define symbols before using them in subsequent statements.

A symbol can be used to define only one geometry element. The same symbol cannot be used to define two different elements. For example. the following statements would be incorrect if they were included in the same program:

Pl = *POINTI20,40,60*

PI = POINT *130,50,70*

Only one symbol can be used to define any given element. For example, the following two statements in the same part program would be incorrect;

PI = *POINTI20,40,60*

P2 = POINT/20,40,60

EXAMPLE 6.3 Part Geometry Using APT

Let us construct the geometry of our sample part in Figure 6.15. The geometry dements of the part to be defined in APT are labeled in Figure 6.18. Reference is also made to Figure 6.16, which shows the coordinate values of the points used to dimension the part. Only the geometry statements are given in the APT sequence that follows:

PI = POINT *10,0,0*

P2 = *POINT/160.0,0,0*

P3 = PUINT /160.0.60.0,0

P4 = POINT/35.0.90.0.0

P5 = POINT/70.0.30.0.0

P6 = POINT/120.0.30.0,0

P7 = POINT /70.0.60.0,0

P8 = POINT /130.0.60.0,0

L1 = LINE/Pl,P2

L2 = LINE/P2,P3

Cl = CIRCLE/CENTER,P8, RADIUS30.0

L3 = L1NE/14,PARLEL,L1

L4 = LINE/P4,PI

Motion Commands. All APT motion statements follow a common format, just as geometry statements have their own format. The format of an APT motion command is

MOTION COMMAND/descriptive data

An example of an APT motion statement is GOTO/PI

The statement consists of two sections separated by a slash. The first section is the basic command that indicates what move the tool should make. The descriptive data following the slash tell the tool where to go. **In** the above example, the tool is directed to go to (GOTO) point PI, which has been defined in a previous geometry statement.

At the beginning of the sequence of motion statements, the tool must be given II starting point. This is likely to be the target point. the location where the operator has positioned the tool at the start of the job. The part programmer keys into this starting position with the following statement:

FROM/PTARO 651

where FROM is an APT vocabulary word indicating that this is the initial point from which all others will be referenced; and PTARO is the symbol assigned to the starting point. Another way to make this statement is the following'

FROM/20.0. 20.0,0

where the descriptive data in this case arc the *X*, *y*, and z coordinates of the starting point. The FROM statement occurs only at the start of the motion sequence.

In our discussion of APT motion statements, it is appropriate to distinguish between point to point motions and contouring motions. For *point to point motions*, there are only two commands: GOTO and GODLTA. The GOTO statement instructs the tool to go to a particular point location specified in the descriptive data. Two examples are:

GOTO/P2

001'0/25.0,40,0,0 (6.6b)

In the first command, P2 is the destination or the too] point. In the second command, the 1001 has been instructed to go to the location whose coordinates are x = 25.0, Y = 40.0, and z = 0

The GODLTA command specifies an incremental move for the tool. To illustrate, the following statement instructs the tool to move from its present position by a distance of 50.0 mm in the x direction, 120.0 mm in the y direction, and 40 rum in the z direction

GODLTA/50.0, 120.0, 40.0

The GODLY A statement is useful in drilling and related machining operations. The tool can be directed to go to a given hole location; then the GODLTA command can be used to drill the hole, as in the following sequence:

GOTO/P2

GODLTA /0.00, 50.0

GODLTA/O,0,50.0

Contouring motion commands are more complicated than PTP commands are because the tool's position must be continuously controlled throughout the move. To exercise this control. the tool is directed along two intersecting surfaces until it reaches a third surface, as shown in Figure 6.20. These three surfaces have specific names in APT; they are

Drive surface. This is the surface that guides the side of the cutler. It is pictured as II plane in our figure.

Part surface. This is the surface, again pictured as a plane, on which the bottom or nose of the tool is guided.

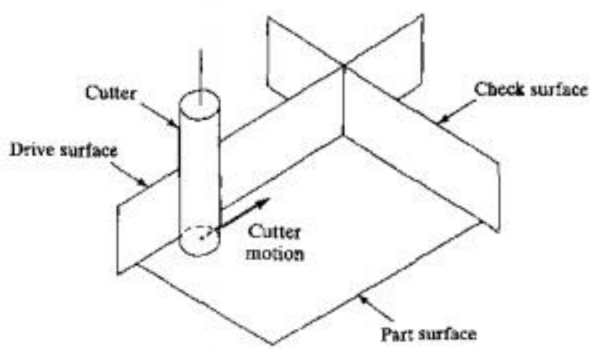


Figure 6.20 Three surfaces in APT contouring motions that guide the cutting tool.

Check; surface. This is the surface that stops the forward motion of the tool in the execution of the current command. One might say that this surface "checks" the advance of the tool.

It should be noted here that the "part surface" mayor may not be an actual surface of the part The part programmer may elect to use an actual part surface or some other previously defined surface for the purpose of maintaining continuous path control of the tool. The same qualification goes for the drive surface and check surface.

There are several ways in which the check surface can be used. This is determined by using any of four APT modifier words in the descriptive data of the motion statemen!. The four modifier words arc TO, ON, PAST. and TANTO. As depicted in Figure 0.21, the word TO positions the leading edge of the tool in contact with the check surface; ON positions the center of the tool on the check surface; and PAST puts the tool beyond the check surface. so that its trailing edge is in contact with the check surface. The fourth modifier word TANTO is used when the drive surface is tangent to a circular check surface, as in Figure 6.22. TANTO moves the cutting tool to the point of tangency with the circular surface

An APT contouring motion command causes the cutter to proceed along a trajectory defined by the drive surface and part surface; when the tool reaches the check surface it stops according to one of the modifier words TO, ON, PAST, or TANTO. In writing a

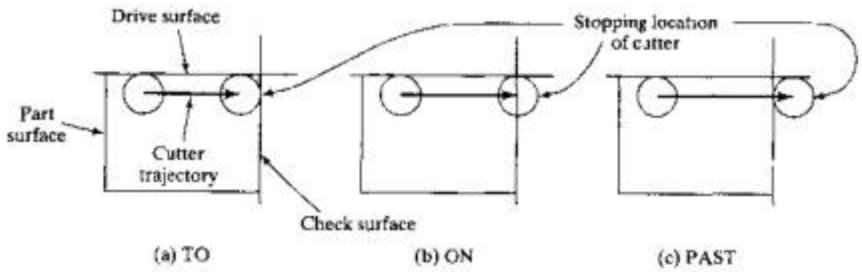


Figure 6.21 Use of APT modifier words in motion statements: (a) TO moves the tool into initial contact with the check surface; (b) ON positions the tool center on the check surface; and (c) PAST moves the tool just beyond the check surface.

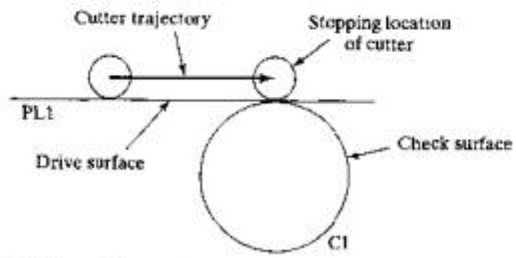


Figure 6.22 Use of the APT modifier word TANTO. TANTO moves the tool to the point of tangency between two surfaces, at least one of which is a circular surface.

Figure 6.23 Use of the APT motion words. The tool has moved from a previous position 10 its present position. The direction of the next move is determined by one of the APT motion words GOLFT. GORGT, GOFWD, GOBACK, GDUP, or GODOWN.

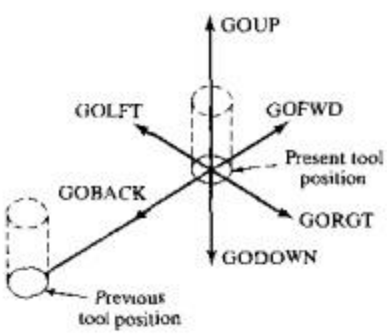


Figure 6.23 Use of the APT motion words. The tool has moved from a previous position to its present position. The direction of the next move is determined by one of the APT motion words GOLFT, GORGT, GOFWD, GOBACK, GOUP, or GODOWN.

motion statement, the part programmer must keep in mind the direction from which the tool is coming in the preceding motion command. The programmer must pretend to be riding on top of the tool, as if driving a car. After the tool reaches the check surface in the preceding move, does the next move involve a right tum or left tum or what? The answer to this question is determined by one of the following six motion words, whose interpretations are illustrated in Figure 6.23:

GOLIT commands the tool to make a left tum relative to tbe last *move*.

GORGT commands the tool to make a right tum relative to the last move.

GOFWD commands the tool to move forward relative to the last move.

GOBACK commands the tool to reverse direction relative to the last move.

GOUP commands the tool to move upward relative to the last move

GODOWN commands the tool to move down relative to the last move.

In many cases, the next move will be in a direction that is a combination of two pure directions. For example, the direction might be somewhere between go forward and go right. In these cases, the proper motion command would designate the largest direction component among the choices available.

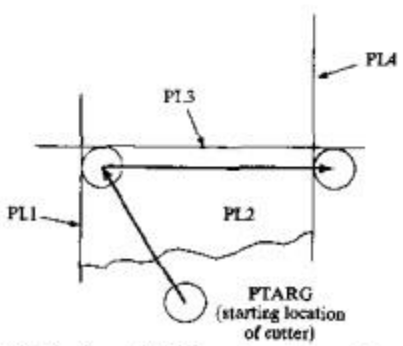


Figure 6.24 Initialization of APT contouring motion sequence.

To begin the sequence of motion commands, the FROM statement Eq. (6.5) is used in the same manner as for point to potnt moves. The statement following the FROM command defines the initial drive surface. part surface, and check surface. With reference to Figure 6.24. the sequence takes the following form:

FROM/PTARO

PTARO, PLl, TO. PL2, TO PL3 (6.7)

The symbol PTARO represents the target point where the operator has. set up the tool. The GO command Instructs the tool to move to the mter secnon of the drive surface (PL1), the part surface (PL2), and the check surface (PL3). Because the modifier word TO has been used for each of the three surfaces, the circumference of the cutter is tangent to PLI and PL3. and the bottom of the cutler is on PL2. The three surfaces included in the GO statement must be specified in the order: (I) drive surface, (2) part surface, and (3)check surface was used.

EXAMPLE 6.5 Drilling Sequence in APT

let us write the APT program to perform the drilling sequence for our sample part in Figure 6.15. We will show the APT geometry statements only for the three hole locations, saving the remaining elements of geometry for Example 6.6

PARTNO SAMPIF PART DRILLING OPERATION

MACHINIDRILL,01

CLPRNT

UNITS/MM

REMARK Part geometry Points are defined 10 mm above part surface.

PTARG = POINT/0,50.0,10.0

P5 = POINT /70.0,30.0,10.0

P6 = *POTNT/120.0,30.0,10.0*

P7 = POINT/70.0,60.0,10.0

REMARK Drill bit motion statement

FROM/PTARG

RAPID

GOTO/P5

SP1NDL/1000, CLW

*FEDRAT/O.05,*IPR

GODLTA/0,0, -25

GODLTA/0,0,25

RAPID

GOTO/P6

SPINDL/1000,CLW

FEDRAT/O.05,IPR

GODLTA/0,0,- 25

GODLTA/0,0,25

RAPID

GOTO/P7

SPINDL/l000,CLW

FED RAT /*0.05*, IPR

GODLTA/0,0,-25

GODLTA/0,0, 25

RAPID

GOTO/PTARG

SPINDL/OFF

FINl

EXAMPLE 6.6 Two Axis Profile Milling in APT

The three holes drilled in Example 6.5 will be used for locating and holding the work part for milling the outside edges. Axis coordinates are given in Figure 6.i6. The top surface of the part is 40 mm above the surface of the machine table. A 20mm diameter end mill with four teeth and a side tooth engagement of 40 mm will be used. The bottom tip of the cutter will be positioned 25 mm below the top surface during machining, thus ensuring that the side cutting edges of the cutter will cut the full thickness of the part. Spindle speed « 1000 rev/min and feed rate = 50 mm/min. The tool path, shown in Figure 6.17, is the same as that followed in Example 6.2.

PARTNO SAMPLE PART MILLING OPERATION

MACHIN/MILLING,02

CLPRNT

UNITS/MM

CUTTER/20.0

```
REMARK Part geometry. Points and lines are defined 25 mm below part top surface
PTARG =  POlNT /0,-5O.O,lO.O
PI  = POINT /0,0,  25
P2 = POINT/I60,0,25
P3 =  POINT /160,60,25
P4  =  POINT/35,90,25
P8 =  POINT/130.60,25
L1 =  LINE/PI,P2
L2 =  LINE/P2,P3
CI  =  CIRCLE/CENTER,P8. RADIUS,30
L3 =  LINE/P4,LEFf,TANTO,CI
L4 = LINE/P4, P1
PL1 =  PLANE/PI,    P2, P4
REMARK     Milling  cutter   motion       statements.
FROM/PTARG
SPINDL/1000, CLW
FFDRAT/50, IPM
GO/TO.L1,TO,PLl, ON,L4
GORGT/Ll,PAST. L2
GOLFT/L2,TANTO,C1
GOFWD/C1, PAST, L3
GOFWD/L3,PAST, L4
GOLFT/L4,PAST, L1
RAPID
GOTO/PTARG
SPINDL/ OFF
FINI
```

MODULE 3

CONTROLS IN CIM

MATERIAL HANDLING IN CIM

Material handling is an activity that involves movement of material or products within an organization from one place to another place or the flow of material or products to vehicles or from vehicles. The activities are usually confined within the boundaries of an organization. The movement of material from one organization to another is categorized as transportation work, which is not part of material handling activities.

It is not only about the movement of material. It also involves storage, protection, and control of material while it moves in different departments like a warehouse, production, and manufacturing departments. It is one of the essential tasks for organizations. A poorly handled material become waste before it can be used for production purpose or before it is sent to retail stores.

In the old times, it was mostly done manually because of the lack of technology. Because of that, the number of accidents during handling work was quite high. In present times, with the introduction of technology, almost all of the work is done using automation or semi-automation. The introduction of technology not only reduced the cases of accidents occurred but also made the work fast.

Objectives of Materials Handling Processes

Material handling is one of the most critical activities taking place in an organization. Material handling makes a large portion of the total business expense of a company.

Therefore, achieving the lowest cost and maximum production can be considered as the main objectives of the material handling process.

1. Reduced cost using a material handling

The first and foremost objective of material handling is lowering the cost of production. Because a large portion of the total production cost is spent on material procurement, storage, and movement. Material is crucial for the production process.

The process of production will halt if the material is not provided in sufficient quantity and on time. Therefore, material handling is given the utmost importance. Companies always look for methods that can be used for the optimized use of material.

By the use of sophisticated methods, the cost of production can be reduced to a significant amount.

2. Reduced waste of material

Another significant concern of an organization is to minimize material waste. Sometimes, the material gets wasted because of poor storage, or sometimes it gets wasted while moving it from one place to another.

An appropriate material handling not only concerns about the movement of material but also takes care of placing orders of the right amount, making the use of the material at the right time, keeping the right amount of inventory, and moving material using better techniques and with caution.

All of this is taken care of to reduce the wastage of material. Moreover, lower wastage for material results in lower costs. As a result of which the profit margin of the organization will increase.

3. Improved work condition

Before the inclusion of technology, all movement and storage works were done manually. Some labors were responsible for performing these tasks. They were responsible for all the loading and unloading work.

Poor results in frequent accidents on-site because of poor work conditions. A proper and well-thought material handling also takes care of people performing the work.

4. Enhanced distribution

Distribution means the delivery of final goods to the retailers and wholesalers. A lot of material gets damaged during transportation because of poor packing and poor storage.

It helps in the reduction of damage to **products** during shipping and handling. In addition to this, it also concerns the storage location of the material. A proper storage location reduced the chances of material gets damaged in the storage house.

5. Optimized warehouse capacity

Warehouse cost also adds to the price of the final product. Warehouse capacity means the ability for storing goods. It is essential to take care of the layout of the warehouse, flooring of the warehouse, and aisle space in the warehouse to have optimized warehouse capacity. Optimized warehouse capacity also helps in reducing the overall production cost.

6. Improved flow of material

A smooth flow of material is when material enters the company in raw material form at the time when it is required and exits the organization in the form of final goods. The flow of material gets disturbed when the material is not available when it is needed for the production or gets damaged rather than being used for the production process.

It concerns with the smooth flow of material in the organization. It improves the circulation of material in the organization as a result of which material stays for less time in the warehouse and is used for production at earliest.

7. Full equipment utilization

Expensive machinery and equipment are used for the production process. These equipment fails to perform at their maximum capacity because of poor material handling.

Because the performance of these equipment depends mainly on the speed at which the material is supplied and received. Therefore, material handling also helps in the full utilization of the capacity of the equipment.

8. Workers' safety

The last but not least objective is the safety of workers. Poor material handling can result in accidents in the factory, which are very risky for workers working there.

Principle

The material handling methods are designed based on the principles that you are going to learn in this section. The followings are the principles:

1. Cost principle: To encourage minimum expenditure while *materials handling*.
2. Computerization principle: To encourage maximum use of computers and automation as materials.
3. Energy principle: This principle is concerns about the consumption of energy.
4. Ergonomic Principle: To identify the human limitations and capabilities to do the work.
5. Ecology principle: To ensure the least impact on the ecological system because of material handling work.
6. Flexibility Principle: To encourage the use of tools and methods which can be used in different *types* of work conditions.
7. Gravity Principle: To promote the consideration of gravity principle in materials handling.
8. Layout Principle: The layout principle is concerned with the sequential order of material handling operations.
9. Maintenance principle: The maintenance principle is for regular maintenance and repair of machinery and device in materials handling.

10. Mechanization principle: Mechanization principle is concerned with the deployment of mechanization methods to speed up the work and reduce the efforts of humans.
11. Orientation principle: To study the existing processes and problems before getting into preliminary planning.
12. Planning principles: To plan by including basic requirements and alternative approaches in materials handling.
13. Standardization principle: The standardization principle encourages the standardization of tools and techniques.
14. Simplification principle: The simplification principle is concerned with making the process of material handling as simple as possible.
15. Space utilization principle: The space utilization principle encourages the optimized use of available space.
16. Systems Principle: The system principle is concerned with material and storage activities in materials handling.
17. System flow principle: The system flow principle is concerned with the integration of physical material flow with the data flow.
18. Safety principle: The safety principle is concerned with the rules and regulations related to the safety of workers working in materials handling.

Importance

It is essential because a large portion of the manufacturing cost is made of material handling costs. The cost of production can be reduced to an exceptional level with the help of proper handling.

Moreover, the material is needed to move to several places before it is converted into final goods. Therefore, the lack of appropriate handling can result in the damage of **products** before they can be converted into final products. The cost of damaged goods also adds to the manufacturing costs, and as a result, the overall profit of the organization reduces.

If I talk about the importance of material handling from the safety of workers working in the organization and the safety of machines and equipment used for the production process, then it has a significant role to play. Workers are responsible for loading and moving material across the organization.

Poor material handling can result in accidents during this process and due to accidents not only the material will get damaged but the risk to the life of workers also increases. Therefore, it is necessary for the sake of workers working in the organization as well as to minimize production costs.

Types

The types of material handling have changed because of the enhancement of technology. In this section, I will discuss all kinds of material handling that are used in the companies to receive, store, and move material in the organization.

Let us learn about different types of material handling in the chronological order of their introduction in industries.

1. Manual material handling

The first method is used for material movement is manual material handling. In this type of handling, the whole work of the movement is dependent on the workers. The workers lift, carry, deliver, empty the container of material by their hands. This type of material handling is a prolonged method for material movement as a result of which it causes a delay in the production work and stops efficient machines to deliver up to their full capacity.

Manual handling not only slows down the production work but is also hazardous for workers who do the work. They do a lot of physical labor, which affects their health. The shoulders and lower back of workers get strained which affects not only their work capacity but also the overall work capacity of the organization. Moreover, they are also prone to accidents because of doing a lot of physical work.

Sometimes, workers get seriously injured in the accidents and left with life long injuries. This is not good for the workers as they become incapable of earning their bread and butter, and it puts an extra financial burden on the company too.

2. Semi-automated material handling:

The semi-automated material handling is when workers do the work of material handling with the help of machinery and other carrying trollies and trams. Semi-automation becomes popular in industry in the initial days of the introduction of technology. It is a good alternative for manual handling. Semi-automation not only reduced the physical work of workers but also speed up the production work.

In semi-automation handling, workers do the work of loading and unloading themselves but rather than carrying material on their backs or by holding in hands; they can move the material using trollies or trams.

It is economical for a company as a company hires a smaller number of workers to do the same amount of work. Moreover, it also lowers the rate of mishappenings in the organization as a result of which the medical expenses of the organizations also reduce.

3. Automated material handling:

The next type is automated material handling. Automated handling reduces or eliminates manual work. Automated handling means machines and robots perform work. Robots have replaced the manual work completely. In developed countries like Japan, most industries have replaced their workforce with worker robots.

There are several advantages to automated handling. The first benefit is that it increases the speed of production work. Robots work 100 times faster than a human worker. Moreover, Automation also reduces the chances of accidents during work. Workers are not required to do physical work in the gruesome work conditions. They can sit comfortably and can control robots do all the physical work.

Automation also reduces the production cost for the company. Rather than hiring many workers, companies can employ a few workers who can control the robots. This reduces the expenses of workers' wages and medical expenses.

For example, Amazon is replacing its fulfillment center jobs with robots. Fulfillment centers were employing a considerable number of employees. Now, at the place of humans, robots will pack orders to send out for delivery.

Transport equipment

Transport equipment is used to move material from one location to another (e.g., between workplaces, between a loading dock and a storage area, etc.), while positioning equipment is used to manipulate material at a single location. The major subcategories of transport equipment are conveyors, cranes, and industrial trucks. Material can also be transported manually using no equipment.

Difference between use of conveyors, cranes, and industrial trucks for transport with respect to their path and area of operation.

Conveyors

Conveyors are used when material is to be moved frequently between specific points over a fixed path and when there is a sufficient flow volume to justify the fixed conveyor investment. Different types of conveyors can be characterized by the type of product being handled: *unit load* or *bulk load*; the conveyor's location: *in-floor*, *on-floor*, or *overhead*, and whether or not loads can *accumulate* on the conveyor. Accumulation allows intermittent movement of each unit of material transported along the conveyor, while all units move simultaneously on conveyors without accumulation capability. For example, while both the roller and flat-belt are unit-load on-floor conveyors, the roller provides accumulation capability while the flat-belt does not; similarly, both the power-and-free and trolley are unit-load overhead conveyors, with the power-and-free designed to include an extra track in order to provide the accumulation capability lacking in the trolley conveyor. Examples of bulk-handling conveyors include the magnetic-belt, troughed-belt, bucket, and screw conveyors. A sortation conveyor system is used for merging, identifying, inducting, and separating products to be conveyed to specific destinations, and typically consists of flat-belt, roller, and chute conveyor segments together with various moveable arms and/or pop-up wheels and chains that deflect, push, or pull products to different destinations.

Cranes

Cranes are used to transport loads over variable (horizontal and vertical) paths within a restricted area and when there is insufficient (or intermittent) flow volume such that the use of a conveyor cannot be justified. Cranes provide more flexibility in movement than conveyors because the loads handled can be more varied with respect to their shape and weight. Cranes provide less flexibility in movement than industrial trucks because they only can operate within a restricted area, though some can operate on a portable base. Most cranes utilize trolley-and-tracks for horizontal movement and hoists for vertical movement, although manipulators can be used if precise positioning of the load is required. The most common cranes include the jib, bridge, gantry, and stacker cranes.

Industrial truck

Industrial trucks are trucks that are not licensed to travel on public roads (*commercial trucks* are licensed to travel on public roads[7]). Industrial trucks are used to move materials over variable paths and when there is insufficient (or intermittent) flow volume such that the use of a conveyor cannot be justified. They provide more flexibility in movement than conveyors and cranes because there are no restrictions on the area covered, and they provide vertical movement if the truck has lifting capabilities. Different types of industrial trucks can be characterized by whether or not they have forks for *handling pallets*, provide *powered* or require *manual* lifting and travel capabilities, allow the operator to *ride* on the truck or require that the operator *walk* with the truck during travel, provide load *stacking* capability, and whether or not they can operate in *narrow aisles*.

Hand trucks (including carts and dollies), the simplest type of industrial truck, cannot transport or stack pallets, is non-powered, and requires the operator to walk. A pallet jack, which cannot stack a pallet, uses front wheels mounted inside the end of forks that extend to the floor as the pallet is only lifted enough to clear the floor for subsequent travel.[8] A counterbalanced lift truck (sometimes referred to as a forklift truck, but other attachments besides forks can be used) can transport and stack pallets and allows the operator to ride on the truck. The weight of the vehicle (and operator) behind the front wheels of truck counterbalances weight of the load (and weight of vehicle beyond front wheels); the front wheels act as a fulcrum or pivot point. Narrow-aisle trucks usually require that the operator stand-up while riding in order to reduce the truck's turning radius. Reach mechanisms and outrigger arms that straddle and support a load can be used in addition to the just the counterbalance of the truck. On a turret truck, the forks rotate during stacking, eliminating the need for the truck itself to turn in narrow aisles. An order picker allows the operator to be lifted with the load to allow for less-than-pallet-load picking. Automated guided vehicles (AGVs) are industrial trucks that can transport loads without requiring a human operator.

AUTOMATED GUIDED VEHICLES

AGVs are guided computerized vehicles that use computer software to determine their positioning, movement, and location. Powered by a battery or electric motor, they are able to complete manufacturing, warehousing, loading, and other operations without human interference. Self-powered AGVs can do load transfers, move and stack pallets, complete assemblies, and tow heavy loads, functions previously performed by people. They have improved production efficiency, removed humans from unsafe and potentially dangerous conditions and overcome possible human errors.

Though the term AGV, or automatic guided vehicle, may seem to be self defining, in actuality, there are multiple ways that AGVs receive their instructions and programming, which include wires implanted in the floor, cameras, radio waves, lasers, or other forms of technology.

AGVs began as a method of towing trailers to speed up production. At the time, they were considered nice conveniences that saved time. During the latter part of the twentieth century, designers explored other ways to use the technology to improve factory conditions, which has led to a wide array of capabilities, uses, and functions for AGV technology.

Types of AGVs

Three types of AGVs are towing, fork trucks, and heavy load carriers. Each is designed to perform repetitive actions such as delivering raw materials, keep loads stable, and complete simple tasks. Unlike human workers, AGVs operate continuously only needing to stop to be recharged or repaired.

Towing AGV:

Towing AGVs, or tugs (otherwise known as a warehouse tugger), pull loads of several tons, reducing the hazards associated with using large heavy equipment. They are capable of moving loads of 10,000 to 50,000 pounds. Heavy-duty towing AGVs can pull sub-assemblies, machine components, equipment, and other materials that are unsafe for manual labor.

Fork AGV:

Fork AGVs are mechanized forklifts that can retrieve stock, place materials, and move and stack pallets. They supply automated machines and take finished products to storage or place them for shipment. Forklift AGVs can prove to be economical and cost savings since they replace lift trucks and Hi-Lo operators that require licensing and training. Heavy-duty forklift AGVs can move large paper rolls, steel coils, engines, and vehicles over any distance depending on their programming

Heavy Load AGV:

Though towing and fork AGVs are capable of handling large loads, certain industries such as aviation, large construction vehicle manufacturers, and shipbuilders require AGVs able to handle huge loads of up to 250,000 pounds. For these processes, AGV producers have created machines with large bases, solid wheels, and wide platforms. In many cases, this form of AGV has to be custom designed to exactly fit the requirements of the customer's industry.

Unit load AGVs have one specialized function, which is transporting totes, pallets, goods, and racks that are too heavy to be moved by other means. They are designed to move goods and heavy materials in a warehouse or storage facility. Unlike fork and towing AGV's, unit load, or unit load decks, are flat tables that can carry one or several individual units to and from conveyors, stands, automated storage, and various types of retrieval systems. Very similar to a flatbed, they usually move along one path in two directions, repetitively, and without variations.

Light duty AGVs are usually found outside of production facilities in hospitals, offices, or commercial locations. They are able to move very small loads of under 500 pounds. Small AGVs are especially useful in places requiring cleanliness where human presence may contaminate the environment. For example, in hospitals, they deliver patient charts and daily medications.

AGV Robots

AGV robots are automatic guided vehicles equipped with robotic limbs. AGV robots are more adept at picking up and moving items than regular AGVS, which are must less dexterous. In short, they combine the intuitiveness of a human and their ability to adjust to their surroundings, and combine them with the brute force of a lifting machine like a palletizer.

AGV robots offer their users many benefits. First, using AGV robots, manufacturers can save time and money. During auto parts assembly, for example, AGV robots can put together large parts much more efficiently than humans. They can even make tooling switches without assistance. Not only that, but they have no learning curve. Once programmed, they will perform their duties perfectly. Also, their programming tends to make them more precise and eliminates human error. Their operation also takes people out of harm's way. For loading and unloading applications, AGV robots offer greater mobility and high strength. Plus, once again, they eliminate the need to people in high stress or high risk situations. Another advantage of AGV robots is the fact that they are easier to set up that regular AGVs, as they require fewer physical markers and guides.


AGV Robots from Transbotics

AGV Systems

The term “AGV systems” refers to automated, or automatic, guided vehicles. AGV systems run on industrial batteries or electricity to perform movement solutions within warehouses and facilities. Solutions include material handling, transportation, assembly, delivery and storage; these solutions have applications within most industries, including: greenhouse, general manufacturing, plastics and metal, newspaper and mail, automotive, aerospace, food and beverage processing and packaging.
To ensure smooth operations, AGV systems usually require monitoring. Especially in large factories or warehouses and/or where multiple AGV systems are in use, a traffic operating systems and controller are very important components. Generally, traffic operating systems consist of locator panels, CRT display and a central logging and report center. With the help of this technology, staff can successfully monitor and track the location and movement of in-house AGV systems and gauge their efficiency, thus avoiding collisions and traffic congestion.

Automated Guided Vehicles

Automated guided vehicles, also known as automatic guided vehicles or AGVs, computer operated, self-powered transportation machines used for applications within the material handling and moving industry. Though they were originally designed to serve only industrial market transportation and lifting, their use is now more widespread. Fields within which they are now used also include: general manufacturing, food and beverage processing, automotive, aerospace, packaging, greenhouse/industrial horticulture, metals and plastics and mail and newspaper.
These systems either operate with fixed guidance systems or free range systems. Fixed guidance makes use of magnetic tape, colored paint or embedded wire to guide vehicles that respond to

antennae, signal emissions and frequencies on simple paths. Fixed guidance systems are reliable and they work well, but they are inflexible and limit the capabilities of their AGVs and they simply may not be well suited to some environments and applications. Fortunately, most automated guided vehicles are not limited by fixed guidance systems. Instead, most contemporary AGV systems are free range. Free range systems are computer-controlled, with onboard microprocessors and supervisory control systems.

Guided Vehicles

Guided vehicles are computer-controlled transportation units that perform applications without any sort of human direction or control. They are used for material handling and transportation applications and can be designed for sorting, storage, delivery or product assembly use. Guided vehicles, or automatic guided vehicles, reduce labor costs in manufacturing processes by providing high volumes of repetitive and tedious movements and actions with around the clock capabilities.

Vehicles can be equipped with an infrared detection system, or a bumper system, which helps to reduce the damage potential of collisions. Free range AVG systems which are controlled by computer software and international navigation capabilities are able to adjust a vehicle's route according to flow of traffic and possible obstructions, therefore making the factory floor a safer place to work.

Laser Guided Vehicles

Laser guided vehicles are becoming increasingly popular worldwide in applications that call for repetitive actions over a distance or for transporting extremely heavy loads. There are four main types of laser guided vehicles: high reach lift LGVs, fork LGVs, conveyor-bed LGVS and reel LGVs. High reach lift LGVs can carry up to 1200 kg and are used for heavy pallet handling and pallet stacking up to 9m. Fork LGVs are used for pallet handling of one to four pallets and the regular delivery of stable loads. Conveyor-bed LGVs can carry numerous products simultaneously and are used for high speed sortation, material flow and transport, distribution and raw material handling.

Self Guided Vehicles

Self guided vehicles are computer-controlled transportation units that perform applications without any sort of human direction or control. Used increasingly in place of forklifts, conveyor systems and manual push-carts, automatic guided vehicles provide high volumes of movement, especially for repetitive and continuous processes. Industries such as aerospace, automotive assembly, food and beverage processing, mail service, assembly, newspaper, pharmaceutical, plastic manufacturing and storage use AGVs for sorting, delivering, transporting and assembling operations.


Self Guided Vehicles from Ward Systems

Depending on the specific application for which a vehicle is to be used, self guided vehicles range significantly in construction and shape. They may have a towing mechanism, room for unit or pallet loading, fork lifts, space for light loads or components needed in assembly lines like robotic arms.

Light load vehicles can be used for small parts distribution and assembly, while much larger vehicles such as towing vehicles can be used for moving heavy and cumbersome loads.
Other self-guided vehicles are designed for use in specific environments such as those used in clean room processes and operations. These electric battery powered vehicles are useful in indoor applications where no sudden or essential decisions are made that cannot be done by automated machinery.

Self Propelled Vehicles

Self propelled vehicles, also known as automatic guided vehicles, are able to perform applications without any sort of human direction or control, thus allowing operational processes and tasks to be achieved more efficiently and more often. AGV systems provide high volumes of repetitive movement and can be designed with the capacity for far greater loads and weights than manual labor provides. They also reduce the factor of human negligence in the movement of vehicles and loads, thereby reducing the risk of bumping, crashes and collisions on the manufacturing floor. Self propelled vehicles are typically powered by industrial strength batteries or electricity. Required power capacity will depend on the intended application and load of the vehicle, and can be adjusted to fit custom specifications. Automated guided vehicles were originally designed for use in industrial activities, but have become popular alternatives to manual cart transports, conveyors and forklift trucks in many types of applications.

Towing Vehicles

Also referred to as tuggers, towing vehicles are unmanned, computer-controlled transport vehicles that are capable of pulling one or more non-powered, wheel-based vehicles and are one of the most effective types of automatic guided vehicles. The non-powered vehicles, or carts, are attached behind the AGV in a train that is adjustable in terms of length and capacity.

Vision Guided Tow Tractor from SEEGRID

They are often used in conjunction with other AGVs such as transfer cars or material handling robots. Towing vehicles allow workers to maneuver large numbers of carts that would not have been efficiently possible through manual labor. By creating a safer work environment as well as increased productivity, towing vehicles prove advantageous for industries such as metal processing, warehouse, automotive, food processing, agriculture, aerospace, construction, communications and military.

AUTOMATED STORAGE SYSTEM

An **automated storage and retrieval system (AS/RS)**—also called AS-RS or ASRS—is a type or genre of warehouse automation technology specifically designed to buffer, store, and retrieve product and inventory on demand.

AS/RS technology varies substantially, and can consist of shuttles, cranes, carousels, vertical lift modules (VLMs), micro-loads, mini-loads, unit-loads, or other systems. It is often integrated with a warehouse execution software (WES), warehouse management software (WMS), or other controls.

Benefits of AS/RS

By automating the low-value and easily repeated task of inventory storage and retrieval, AS/RS brings many powerful benefits to the operations that utilize it, including:

- More efficient use of floor space
- Ability to reclaim unused vertical space
- Increased inventory storage density
- Improved ergonomics and safety, resulting in fewer accidents
- Increased throughput
- Reduced labor costs
- Fewer labor constraints due to labor shortages
- Often modular design for maximum flexibility
- Increased order picking accuracy
- Improved product security for premium inventory

Uses & Applications of AS/RS

1. Goods-to-Person for Order Picking and Packing

Picking, packing, and processing orders is one of the most time-consuming tasks in the order fulfillment process. In fact, the process of walking and manually picking orders can account for more than 50 percent of the time associated with picking. AS/RS offers an alternative to this through the use of Goods-to-Person (GTP, or G2P) order picking.

In a **goods-to-person** order picking system, the worker does not physically move from product location to product location to pick an order. Instead, a mini-load AS/RS crane, shuttle, AMR, carousel or VLM is able to retrieve the necessary stock from storage and delivery it directly to the worker, who operates in a pick/pack station. Once the appropriate amount of product has been picked, the stock is returned to storage and the next item needed for the order is delivered to the worker for picking.

This can be done on a full-case or split-case basis, depending on the operation. In either scenario, the AS/RS can sequence product so that it makes the most logistical sense—allowing cases of heavy product to be placed on the bottom of a pallet, for example, or organizing product so that similar products are together or in sequence to match a store's layout, shipping zone, and cut-off time, to name just a few options.

2. Staging Orders for Shipping

The impact of e-commerce and omni-channel delivery on the order fulfillment process can not be overstated. Customers are now able to shop and place orders around the clock, and they want their product delivered fast and on time. But even if an operation accepts and processes orders 24/7, there are often constraints to shipping windows: Due to worker shifts, for example, or exorbitant night and weekend delivery fees.
To make up for these constraints, an operation can pick and process orders continuously and use an AS/RS to place them in a buffer storage to stage them until the shipping window is open. This saves time and allows an operation to continuously produce, even when orders can not physically leave the facility.

3. Managing Buffer Storage

In a typical warehouse, different processes take different amounts of time to complete. If these discrepancies are not properly managed, then all it takes is a poorly-timed piece of equipment or zone slowdown in any stage to bring an entire operation to a standstill or mass slowdown. Buffering aims to prevent such a breakdown by ensuring that enough supplies/product are always on hand in different stages to keep an operation running. But while buffering makes sense, poorly managed it can become a logistical nightmare, requiring miles of conveyor to properly buffer and stage.
AS/RS has the potential to replace these conveyor buffering systems, allowing an operation to efficiently store buffer product and retrieve it as necessary. Depending on the specifics of the operation, this buffer management can be put in place in multiple areas of an operation's workflow, whether that is staging product/raw material as it is delivered ("Inbound Receiving Buffer") or storing inventory exactly where it will be needed along the production line ("Assembly Line Point-of-Use Buffering") or (Order Consolidation) holding multiple portions of an order picked in different zones and then consolidating them for final packing and shipping.

4. Storage and Point of Use Storage

One of the primary benefits of AS/RS is its ability to store product in a way that makes the most efficient use of available space, especially over the long term. By implementing AS/RS, an operation can automate their long-term storage of raw material or product and retrieve what they need, when they need it.
By integrating the AS/RS with their Warehouse Execution Software (WES) it is also possible to intelligently utilize and optimize inventory via FIFO (First in First Out), LIFO (Last In First Out), lot numbers, expiration dates, order cut off times, packaging requirements and many organization and industry specific requirements.

Types of Automated Storage & Retrieval Systems (AS/RS)

Automated storage and retrieval systems (AS/RS) come in two main varieties: Unit-Load AS/RS and Mini-Load AS/RS. Between these two main buckets, there are six primary types of AS/RS systems:

- Unit-Load AS/RS Cranes (Fixed-Aisle & Moveable Aisle)
- Mini-Load AS/RS Cranes
- Shuttle- and Bot-based AS/RS
- Carousel-based AS/RS (Vertical, Horizontal, and Robotic)
- Vertical Lift Module (VLM) AS/RS
- Micro-Load (Stocker)

We explore each of these in more detail below.

Unit-Load AS/RS

Unit-load AS/RS systems are typically used to handle exceptionally large and heavy loads ranging from 1,000 to 5,500 pounds. This capability allows for unit-load AS/RS to handle full or partial pallets and cases.

Usually, unit-load AS/RS consists of narrow aisle racks, which can extend to heights greater than 100 feet and which house pallets of product and inventory. These racks are paired with a crane, which is used to physically place and retrieve pallets as needed.

Unit-load AS/RS is a particularly helpful option when pallet-level storage is limited and quick retrieval is critical.

The two primary forms that unit-load AS/RS takes are fixed-aisle and moveable aisle cranes.

Fixed-Aisle Unit-Load AS/RS Crane

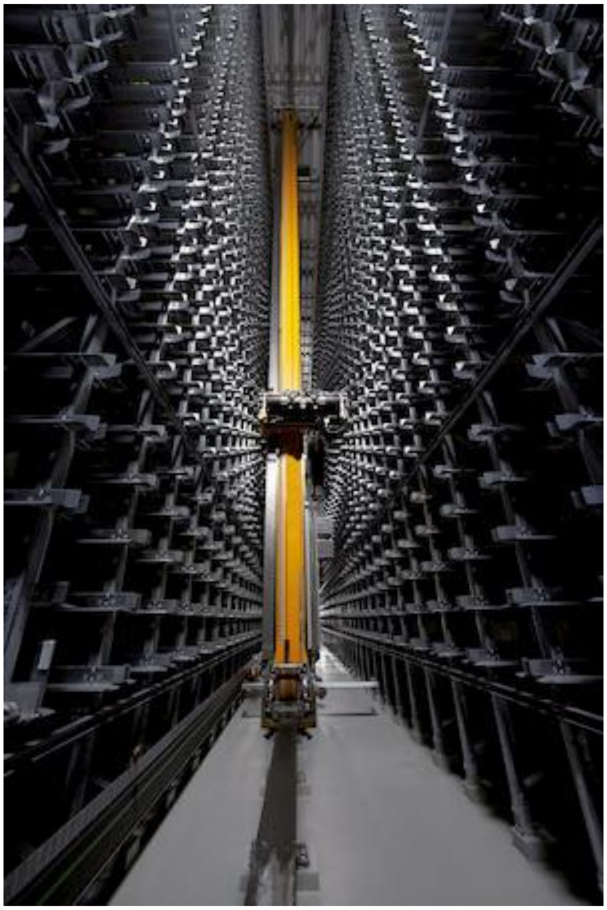
In **fixed-aisle unit-load AS/RS systems**, pallet racks are arranged with narrow aisles between them. A crane travels between these aisles moving both vertically and horizontally to retrieve and store product. The crane is fixed to a single aisle of pallets.

Moveable-Aisle Unit Load AS/RS Crane

Moveable-aisle unit load AS/RS works much the same way as fixed-aisle unit-load AS/RS. It consists of a crane moving between narrow aisles of pallets along some kind of track. The key difference is that it is not fixed to a specific aisle. This capability allows a single piece of equipment to service multiple aisles and, ultimately, a greater working space.

Mini-Load AS/RS

Mini-load AS/RS typically handles smaller loads (up to 75 pounds) compared to unit-load systems. Instead of full pallets, mini-load AS/RS handles totes, trays, and/or cartons. Sometimes, these systems are called "case-handling" or "tote-stacking" systems.



Mini-load AS/RS is especially well-suited for operations that require storage locations for a large amount of SKUs, but which lack the floor space required for traditional carton-flow shelving to provide a pick face for each SKU. Mini-load AS/RS systems can also be used to buffer and efficiently release/sequence product to picking or palletizing stations, and can be used to automatically replenish pick locations like carton-flow.

Shuttle-based AS/RS

Shuttle-based AS/RS delivers inventory via a shuttle or "bot" that runs on a track between a racking structure.

They can operate on a single level or multiple levels, depending on the needs of the operation, and can be battery- or capacitor-powered. The shuttles deliver the tote or carton to a workstation integrated with the system.

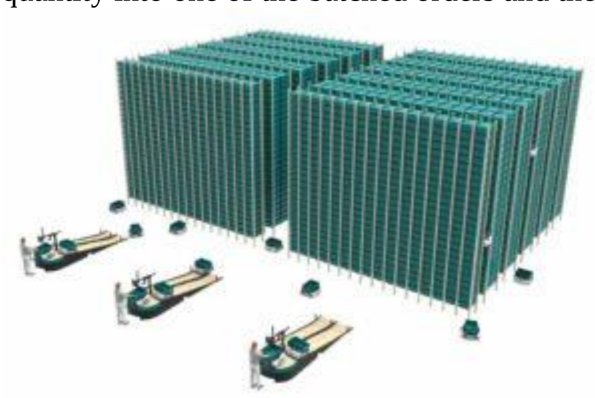
When an item is requested, the shuttle drives to the location of the product and retrieves the tote or carton that contains the requested item. The shuttle will then take the tote/carton directly to a workstation or transfer it to a conveyor to convey the tote/carton to a workstation.

Different shuttle models utilize different designs to provide different benefits. For example, one model is vertically oriented to optimize floor space. The shuttles move on the perimeter of the rack and then move into an aisle to extract a tote and delivers it to its integrated workstation.

A third shuttle model utilizes vertical rack, but each bot moves on the floor and climbs vertically to extract its tote. Then it comes down to the floor and independently delivers the inventory to a remote workstation. It will queue at the workstation until picked and then is automatically assigned a new task and it repeats the process.

AMR-Based High-Density AS/RS

An **autonomous mobile robot-based high-density automated storage and retrieval system** is designed in a way that uses three-axis AMR robots to travel vertically up storage rack to retrieve the required inventory tote or case. The AMR stores the inventory or tote on itself, and then navigates down the rack and on the floor to any one of the remote order picking workstations. The AMR rides up the workstation's ramp, and the integrated pick-to-light and software system indicates which item and how many to pick. The operator then places the appropriate item and quantity into one of the batched orders and the AMR leaves for its next assignment.



This system provides a tremendous amount of flexibility in storage density, throughput and labor requirements. Additional rack and AMR bots can be added, subtracted or moved to meet current and anticipated activity levels.

Carousel-based AS/RS

Carousel-based AS/RS systems consist of bins of product or inventory which rotate continuously along a track. When the operator requests a particular item, the system will automatically rotate so that the appropriate bin is accessible so that the item can be picked. An integrated lightree will indicate to the picker which carousel, shelf, and item to pick.

Carousel-based AS/RS may consist of either a **horizontal carousel** (bins move horizontally, as on a merry-go-round) or a **vertical carousel** (bins move vertically, as on a ferris wheel). Horizontal carousels are often utilized for small items and parts, as well as documents or raw materials.

Robotic horizontal carousel AS/RS is another variety which provides fully automated AS/RS functionality.

In these systems, up to three tiers of carousels are stacked on top of each other, and totes or cases are loaded on each shelf level. All three vertical carousels work independently to present the necessary inventory to an inserter/extractor device that runs horizontally in front of them. The inserter/extractor takes as many as two totes or cartons per trip to take-away conveyor, which delivers the goods to a workstation, and picks up returning inventory, placing it back in a waiting shelf. It is possible to increase capacity and throughput by increasing the number of carousel rows with an inserter/extractor in front of it.

Vertical Lift Module (VLM)

A **vertical lift module (VLM)** is an enclosed system consisting of an inserter/extractor in the center and a column of trays on either side. It is a form of goods-to-person technology.
When an item is requested, the inserter/extractor locates the necessary tray, retrieves it, and delivers it to an operator, who completes the order. Once the order is complete, the VLM will return the tray to its proper location before retrieving the next requested tray.
Trays may either be fixed or dynamic. In fixed systems, individual trays will always be returned to the same location; in a dynamic system, where individual trays are stored will vary.

Micro-Load Stocker

A **Micro-Load Stocker** provides discrete or individual totes or carton storage and retrieval. It is ideal for buffering, sequencing, and point-of-use items in a high-density footprint.
The system is enclosed, and has an inserter/extractor device that runs in the center of the system, picking a specific queue of inventory and then discharging them onto awaiting conveyor or workstation. Different models store and retrieve differently, by taking either one item or a group of up to five items in one pass.
This system can also be used to store SKUs until needed, discharging them onto awaiting conveyor. It can be integrated with other AS/RS systems to improve the other systems' performance and dramatically reduce conveyor and floor space requirements.

AS/RS Cost Factors

As is the case for virtually any warehouse automation technology, the final cost of an automated storage and retrieval system can vary widely from operation to operation and even from industry to industry. The surest way to get a clear picture of what it will cost to implement AS/RS in your operation is to request a consultation from a knowledgeable and trusted systems integrator. That being said, by understanding the different factors that typically influence the final cost of investment, it is possible to estimate where on the cost spectrum your new system is going to fall. Here are the seven most important cost factors of AS/RS that you should consider:

- Available clear height in your facility
- The type of environment where it will be implemented (ambient, refrigerated, freezer, clean room, etc.)
- The size (cube) plus (and quality) of the load to be handled
- The weight of each piece
- The inbound and outbound systems in place to convey inventory to and from the system
- Whether the facility is steel-frame or rack-supported
- Current labor costs and quantity of labor

MODULE 4

SENSORS

Sensors have played a role in manufacturing for years, but until recently they have been largely constrained by issues such as system noise, signal attenuation, and response dynamics. Today, integration of local computing power and the Internet of Things (IoT) has transformed ordinary sensors into smart sensors, enabling them to carry out complex calculations on measured data locally within a sensor module. Along with their increased capabilities, sensors have also become remarkably small (some are no larger than a pencil eraser) and extremely flexible, allowing them to be attached to difficult-to-reach and potentially dangerous equipment, turning bulky machines into high-tech intel. This fusion of sensing and signal-processing functions is redefining the sensor landscape.

Smart Sensors Defined

For a proper definition, we turned to an expert. Tom Griffiths, Product Manager at Honeywell Industrial, which produces smart sensors, defines the technology this way:

"Smart sensors … are microprocessor driven and include features such as communication capability and on-board diagnostics that provide information to a monitoring system and/or operator to increase operational efficiency and reduce maintenance costs."

Five additional characteristics of a smart sensor include:

1. Signaling conditioning that preserves integrity and ensures isolation in harsh industrial environments
2. Using the local computing power to process and interpret data locally; make decisions based on the physical parameters measured; and communicate accordingly
3. Creating boundary conditions without a human operator
4. Enabling in-fault alarms and processing efficiency
5. Complying with a variety of communication standards such as Wi-Fi, Bluetooth, and ZigBee

Three Main Benefits of Smart Sensors

Aside from the aforementioned size, which allows smart sensors to be placed just about anywhere imaginable, what really gets manufacturers excited is the prospect of greater profitability, happier customers, wider market-share, and more productive assets. Smart sensors offer three key benefits that help achieve these goals:

1. Equipment and environmental conditions

Which parts need replacement? Which need maintenance? In the past, this could be a guessing game that resulted in major inefficiencies and loss of productivity. But, it was better than the alternative: waiting until a machine overheated or broke down, which could really throw production schedules off course and even lead to potential accident and injury. With smart sensors, this is all in the past. Applied throughout the supply chain and constantly collecting data, smart sensors monitor the conditions of equipment and its utilization rate in real time, giving workers a 360-degree view of all activities. With the aid of smart sensors, manufacturing employees can view machine performance and receive advance notice of potential problems or anomalies so they can be addressed proactively. Smart sensors monitor the following conditions and more:

- Temperature
- Speed
- Weight
- Operational failures
- Changes in operations
- Object movement (target too close/too far)
- Valve status (open/closed)

A smart sensor is also able to report oxygen levels and the heart rate of employees to make the workplace a safer place.

2. Improving and automating logistics and asset management

Outfitting with GPS, smart sensors can track location of assets, vehicles, inventory, or even people. The data is utilized by manufacturers to see at what point in its journey a shipment is at, the whereabouts of a fleet truck, and more. Manufacturers can also use sensor data to predict and confirm when assets arrive and when they leave warehouses, distribution centers, and retail stores. Notifications that an asset is not where it should be alert manufacturers to a potential problem in the supply chain that needs to be addressed, and they could also be an indicator of potential inventory theft. Another sensor benefit? They help keep shelves stocked by notifying automated storage and retrieval systems of needed inventory. Smart sensors monitor the following conditions and more:

- Asset location
- Asset presence in shelf
- Asset temperature
- Inventory control

3. Controlling energy costs and meeting specific regulatory requirements of each industry

We've come a long way from "The Clapper". While motion sensors in homes and offices have been saving energy costs for years by turning on and off lights based on activity, smart sensors are a giant leap forward, giving manufacturers the ability to view and control temperatures and activity on the factory floor and in distribution centers; they can now control energy usage on a large scale. The benefits are twofold: they help manufacturers combat the increasing cost of energy use, and enable them to meet the strict energy use regulations imposed upon the manufacturing sector.

Managing Smart Sensor Data

All sensors have the ability to collect, store, and monitor data. Smart sensors take it a step further, offering a 360-degree view of each of the following:

- **Context.** In order to use the data, you need to know something about the contributing factors. Time stamps, GPS coordinates, weather, and relevant machine/asset/vehicle are the most common variables which provide valuable context for the manufacturer.
- **Relevance** - How is the data being collected relate to company goals? Does it impact the bottom line, or indicate risk to customer satisfaction? Relevance is subjective, but data needs to point to a significant end result that benefits the business in some way.
- **Communication** - Data must be conveyed to another machine (typically the internet or an intranet) that can record, store, and organize data. Security surrounding the data is also critical if it is sensitive information.
- **Analysis** - Raw data is often useless; once captured, it needs to be aggregated and analyzed to recognize anomalies, or the data points which indicate that something isn't operating properly and needs attention.
- **Action** - At last, the ROI! Some data points can trigger predetermined actions, saving both time and resources. They also ensure the proper response is initiated without human intervention.

Smart sensors, especially when combined with IoT, are changing the way manufacturers collect data and communicate. They are helping to created better products, and produce them faster. Rapid adoption of smart sensors has also resulted in falling prices (small smart sensors go for less than 50 cents) enabling manufacturers of every size to get in the game

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LIGHT SENSORS

A light sensor is a photoelectric device that converts light energy (photons) detected to electrical energy (electrons).

Candela

- Originated from the term candles, candela refers to luminous intensity; how strong is the light to a naked eye
- The higher the luminous intensity, the higher the sensitivity it is to our eyes

Lumen

- Measures the total amount of visible light from a light source through the relationship between luminous intensity and the angle that a light beam fills
- Commonly used to rate the brightness of a lightbulb
- To simply put it Lumen = Total amount of light emitted in all directions

Lux

- Used to measure illuminance, the area where the luminous flux is spread
- It's similar to Lumen but it takes into account the surface area
- To simply put it, Lux = total amount of light that falls on a parrticular surface

What are the types of light sensor

There are different types of light sensors available; mainly Photoresistor, Photodiodes, and Phototransistors. Sounds technical? I'll break it down with the explanations below!

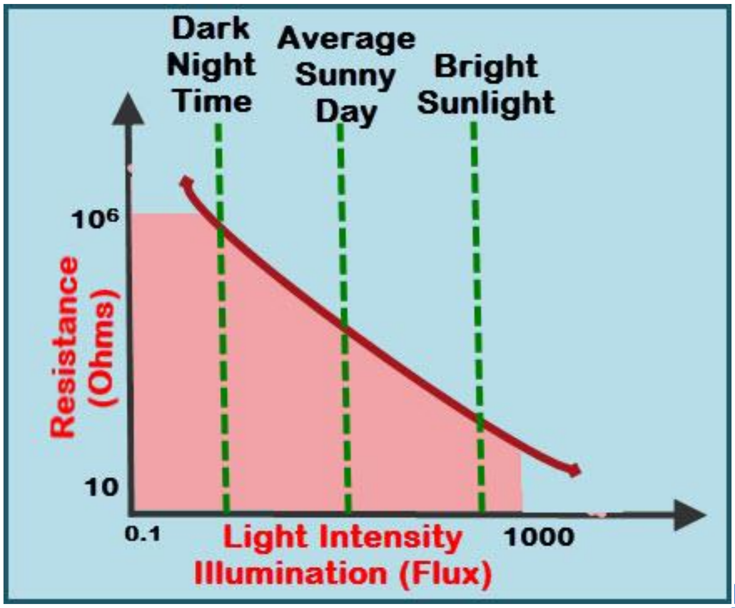
1. Photoresistors (LDR)

The most common light sensor type that's used in a light sensor circuit are photoresistors, also known as a light-dependent resistor (LDR). Photoresistors are used to simply detect whether a light is on or off and compare relative light levels throughout a day.

What are photoresistors made of?

- A high resistance Semiconductor material called cadmium sulfide cells, highly sensitive to visible and near-infrared light

How photoresistors work?



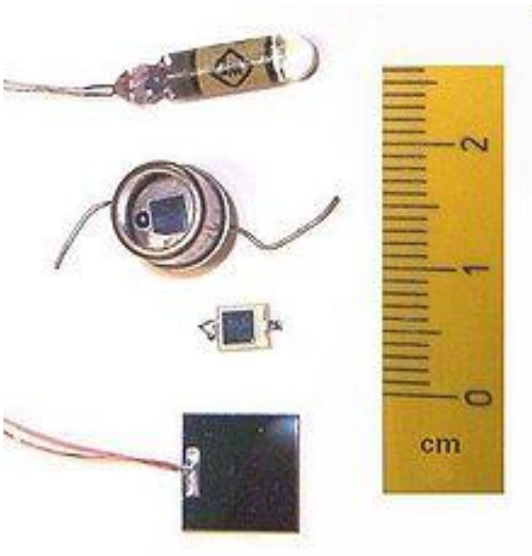
Photoresistor Working Principle

As its name suggests, photoresistors work similarly to your regular resistors, but instead resistance change is dependent on the amount of light it's exposed to.

- High intensity of light causes a lower resistance between the cadmium sulfide cell
- The low intensity of light results in a higher resistance between the cadmium sulfide cells

This working principle can be seen in applications such as street lamps, wherein the day, the higher light intensity results in lower resistance and no light produced.

2. Photodiodes



How photodiodes look like

Photodiodes are another type of light sensor. But instead of using the change in resistance like LDR, it's more complex to light, easily changing light into a flow of electric currents.

Also known as a photodetector, photo sensor

What are photodiodes made of?

- Photodiodes are mainly made from silicon and germanium materials and comprise of optical filters, built-in lenses and surface areas

How photodiodes work?

Photodiodes work on the working principle called the inner photoelectric effect. To simply put it, when a beam of light hits, electrons are loosened, causing electron-holes which results in electrical current to flow through.

- The brighter the light present, the stronger the electrical current will be

Photodiode light sensor applications

Since current generated by photodiodes are directly proportional to the intensity of light, it makes it favourable for light sensing that requires fast light response changes.

Since photodiodes are responsive to infrared light, it's applicable for more usages as well.

Here are some of the applications of photodiode:

- Consumer electronics ranging from compact disc players to smoke detectors and even remote control devices
- Medical applications such as equipment/instruments used for measuring and analysis purposes
- Solar energy systems such as solar panels

3. Phototransistors

The last light sensor type we'll be exploring today is the phototransistor. The phototransistor light sensor can be described as a photodiode + amplifier. With the added amplification, light sensitivity is far better on the phototransistors.

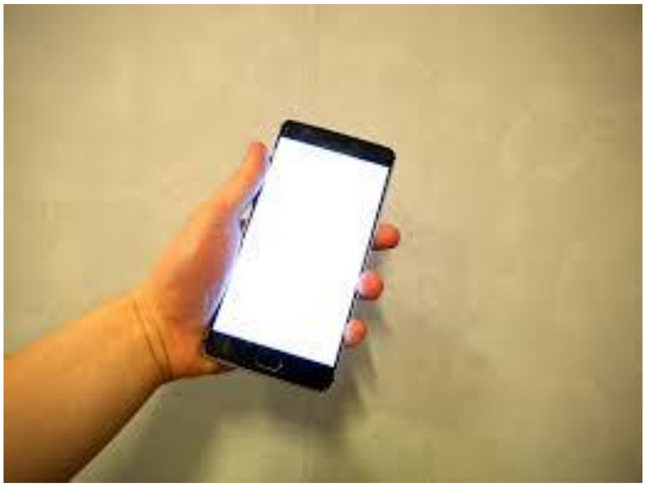
- However, it doesn't fair better in low light level detection as compared to photodiodes.

Since both light sensor types share a similar working principle, do refer to the previous explanation

What is a light sensor used for? Applications

Despite the different types of light sensors, it can still be used in a variety of applications as seen below:

Consumer electronics



Ever wonder what's behind your smartphone and tablets that allow for auto screen brightness adjustments? Yes, it's an ambient light sensor! It measures the ambient light level of your surroundings and determines the suitable brightness of your screen!

Automobiles

Similarly to how light sensor works on your smartphones, it is used in automobiles to support the drivers' field of vision. The present light sensor detects surrounding ambient light, and if it's getting too dark, it'll automatically turn on light systems!

Agricultural Usages


Image Reference: Trusty Joe

We all know crops need mainly two things for growth; Sunlight and water. This is where a light sensor comes to play, helping farmers keep their crops hydrated yet not over-hydrating it. Here's how:

- A light sensor is connected to a sprinkler system, detecting levels of sunlight and only activating it when the sun isn't at its brightest
- It is used alongside other temperature sensors to help gather informative data as well

Security applications

Commonly used in circuits for shipment cargos, light sensors are connected to circuits and placed inside as it can detect whenever a container is open due to the change in light exposure. This helps in better processing of lost goods and tracking of personnel.

- As such, photoresistors are commonly used due to its suitability

Light sensors available at Seeed

Since photoresistors, photodiodes, and phototransistors offer versatility at affordable pricing, you can collect illuminance data using Arduino or Raspberry Pi through our selection of light sensors available at Seeed!

ENCODERS

Encoders are used in machinery for motion feedback and motion control. Encoders are found in machinery in all industries. You'll find encoders used in cut-to-length applications, plotters, robotics, packaging, conveying, automation, sorting, filling, imaging, and many, many more. You may have never noticed them, but they are there. In this blog post and video, we will give you a very basic introduction into what an encoder is, and what it does.

What IS an encoder?

Simply put, an encoder is a sensing device that provides feedback. Encoders convert motion to an electrical signal that can be read by some type of control device in a motion control system, such as a counter or PLC. The encoder sends a feedback signal that can be used to determine position, count, speed, or direction. A control device can use this information to send a command for a particular function. For example:

- In a **cut-to-length application**, an encoder with a measuring wheel tells the control device how much material has been fed, so the control device knows when to cut.
- In an **observatory**, the encoders tell actuators what position a moveable mirror is in by providing positioning feedback.
- On **railroad-car lifting jacks**, precision-motion feedback is provided by encoders, so the jacks lift in unison.
- In a **precision servo label application system**, the encoder signal is used by the PLC to control the timing and speed of bottle rotation.
- In a printing application, feedback from the encoder activates a print head to create a mark at a specific location.
- With a **large crane**, encoders mounted to a motor shaft provide positioning feedback so the crane knows when to pick up or release its load.
- In an application where **bottles or jars are being filled**, feedback tells the filling machines the position of the containers.
- In an elevator, encoders tell the controller when the car has reached the correct floor, in the correct position. That is, encoder motion feedback to the elevator's controller ensures that elevator doors open level with the floor. Without encoders, you might find yourself climbing in or out of an elevator, rather than simply walking out onto a level floor.
- On automated assembly lines, encoders give motion feedback to robots. On an automotive assembly line, this might mean ensuring the robotic welding arms have the correct information to weld in the correct locations.

In any application, the process is the same: a count is generated by the encoder and sent to the controller, which then sends a signal to the machine to perform a function.

How does an encoder work?

Encoders use different types of technologies to create a signal, including: mechanical, magnetic, resistive and optical – optical being the most common. In optical sensing, the encoder provides feedback based on the interruption of light.

The graphic at right outlines the basic construction of an incremental rotary encoder using optical technology. A beam of light emitted from an LED passes through the Code Disk, which is patterned with opaque lines (much like the spokes on a bike wheel). As the encoder shaft rotates, the light beam from the LED is interrupted by the opaque lines on the Code Disk before being picked up by the Photodetector Assembly. This produces a pulse signal: light = on; no light = off. The signal is sent to the counter or controller, which will then send the signal to produce the desired function.

What's the difference between absolute and incremental encoders?

Encoders may produce either incremental or absolute signals. Incremental signals do not indicate specific position, only that the position has changed. Absolute encoders, on the other hand, use a different "word" for each position, meaning that an absolute encoder provides both the indication that the position has changed and an indication of the absolute position of the encoder.

An encoder is a device that is used in many industries to provide feedback.
In the most basic terms, an encoder, regardless of the type, which we will cover later, senses "position", "direction", "speed", or "counts". Below we'll also discuss various encoder applications.

Encoder Types and Technologies

Some of the technologies involved in encoders are:
– Magnetic
– Mechanical
– Resistive
– Optical
"Optical" is the most widely used encoder motion translating technology.
There are different types of encoders such as "Absolute" and "Incremental". We will describe those in greater detail in a future article.

Encoder Working Principle

For now, an example of an incremental, optical type encoder uses a beam of light that passes through a disk that has opaque lines in a specific pattern, somewhat like the spokes of a wheel. On the other side of the disk is a photo sensing device that will interpret the light, based on the pattern on the disk, picture a shutter, blocking and unblocking the light.

The pulses of light are then converted to an electrical signal to be sent back to the processor, through the encoder's output

Encoders have a wide range of uses which include "closed-loop" applications such as "servo or VFD control", "measuring", and "counts".
Here are some examples of processes that may use an encoder.

Encoders for Controlling the Speed of a VFD

For VFD control, you may be running a pump, on a VFD, to fill a tank full of a liquid. You are requesting a certain speed and want to verify that the pumps VFD is at the requested speed.
An "encoder" on the VFD may be used for feedback of speed.

Encoder in Measuring Processes

Next, let's give an example for a "measuring" process.
In this application, you will need to cut some aluminum product to a particular size. You are passing a long roll, meaning hundreds of feet, of the aluminum sheet through a cutting mechanism.
You need to determine the amount of aluminum fed, so that you can cut the sheets to the proper size that will be used in a separate manufacturing process.
An encoder, attached to the conveyor and reading the material that is feeding through your cutting assembly, will indicate the length of material that has been fed since the last cut. That feedback can then be used to adjust the cutting blade to sever the length required.

Encoder in Counting Applications

For an example of "counts", consider this process. You have a conveyor line that has bottles running on a conveyor. They are counted by a photo-eye sensor when entering the assembly. They have a cap with an aluminum, tamper-proof foil on top that needs to adhere to the bottle.
Once the foil is sealed, the bottle will then move down the conveyor line and verified that it exited the cap sealing assembly via an exit photo-eye sensor.

Some of the requirements for this station are:
– The same number of bottles that enter the assembly must exit in a "predetermined time frame".
– The bottle must not remain in front of an "entrance" or "exit" sensor.
– The bottle must not be exposed to the inductive sealer longer than a predetermined amount of time.
– You must make this assembly flexible enough to handle many types of bottles and entrance and exit sensor placement.

Consider a prescription bottle, easy right? No handles, just a bottle that is a standard size.
Now consider an antifreeze bottle with a somewhat small cap and a very large handle.

How in the world are you going to meet the requirements for the machine and remain flexible? If you put a pill bottle in, yep, easy right? Bottle in, seal, bottle out, no sensors blocked. If any of the requirements fail, bottle in, seal, tips over and isn't counted out, machine halts and alerts an operator of a malfunction.

How about the "antifreeze" bottle?
Bottle in, cap passes in front of an entrance sensor, bottle counted, then the handle; the system faults because it sees a blockage at the entrance. How do you tell the machine that this is expected behavior? "An encoder" of course, and a "selector switch" for a setup mode.
To set up, insert your product, in this case, the antifreeze bottle. You make sure to feed cap first and it must contain a foil.
Your program reads an entrance on the sensor and records "an encoder reading" as well as determines that this is a "cap" and records that fact. Your program then reads another entrance and determines that this is not "cap" and must be some other acceptable part of the bottle, possibly a handle.
The single bottle continues down the line where the exit sensor is triggered. At that point, you again record the encoder value. You now have an encoder count that registered at the entrance and exit.

RESOLVER

A **resolver** is a type of rotary electrical transformer used for measuring degrees of rotation. It is considered an analog device, and has digital counterparts such as the digital resolver, rotary (or pulse) encoder.

The most common type of resolver is the brushless transmitter resolver (other types are described at the end). On the outside, this type of resolver may look like a small electrical motor having a stator and rotor. On the inside, the configuration of the wire windings makes it different. The stator portion of the resolver houses three windings: an exciter winding and two two-phase windings (usually labeled "x" and "y") (case of a brushless resolver). The exciter winding is located on the top; it is in fact a coil of a turning (rotary) transformer. This transformer induces current in the rotor without a direct electrical connection, thus there are no wires to the rotor limiting its rotation and no need for brushes. The two other windings are on the bottom, wound on a lamination. They are configured at 90 degrees from each other. The rotor houses a coil, which is the secondary winding of the turning transformer, and a separate primary winding in a lamination, exciting the two two-phase windings on the stator.

The primary winding of the transformer, fixed to the stator, is excited by a sinusoidal electric current, which by electromagnetic induction induces current in the rotor. As these windings are arranged on the axis of the resolver, the same current is induced no matter what its position. This current then flows through the other winding on the rotor, in turn inducing current in its secondary windings, the two-phase windings back on the stator. The two two-phase windings, fixed at right (90°) angles to each other on the stator, produce a sine and cosine feedback current. The relative magnitudes of the two-phase voltages are measured and used to determine the angle of the rotor relative to the stator. Upon one full revolution, the feedback signals repeat their waveforms. This device may also appear in non-brushless type, i.e., only consisting in two lamination stacks, rotor and stator.

Resolvers can perform very accurate analog conversion from polar to rectangular coordinates. Shaft angle is the polar angle, and excitation voltage is the magnitude. The outputs are the [x] and [y] components. Resolvers with four-lead rotors can rotate [x] and [y] coordinates, with the shaft position giving the desired rotation angle.

Resolvers with four output leads are general sine/cosine computational devices. When used with electronic driver amplifiers and feedback windings tightly coupled to the input windings, their accuracy is enhanced, and they can be cascaded ("resolver chains") to compute functions with several terms, perhaps of several angles, such as gun (position) orders corrected for ship's roll and pitch.

For the position evaluation, resolver-to-digital converters are commonly used. They convert the sine and cosine signal to a binary signal (10 to 16 bits wide) that can more easily be used by the controller.

TYPES

Basic resolvers are two-pole resolvers, meaning that the angular information is the mechanical angle of the stator. These devices can deliver the absolute angle position. Other types of resolver are multipole resolvers. They have 2*p* poles (*p* pole pairs), and thus can deliver *p* cycles in one rotation of the rotor: the electrical angle is *p* times the mechanical angle. Some types of resolvers include both types, with the 2-pole windings used for absolute position and the multipole windings for accurate position. Two-pole resolvers can usually reach angular accuracy up to about ±5′, whereas a multipole resolver can provide better accuracy, up to 10″ for 16-pole resolvers, to even 1″ for 128-pole resolvers.

Multipole resolvers may also be used for monitoring multipole electrical motors. This device can be used in any application in which the exact rotation of an object relative to another object is needed, such as in a rotary antenna platform or a robot. In practice, the resolver is usually directly mounted to an electric motor. The resolver feedback signals are usually monitored for multiple revolutions by another device. This allows for geared reduction of assemblies being rotated and improved accuracy from the resolver system.

Because the power supplied to the resolvers produces no actual work, the voltages used are usually low (<24 VAC) for all resolvers. Resolvers designed for terrestrial use tend to be driven at 50–60 Hz (utility frequency), while those for marine or aviation use tend to operate at 400 Hz (the frequency of the on-board generator driven by the engines). Aerospace applications utilize 2,930 Hz to 10 kHz at voltages ranging from 4 V_{RMS} to 10 V_{RMS}. Many of the aerospace applications are used to determine the position of an actuator or torque motor position. Control systems tend to use higher frequencies (5 kHz).

Other types of resolver include:

Receiver resolvers

These resolvers are used in the opposite way to transmitter resolvers (the type described above). The two diphased windings are energized, the ratio between the sine and the cosine representing the electrical angle. The system turns the rotor to obtain a zero voltage in the rotor winding. At this position, the mechanical angle of the rotor equals the electrical angle applied to the stator.

Differential resolvers

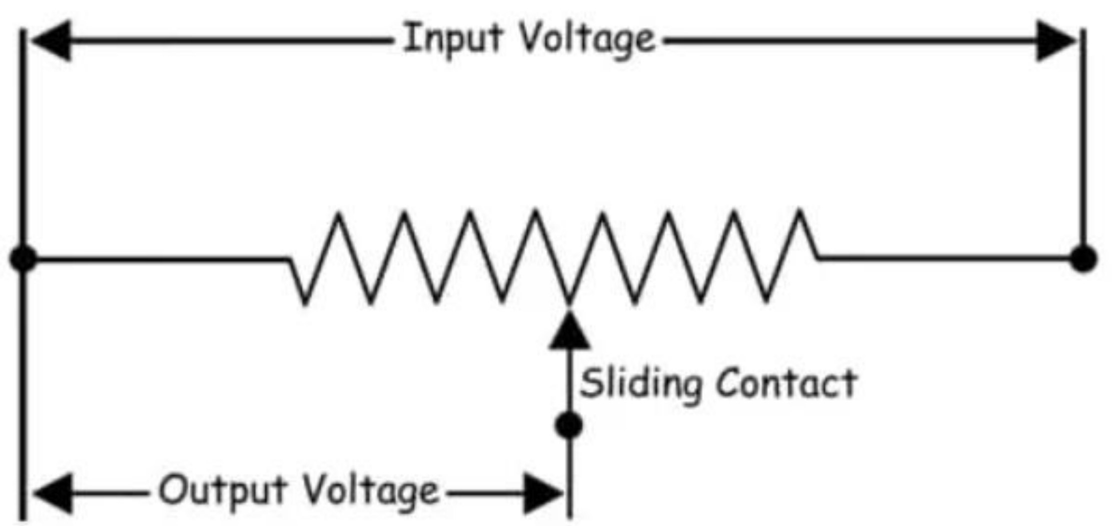
These types combine two diphased primary windings in one of the stacks of sheets, as with the receiver, and two diphased secondary windings in the other. The relation of the electrical angle delivered by the two secondary windings and the other angles is secondary electrical angle, mechanical angle, and primary electrical angle. These types were used, for instance, as analog trigonometric-function calculators.

POTENTIOMETER

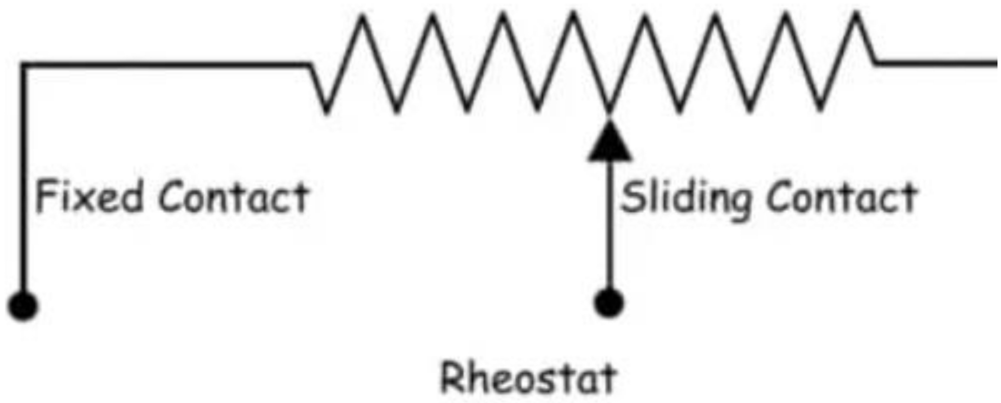
A **potentiometer** (also known as a **pot** or **potmeter**) is defined as a 3 terminal variable resistor in which the resistance is manually varied to control the flow of electric current. A potentiometer acts as an adjustable voltage divider.

How Does a Potentiometer Work?

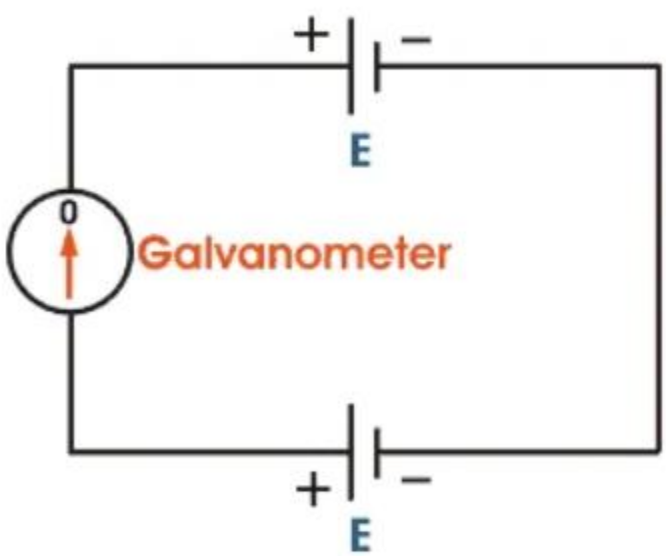
A potentiometer is a passive electronic component. Potentiometers work by varying the position of a sliding contact across a uniform resistance. In a potentiometer, the entire input voltage is applied across the whole length of the resistor, and the output voltage is the voltage drop between the fixed and sliding contact as shown below.
A potentiometer has the two terminals of the input source fixed to the end of the resistor. To adjust the output voltage the sliding contact gets moved along the resistor on the output side.



This is different to a rheostat, where here one end is fixed and the sliding terminal is connected to the circuit, as shown below.



This is a very basic instrument used for comparing the emf of two cells and for calibrating ammeter, voltmeter, and watt-meter. The basic **working principle of a potentiometer** is quite simple. Suppose we have connected two batteries in parallel through a galvanometer. The negative battery terminals are connected together and positive battery terminals are also connected together through a galvanometer as shown in the figure below.



Here, if the electric potential of both battery cells is exactly the same, there is no circulating current in the circuit and hence the galvanometer shows null deflection. The **working principle of potentiometer** depends upon this phenomenon.

Potentiometer Types

There are two main types of potentiometers:

- Rotary potentiometer
- Linear potentiometer

Although the basic constructional features of these potentiometers vary, the working principle of both of these types of potentiometers is the same.

Note that these are types of DC potentiometers – the types of AC potentiometers are slightly different.

Rotary Potentiometers

The rotary type potentiometers are used mainly for obtaining adjustable supply voltage to a part of electronic circuits and electrical circuits. The volume controller of a radio transistor is a popular example of a rotary potentiometer where the rotary knob of the potentiometer controls the supply to the amplifier.

This type of potentiometer has two terminal contacts between which a uniform resistance is placed in a semi-circular pattern. The device also has a middle terminal which is connected to the resistance through a sliding contact attached with a rotary knob. By rotating the knob one can move the sliding contact on the semi-circular resistance. The voltage is taken between a resistance end contact and the sliding contact. The potentiometer is also named as the POT in short. POT is also used in substation battery chargers to adjust the charging voltage of a battery. There are many more uses of rotary type potentiometer where smooth voltage control is required.

Linear Potentiometers

The linear potentiometer is basically the same but the only difference is that here instead of rotary movement the sliding contact gets moved on the resistor linearly. Here two ends of a straight resistor are connected across the source voltage. A sliding contact can be slide on the resistor through a track attached along with the resistor. The terminal connected to the sliding is connected to one end of the output circuit and one of the terminals of the resistor is connected to the other end of the output circuit.

This type of potentiometer is mainly used to measure the voltage across a branch of a circuit, for measuring the internal resistance of a battery cell, for comparing a battery cell with a standard cell and in our daily life, it is commonly used in the equalizer of music and sound mixing systems.

Digital Potentiometers

Digital potentiometers are three-terminal devices, two fixed end terminals and one wiper terminal which is used to vary the output voltage.

Digital potentiometers have various applications, including calibrating a system, adjusting offset voltage, tuning filters, controlling screen brightness, and controlling sound volume.

However mechanical potentiometers suffer from some serious disadvantages which make it unsuitable for applications where precision is required. Size, wiper contamination, mechanical wear, resistance drift, sensitivity to vibration, humidity, etc. are some of the main disadvantages of a mechanical potentiometer. Hence to overcome these drawbacks, digital potentiometers are more common in applications since it provides higher accuracy.

Digital Potentiometer Circuit

The **circuit of a digital potentiometer** consists of two parts, first the resistive element along with electronic switches and second the control circuit of the wiper. The figure below shows both the part respectively.
The first part is an array of resistors, and each node is connected to a common point W, except the endpoints A and B, via a two-way electronic switch. The terminal W is the wiper terminal. Each of the switches is designed using CMOS technology and only one of the switches out of all is in ON state at any given time of the potentiometer operation.

The switch which is ON determines the potentiometer resistance and the number of switches determines the resolution of the device. Now which switch is to be made ON is controlled by the control circuit. The control circuit consists of an RDAC register which can be written digitally using interface such as SPI, I^2C, up/down or can be manually controlled by push buttons or a digital encoder. The diagram above shows that of a push-button controlled digital potentiometer. One button is for "UP" or increasing the resistance and the other for "DOWN" i.e. decreasing the resistance.
Generally, the wiper position is at the middle switch when the digital potentiometer off. After power is switched on, depending upon our requirement we can increase or decrease the resistance by a suitable push-button operation. Besides, advanced **digital potentiometers** also have an inbuilt onboard memory which can store the last position of the wiper. Now this memory can be of the volatile type or permanent type both, depending upon the application.
For example, in the case of volume control of a device, we expect the device to remember the volume setting we used last even after we switch it on again. Hence a permanent type of memory such as EEPROM is suitable here. On the other hand for systems that recalibrates the output continuously and it is not necessary to restore previous value, a volatile memory is used.

Advantages of Digital Potentiometers

The advantages of digital potentiometers are:

- Higher reliability
- Increased accuracy
- Small size, multiple potentiometers can be packed on a single chip
- Negligible resistance drift

- Unaffected by environmental conditions like vibrations, humidity, shocks and wiper contamination
- No moving part
- Tolerance up to ±1%
- Very low power dissipation, up to tens of milliwatts

Disadvantages of Digital Potentiometers

The disadvantages of digital potentiometers are:

- Not suitable for high temperature environment and high power application.
- Due to the parasitic capacitance of the electronic switches, there is a bandwidth consideration that comes into the picture in **digital potentiometers**. It is the maximum signal frequency that can cross the resistance terminals with less than 3 dB attenuation in the wiper. The transfer equation is similar to that of a low pass filter.
- The nonlinearity in the wiper resistance adds a harmonic distortion to the output signal. The total harmonic distortion, or THD, quantifies the degree to which the signal is degraded after crossing through the resistance.

Applications of Potentiometer

There are many different uses of a potentiometer. The three main applications of a potentiometer are:

1. Comparing the emf of a battery cell with a standard cell
2. Measuring the internal resistance of a battery cell
3. Measuring the voltage across a branch of a circuit

TEMPERATURE SENSORS

We all use temperature sensors in our daily lives, be it in the form of thermometers, domestic water heaters, microwaves, or refrigerators. Usually, temperature sensors have a wide range of applications, geotechnical monitoring field, being one of them.

Temperature sensors are a simple instrument that measures the degree of hotness or coolness and converts it into a readable unit. But, have you ever wondered how the temperature of the soil, boreholes, huge concrete dams or buildings is measured? Well, this is accomplished through some of the specialised temperature sensors.

Temperature sensors are designed to keep a regular check on concrete structures, bridges, railway tracks, soil, etc.

Here we are going to tell you what is a temperature sensor, how does it work, where is it used, and what are its different types.

What are the temperature sensors?

A temperature sensor is a device, typically, a thermocouple or resistance temperature detector, that provides temperature measurement in a readable form through an electrical signal.

A thermometer is the most basic form of a temperature meter that is used to measure the degree of hotness and coolness.

Temperature meters are used in the geotechnical field to monitor concrete, structures, soil, water, bridges etc. for structural changes in them due to seasonal variations.

A thermocouple (T/C) is made from two dissimilar metals that generate an electrical voltage in direct proportion with the change in temperature. An RTD (Resistance Temperature Detector) is a variable resistor that changes its electrical resistance in direct proportion with the change in the temperature in a precise, repeatable and nearly linear manner.

What do temperature sensors do?

A temperature sensor is a device that is designed to measure the degree of hotness or coolness in an object. The working of a temperature meter depends upon the voltage across the diode. The temperature change is directly proportional to the diode's resistance. The cooler the temperature, lesser will be the resistance, and vice-versa.

The resistance across the diode is measured and converted into readable units of temperature (Fahrenheit, Celsius, Centigrade, etc.) and, displayed in numeric form over readout units. In geotechnical monitoring field, these temperature sensors are used to measure the internal temperature of structures like bridges, dams, buildings, power plants, etc.

What is a temperature sensor used for? | What are the functions of a temperature sensor?

Well, there are many types of temperature sensors, but, the most common way to categorise them is based upon the mode of connection which includes, contact and non-contact temperature sensors.

Contact sensors include thermocouples and thermistors because they are in direct contact with the object they are to measure. Whereas, the non-contact temperature sensors measure the thermal radiation released by the heat source. Such temperature meters are often used in hazardous environments like nuclear power plants or thermal power plants.

In geotechnical monitoring, temperature sensors measure the heat of hydration in mass concrete structures. They can also be used to monitor the migration of groundwater or seepage. One of the most common areas where they are used is while curing the concrete because it has to be relatively warm in order to set and cure properly. The seasonal variations cause structural expansion or contraction thereby, changing its overall volume.

How does temperature sensor work?

The basic principle of working of the temperature sensors is the voltage across the diode terminals. If the voltage increases, the temperature also rises, followed by a voltage drop between the transistor terminals of base and emitter in a diode.

Besides this, Encardio-Rite has a vibrating wire temperature sensor that works on the principle of stress change due to temperature change.

The vibrating wire temperature meter is designed on the principle that dissimilar metals have a different linear coefficient of expansion with temperature variation.

It primarily consists of a magnetic, high tensile strength stretched wire, the two ends of which are fixed to any dissimilar metal in a manner that any change in temperature directly affects the tension in the wire and, thus, its natural frequency of vibration.

The dissimilar metal, in the case of the Encardio-Rite temperature meter, is aluminium (Aluminum has a larger coefficient of thermal expansion than steel.) As the temperature signal is converted into frequency, the same read-out unit which is used for other vibrating wire sensors can also be used for monitoring temperature also.

The change in temperature is sensed by the specially built Encardio-rite vibrating wire sensor and is converted to an electrical signal which is transmitted as a frequency to the read-out unit.

The frequency, which is proportional to the temperature and in turn to the tension ‘σ’ in the wire, can be determined as follows:

f = 1/2 [σg/ρ] / 2l Hz

Where:

σ = tension of the wire

g = acceleration due to gravity

ρ = density of the wire

l = length of wire

What are the different types of temperature sensors?

Temperature sensors are available of various types, shapes, and sizes. The two main types of temperature sensors are:

Contact Type Temperature Sensors: There are a few temperature meters that measure the degree of hotness or coolness in an object by being in direct contact with it. Such temperature sensors fall under the category contact-type. They can be used to detect solids, liquids or gases over a wide range of temperatures.

Non-Contact Type Temperature Sensors: These types of temperature meters are not in direct contact of the object rather, they measure the degree of hotness or coolness through the radiation emitted by the heat source.

The contact and non-contact temperature sensors are further divided into

Thermostats

A thermostat is a contact type temperature sensor consisting of a bi-metallic strip made up of two dissimilar metals such as aluminium, copper, nickel, or tungsten.

The difference in the coefficient of linear expansion of both the metals causes them to produce a mechanical bending movement when it's subjected to heat.

Thermistors

Thermistors or thermally sensitive resistors are the ones that change their physical appearance when subjected to change in the temperature. The thermistors are made up of ceramic material such as oxides of nickel, manganese or cobalt coated in glass which allows them to deform easily.

Most of the thermistors have a negative temperature coefficient (NTC) which means their resistance decreases with an increase in the temperature. But, there are a few thermistors that have a positive temperature coefficient (PTC) and, their resistance increases with a rise in the temperature.

Resistive Temperature Detectors (RTD)

RTDs are precise temperature sensors that are made up of high-purity conducting metals such as platinum, copper or nickel wound into a coil. The electrical resistance of an RTD changes similar to that of a thermistor.

Thermocouples

One of the most common temperature sensors includes thermocouples because of their wide temperature operating range, reliability, accuracy, simplicity, and sensitivity.

A thermocouple usually consists of two junctions of dissimilar metals, such as copper and constantan that are welded or crimped together. One of these junctions, known as the Cold junction, is kept at a specific temperature while the other one is the measuring junction, known as the Hot junction.

On being subjected to temperature, a voltage drop is developed across the junction.

Negative Temperature Coefficient (NTC) Thermistor

A thermistor is basically a sensitive temperature sensor that reacts precisely to even the minute temperature changes. It provides a huge resistance at very low temperatures. This means, as soon as the temperature starts increasing, the resistance starts dropping quickly.

Due to the large resistance change per degree Celsius, even a small temperature change is displayed accurately by the Negative Temperature Coefficient (NTC) Thermistor. Because of this exponential working principle, it requires linearization. They usually work in the range of -50 to 250 °C.

Semiconductor-Based Sensors

A semiconductor-based temperature sensor works with dual integrated circuits (ICs). They contain two similar diodes with temperature-sensitive voltage and current characteristics to measure the temperature changes effectively.

However, they give a linear output but, are less accurate at 1 °C to 5 °C. They also exhibit the slowest responsiveness (5 s to 60 s) across the narrowest temperature range (-70 °C to 150 °C).

PRESSURE SENSORS

To understand pressure sensors, first, you need to understand the pressure. Pressure is an expression of force exerted on a surface per unit area.

We commonly measure the pressure of liquids, air, and other gases, amongst other things.

The standard unit for pressure is the "Pascal". This is equivalent to one "Newton per meter squared".

A pressure sensor simply monitors this pressure and can display it in one of the several units known around the world. This is commonly the "Pascal", "Bar", and "PSI" (Pounds per Square Inch) in the United States.

The pressure of the air in your tire is a great example of pressure and how it is measured.

As we air the tire up, the force it exerts on the tire increases, causing the tire to inflate. This is monitored with a pressure sensor inside the tire on newer vehicles.

How does Pressure Sensor Work?

In a nutshell, a pressure sensor converts the pressure to a small electrical signal that is transmitted and displayed.

These are also commonly called pressure transmitters because of this. Two common signals that are used is a 4 to 20 milliamps signal and a 0 to 5 Volts signal.

Most pressure sensors work using the piezoelectric effect.

This is when a material creates an electric charge in response to stress. This stress is usually pressure but can be twisting, bending, or vibrations.

The pressure sensor detects the pressure and can determine the amount of pressure by measuring the electric charge.

Pressure sensors need to be calibrated so it knows what voltage or milliamp (mA) signal corresponds to what pressure. This is a basic "Zero" and "Span" calibration or minimum and maximum which is a common job for maintenance personnel.

In the RealPars video "What is Sensor Calibration and Why is it Important?" we described the sensor calibration in detail.

Most Common Types of Pressure Sensors

What are some of the common types of pressure that you can measure with a pressure sensor?

There are three common types that we use in the industry.

First being "**Gauge Pressure**".

This is measured in reference to atmospheric pressure which is typically 14.7 PSI.

You will show a "positive" pressure when it is above atmospheric pressure and a "negative" when it is below atmospheric pressure.

The next type is "**Absolute Pressure**".

Simply put, this is the pressure as measured against absolute vacuum. A full vacuum will have an absolute pressure of zero PSIa and increase from there.

If you need to read a pressure that is lower than atmospheric pressure, this is the type of sensor you would use.

The last type that is commonly monitored in the industry is "**Differential pressure**".

This is exactly what it sounds like, the difference between two pressures, a pressure being measured and a reference pressure.

Industrial Pressure Sensor Applications

1. Steam Systems

In industry, pressure sensors are used for a wide variety of processes. Some common uses are to measure the pressure of steam. Steam is commonly used to heat many processes in manufacturing facilities.

This pressure sensor on the steam system can serve multiple purposes though. First and most obvious is to observe and monitor the pressure.

Another purpose is to control when and where steam can flow and regulate its pressure.

Steam can build up a pressure in a vessel and become dangerous. We can use the pressure sensor as an input device to open and close a control valve to keep the pressure and steam flow regulated. This only requires simple programming in the PLC to achieve this.

2.Filters

Pressure sensors are also installed next to filters in many industrial processes.

If the filter begins to clog, the flow will decrease. As the flow of the liquid decreases, pressure can increase or decrease depending on which side of the filter is monitored.
If you monitor the pressure, it will give you a simple indication that the filter is clogged and needs to be cleaned or replaced.

3.Level Measurement

A common use that isn't as obvious is the use of a pressure sensor as a level sensor.
In an open tank, you can use the hydrostatic pressure that is measured at the sensor. With a little math, using the size of the tank and specific gravity of the liquid, we can determine how much of that liquid is in the tank.
If the tank is closed, it isn't as simple of an installation. It is still a viable option though. This will require at least two sensors to measure differential pressure.
The high-pressure sensor would be located at the bottom of the tank measuring the liquid pressure and the low-pressure sensor near the top measuring the air pressure inside. A calculation can then be performed to figure out how much liquid is in the tank.

Position Sensor

Sensors are very important organs of any measurement system. They collect data from the surroundings/ physical parameter and provide electrical signal as the input to the systems. Amongst wide variety of sensors operating on different sensing principles and used in different applications, position sensors play an important role in different systems. Whether it is fly-by-wire aircraft systems, drive-by-wire cars, bullet trains taking round curves, injection molding machines, packaging machines, medical equipments, and so on, position sensors finds their applications, of course in different ways.

Position Sensors

Most common way of classifying the wide spectrum of sensors is based on the specific application of the sensor. Sensor used for measuring humidity is termed as humidity sensor, the one used for measurement of pressure is called pressure sensor, sensor used for measurement of liquid level is called level sensor and so on though all of them may be using the same sensing principle. In a similar fashion, the sensor used for measurement of position is called a position sensor.

Position sensors are basically sensors for measuring the distance travelled by the body starting from its reference position. How far the body has moved from its reference or initial position is sensed by the position sensors and often the output is given as a fed back to the control system which takes the appropriate action. Motion of the body can be rectilinear or curvilinear; accordingly, position sensors are called linear position sensors or angular position sensors.

Types of Position Sensor

Position sensors use different sensing principles to sense the displacement of a body. Depending upon the different sensing principles used for position sensors, they can be classified as follows:

1. Resistance-based or Potentiometric Position sensors
2. Capacitive position sensors
3. Linear Voltage Differential Transformers
4. Magnetostrictive Linear Position Sensor
5. Eddy Current based position Sensor
6. Hall Effect based Magnetic Position Sensors
7. Fiber-Optic Position Sensor
8. Optical Position Sensors

POTENTIOMETRIC POSITION SENSORS

Potentiometric position sensor use resistive effect as the sensing principle. The sensing element is simply a resistive (or conductive) track. A wiper is attached to the body or part of the body whose displacement is to be measured. The wiper is in contact with the track. As the wiper(with the body or its part) moves, the resistance between one end of the track and the wiper changes. Thus, the resistance becomes a function of the wiper position. The change in resistance per unit change in wiper position is linear.

Resistance, proportional to wiper position, is measured using voltage divider arrangement. A constant voltage is applied across the ends of the track and the voltage across the resistance between the wiper and one end of the track is measured. Thus, voltage output across the wiper and one end of the track is proportional to the wiper position.

The conductive track can be made linear or angular depending upon the requirements. The tracks are made from carbon , resistance wire or piezo resistive material.

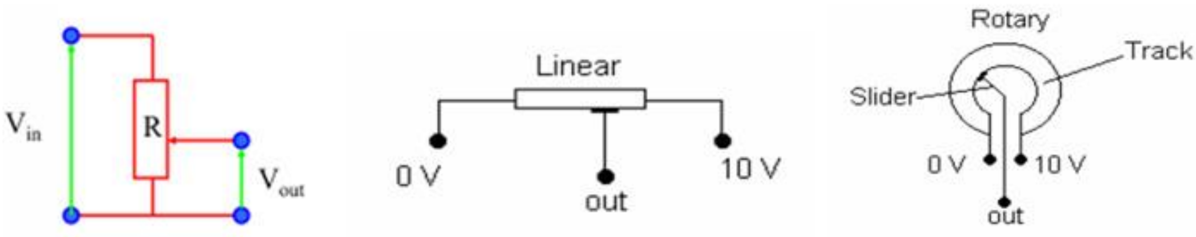


Fig. 1: Different Types of Conductive Tracks in Potentiometric Position Sensor

Three types of potentiometers are used.

a) Wirewound

Wiper slides along coil of Ni-chrome wire

Wire tends tofail, temperature variations

b) Cermet

Wiper slides on conductive ceramic track

Better than wire inmost respects

c) Plastic film

High resolution.

Advantages of these sensors are their ease of use.

Capacitive Position sensors

Capacitance between any two plates depends upon the permittivity of the dielectric between the plates, overlapping area between the plates and the distance between the two plates. Any of these three parameters can be varied in order to design a capacitive sensor.

Capacitive position sensors can use following two configurations:

1. By changing dielectric constant

In this configuration, the body or its part whose displacement is to be measured is connected to the dielectric material between the plates. As the body moves, the effective dielectric constant between the plates is the resultant of the dielectric constant due to air and dielectric constant due to the dielectric material. The changing dielectric constant leads to change in capacitance between the plates. Thus, capacitance becomes a function of the body position.

Fig. 2: Configuring Capacitive Position Sensor by Changing Dielectric Constant

This principle is commonly used in level position sensors wherein two concentric tubes are used and fluid acts as the dielectric. The variation in capacitance with the fluid level is linear.

2. By changing overlapping area

In this configuration, the body or its part whose displacement is to be measured is connected to one of the plates, the other plate remains fixed. With the movement of the body, overlapping area between the plates changes. The changing overlapping area between the plates leads to change in capacitance between the plates. Thus, capacitance becomes a function of the body position.

This principle can be employed for both linear as well as angular motions.

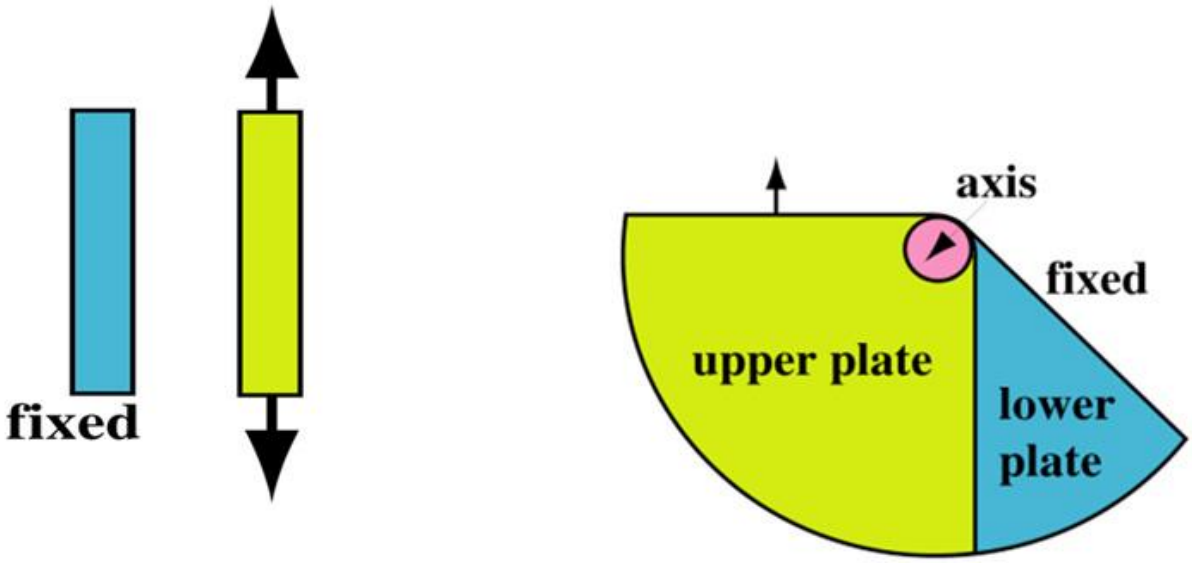


Fig. 3: Configuring Capacitive Position Sensor by Altering Overlapping Area

LINEAR VOLTAGE DIFFERENTIAL TRANSFORMER

Linear Variable Differential Transformer commonly known by its acronym, LVDT is an electromechanical transducer which converts rectilinear motion of an object into a corresponding electrical signal. It is used for measuring movements ranging from microns upto several inches.

LVDT consists of a primary winding and a pair secondary windings. Primary winding is sandwiched between the secondary windings. Secondary windings are symmetrically spaced about the primary and are identically wound. The coils are wound on a hollow form of glass reinforced polymer and then secured in a cylindrical stainless steel housing. The windings form the stationary part of the sensor.

The moving element of an LVDT is called the core made of highly permeable magnetic material; the core moves freely axially in the coil's hollow bore. The core is mechanically coupled to the object whose displacement is to be measured.

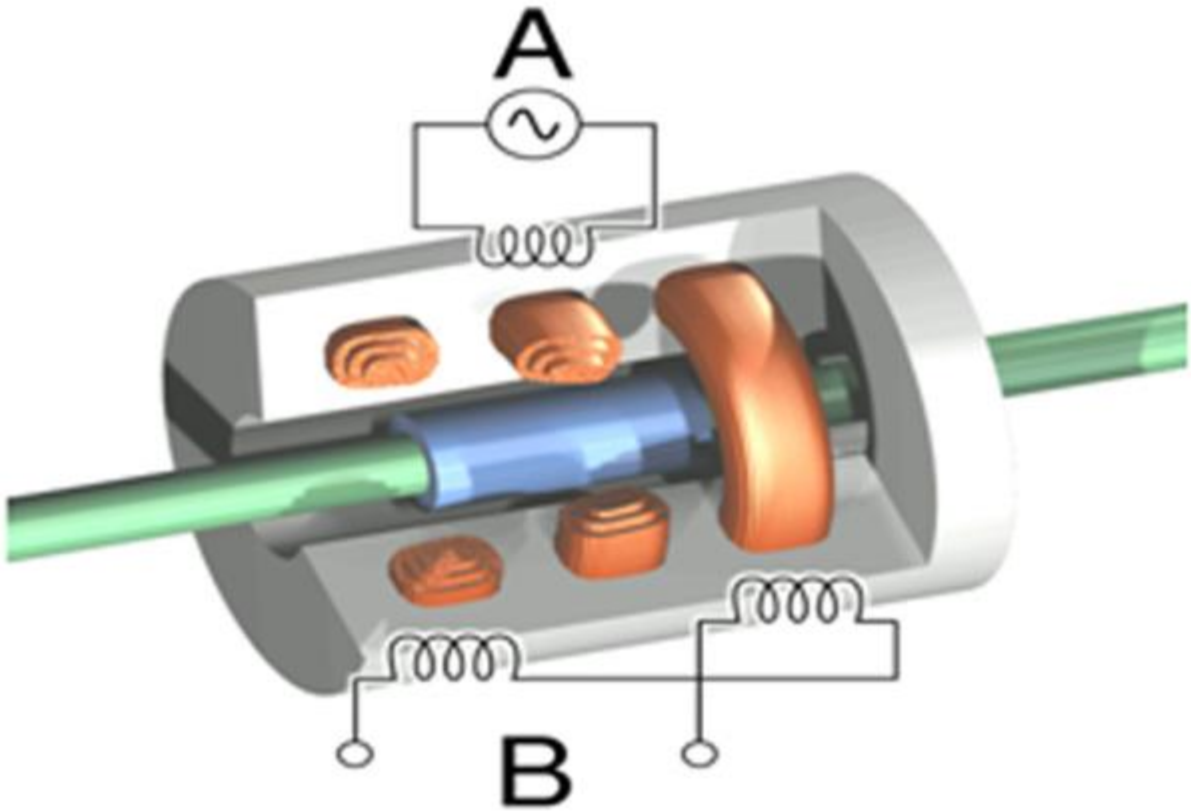


Fig. 4: Graphical Image Showing Insides of a Typical Linear Voltage Differential Transformer

When the primary winding of LVDT is energized by alternating current of suitable amplitude and frequency, AC voltage is induced in the secondary. The output of the LVDT is the differential voltage between the two secondary windings; the differential voltage varies with the position of the core. Often, differential AC output voltage is converted into DC voltage for use in measurement systems.

When primary winding is excited, the voltage induced in the secondary depends upon the coupling of the magnetic flux by the core to the secondary windings. When the core is at the centre, equal flux is coupled to the two secondary windings and hence, the differential voltage output is zero. However, when the core is at off-centre, unequal flux is induced in the secondary windings and the amount of flux in the two windings and hence the differential voltage between the two wingings depend upon the position of the core.

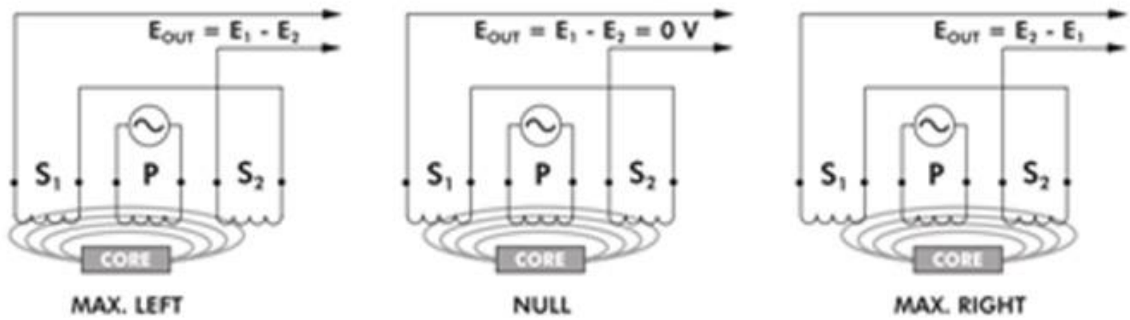


Fig. 5: Image Showing MAGNETOSTRICTIVE Effect

LVDTs offer various advantages like Friction-Free Operation, very high resolution, unlimited mechanical life, high reliability, no cross sensitivity, environmentally rugged, and so on.

For measuring angular motions, a variant of LVDT, i.e, Rotary Voltage Differential Transformer is used. RVDT is exactly similar to LVDT in terms of operation; difference is in their construction.

MAGNETOSTRICTIVE LINEAR POSITION SENSORS

Magnetostriction refers to the effect wherein a material changes its size or shape in the presence of the magnetic field the material due to the alignment of the magnetic domains, within the material, with the applied magnetic field. Materials having such properties are ferromagnetic materials such as iron, nickel and cobalt. Reverse effect, i.e. property of changing magnetic properties due to applied stress, is called Villari effect.

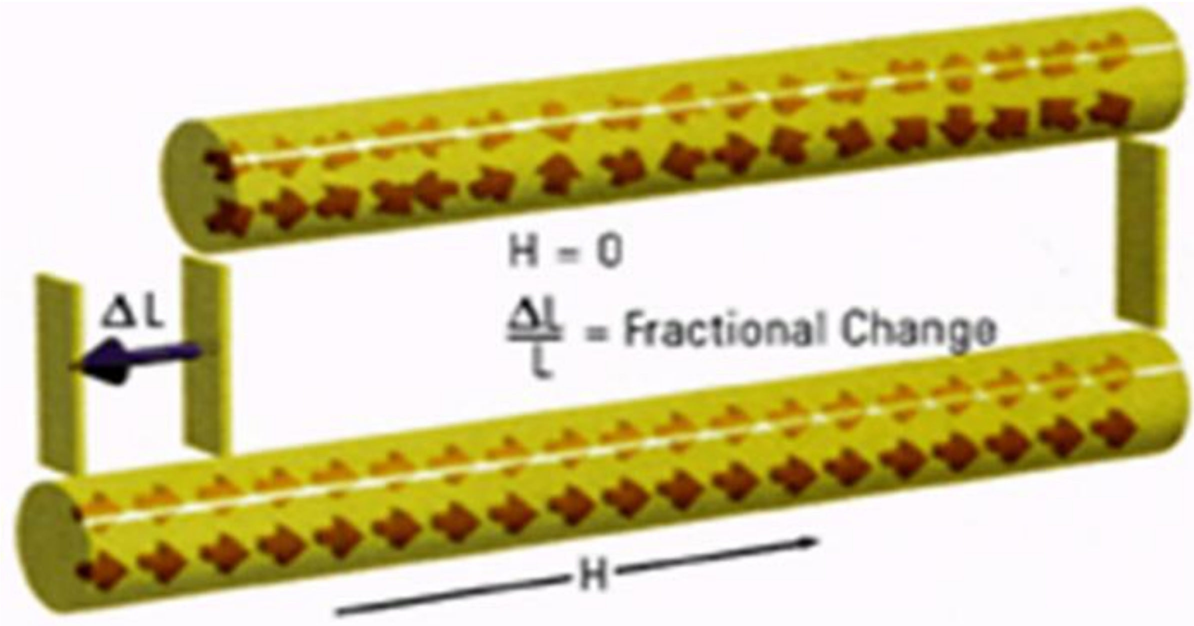


Fig. 6: Image Showing Construction of Magnetostrictive Position Sensor

Primarily comprising of five components, i.e, the position magnet, waveguide, pickup, damp, and electronics module, a magnetostrictive position sensor measures the distance between a position magnet and the head end of the sensing rod. The sensing rod is mounted along the motion axis to be measured. The position magnet is a ring shaped permanent magnet attached to the member that will be moving and it travels along the sensing rod.

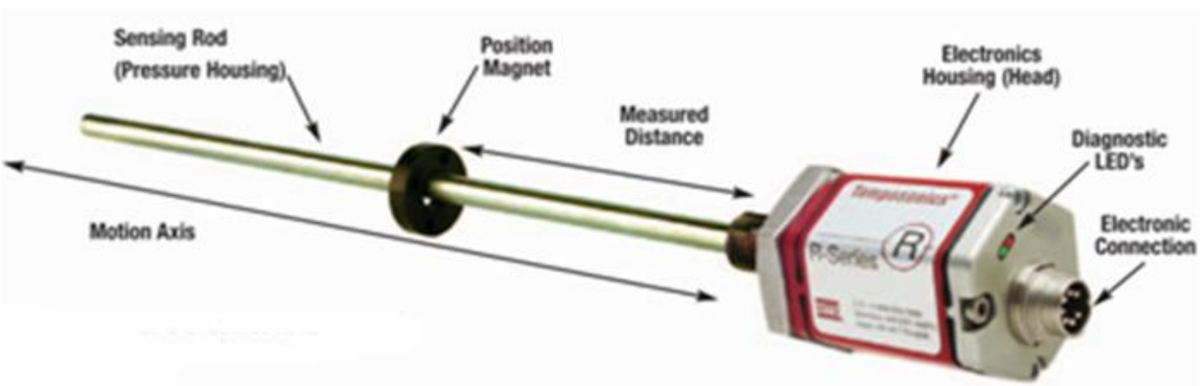


Fig. 7: Graphic Image Showing Insides of a Magnetostrictive Position Sensor

An interrogation(or current) pulse is sent down the waveguide from the electronics module. At the location of position magnet, magnetic field generated by the current pulse interacts with the magnetic field from the position magnet. The result is the generation of sonic wave or torsional strain wave in the waveguide. The strain wave travels towards the head end where the pickup device senses its arrival. Strain wave travelling away from the head end is removed by the damping module.

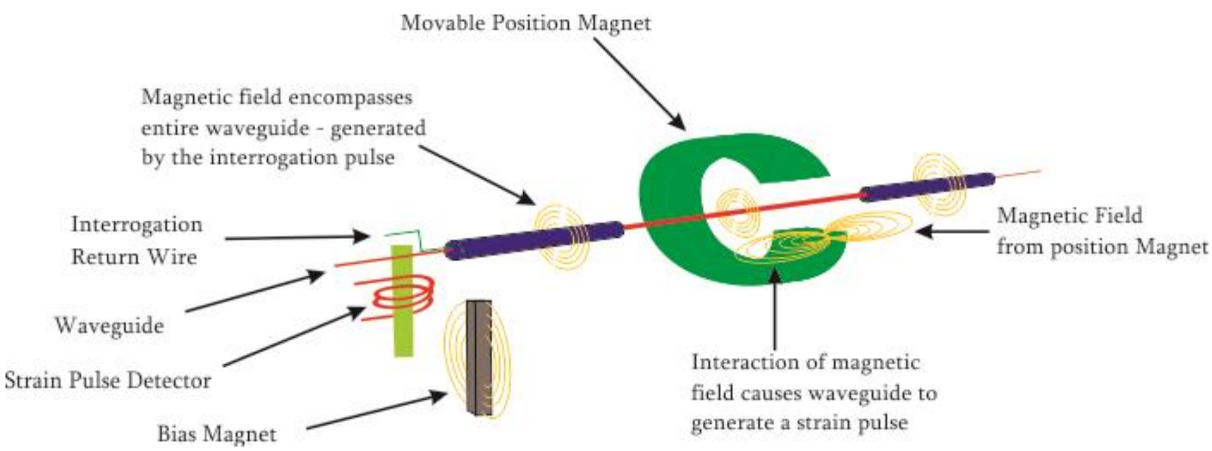


Fig. 8: Image of an Eddy Current Based Position Sensor

Time difference between the generation of the interrogation pulse and the arrival of the return pulse(strain wave) indicates the location of the position magnet(or the body connected to it)

Eddy Current based position Sensor

Eddy Currents are closed loops of induced current circulating in planes perpendicular to the magnetic flux. They normally travel parallel to the coil's winding and the flow is limited to the area of the inducing magnetic field.

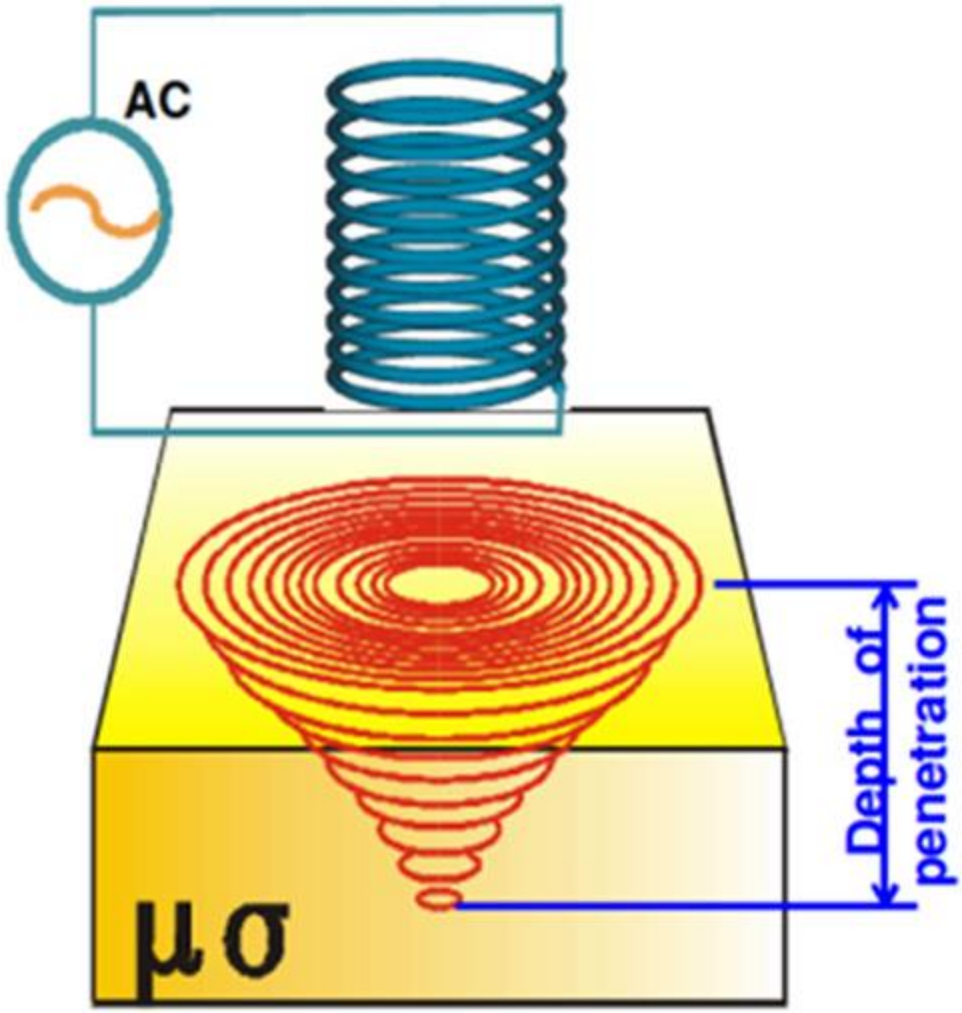


Fig. 9: Diagrammatical Image Explaining Principle of Operation of Eddy Current Sensors

Principle of operation of eddy current sensors is as follows:

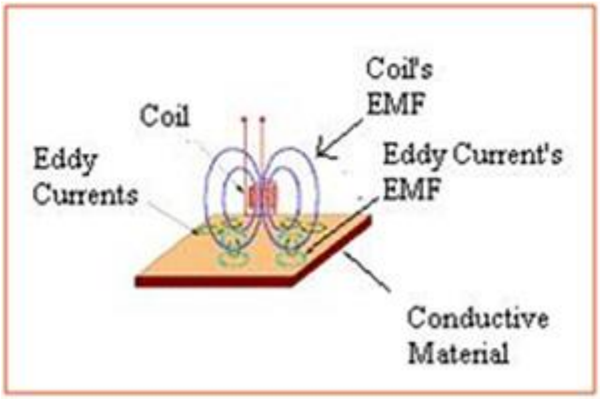


Fig. 10: A Cross Sectional Diagram Showing Operation of Eddy Current Position Sensors

Applied alternating current fed to the coil induces a primary magnetic field. Primary magnetic field induces eddy currents in the electrical conducting material (in vicinity of the coil). Eddy currents, in turn, induce secondary field. This secondary magnetic field has an effect on the coil impedance. Presence or absence of the conducting material alters the secondary field and in turn, the coil impedance. Change in the coil impedance can be used measure the distance of the electrical conducting body.

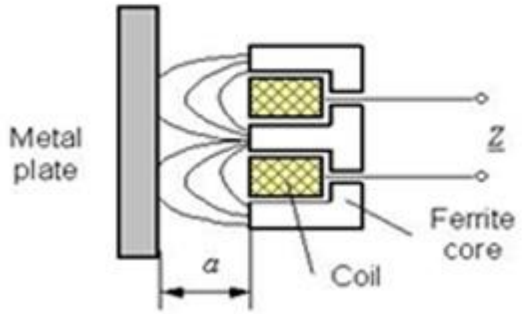


Fig. 11: Diagram showing Change of Coil Impedance as a Function of Distance in Eddy Currents

For a defined measuring target the change of coil impedance is a function of the distance. Therefore, the distance can be derived by measuring impedance change.

HEBM & Fiber-Optic Position Sensor

Hall Effect based Magnetic Position Sensors

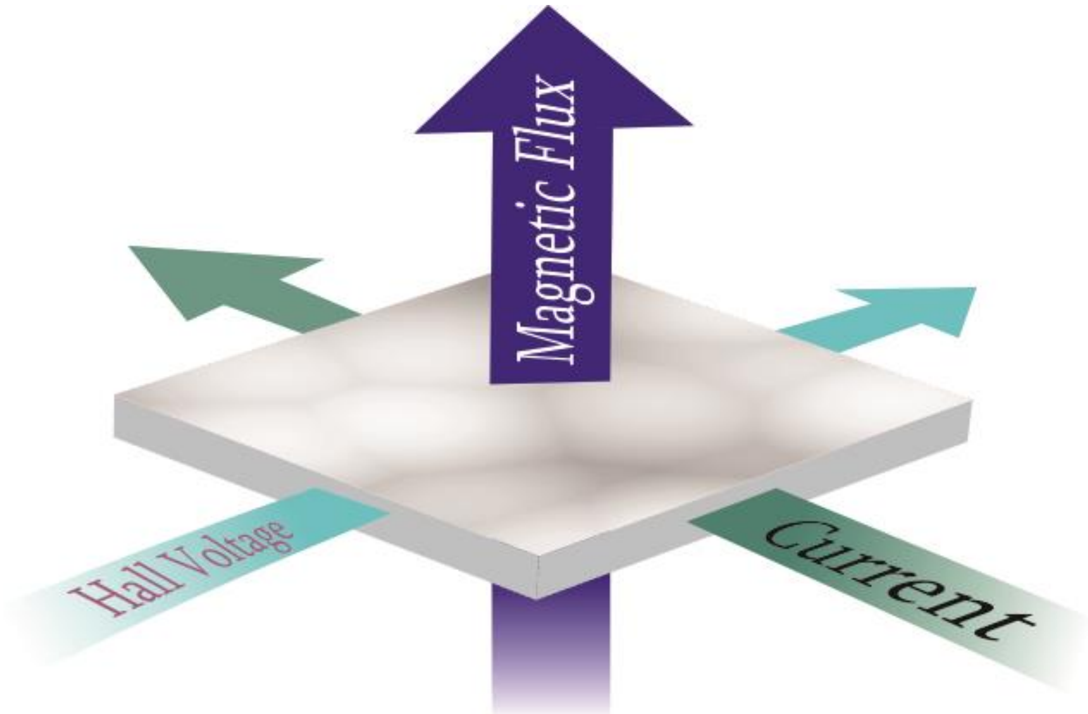


Fig. 12: Representational Image Explaining Working of Hall Effect Based Magnetic Position Sensors

The Hall Effect principle states that when a current carrying conductor is placed in a magnetic field, a voltage will be generated perpendicular to the direction of the field and the flow of current.

When a constant current is passed through a thin sheet of semiconducting material, there is no potential difference at the output contacts if the magnetic field is zero. However, when a perpendicular magnetic field is present, the current flow is distorted. The uneven distribution of electron density creates a potential difference across the output terminals. This voltage is called the Hall voltage. If the input current is held constant the Hall voltage will be directly proportional to the strength of the magnetic field.

Fig. 13: Image Shoiwng Hall Effect Based Magnetic Sensor

In position sensors which use hall efffect, the moving part is connected to a magnet.Thus, the sensor consists of a Hall element and a magnet housed within the sensor shaft. With the movement of the body or its part the magnet also moves and therefore, the magnetic field across the Hall element and so the Hall voltage. Thus Hall voltage becomes a function of the position of the moving part.

Commercially available Hall elements are made of Bulk Indium Arsenide (InAs), Thin Film InAs, Gallium Arsenide (GaAs), Indium Antimonide (InSb).

Fiber-Optic Position Sensor

Optical fibers offer distinct advantages of their immunity to EMI, inability to generate sparks in potentially explosive environment. Position sensors based on optical fibers can be used for measurement ranging from few centimeters to few meters where very high resolution is not of paramount importance.

Fluorescence followed by absorption is at the heart of this sensor. Pump source is connected to the body or its part whose motion is to be sensed. The fiber is fluorescent, and at the ends of the fiber are placed two photo-detectors.

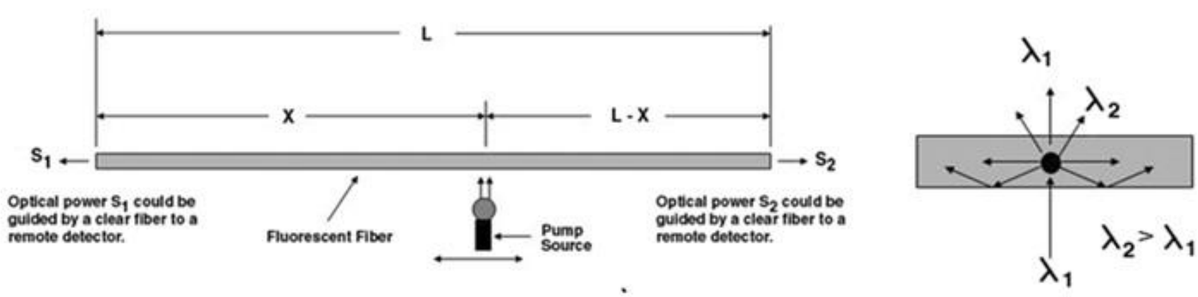


Fig. 14: Diagram Showing Working of a Optical Fiber Based Position Sensor

The logarithm of the ratio of the two signals S1 and S2 is linear in x and independent of the strength of the pump source.

OPTICAL POSITION SENSOR

Optical sensors are based one of the two mechanisms. In first type, light is transmitted from one end and received at the other. Change in one of the characteristics- intensity, wavelength, polarization or phase- by the physical parameter is monitored. In second type, transmitted light is reflected from the object and light returned towards the source is monitored.

First type of optical sensors are used in optical encoders commonly used to provide feedback to provide position feedback for actuators. Optical encoders consists of a glass or plastic disc that rotates between a light source(LED) and light receiver(photodetector). The disc is encoded with alternate light and dark sectors so that pulses are generated as the disc rotates. Based on the count of the pulses, speed of the disc and hence the angular position is computed. To identify the direction of movement, two photodetectors are used. Absolute optical encoders have a unique code that can be detected for every angular position.

An example of second types of sensors is found on machine tools measure the position of the work table is measured and displayed.

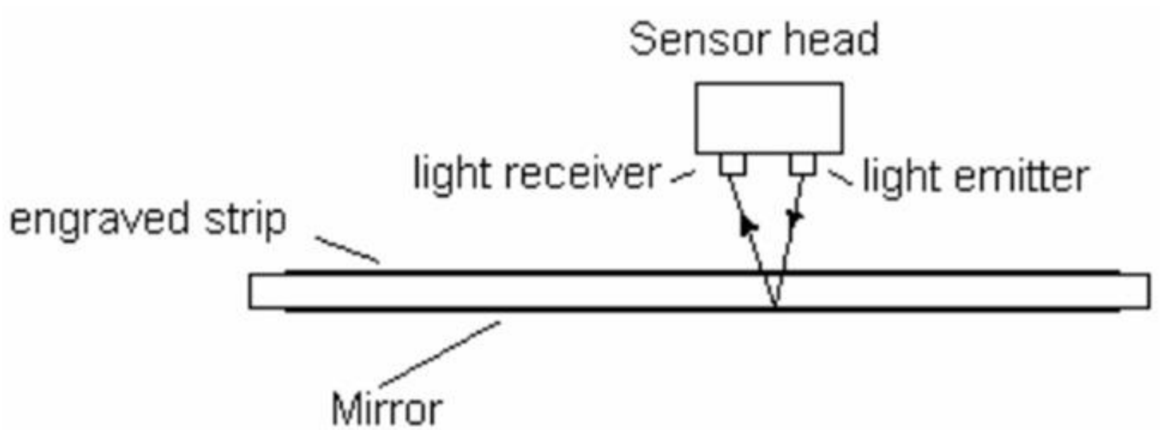


Fig. 15: Image Showing an Application of Position Sensor used in Machine Tools

The strip or disc has very fine lines engraved on it which interrupt the beam. The number of interruptions is counted electronically and this represents the position or angle.

DISPLACEMENT SENSOR

Capacitive displacement sensors "are non-contact devices capable of high-resolution measurement of the position and/or change of position of any conductive target". They are also able to measure the thickness or density of non-conductive materials. Capacitive displacement sensors are used in a wide variety of applications including semiconductor processing, assembly of precision equipment such as disk drives, precision thickness measurements, machine tool metrology and assembly line testing. These types of sensors can be found in machining and manufacturing facilities around the world.

Capacitance is an electrical property which is created by applying an electrical charge to two conductive objects with a gap between them. A simple demonstration is two parallel conductive plates of the same profile with a gap between them and a charge applied to them. In this situation, the Capacitance can be expressed by the equation:

Where C is the capacitance, ε_0 is the permittivity of free space constant, K is the dielectric constant of the material in the gap, A is the area of the plates, and d is the distance between the plates.

There are two general types of capacitive displacement sensing systems. One type is used to measure thicknesses of conductive materials. The other type measures thicknesses of non conductive materials or the level of a fluid.

A capacitive sensing system for conductive materials uses a model similar to the one described above, but in place of one of the conductive plates, is the sensor, and in place of the other, is the conductive target to be measured. Since the area of the probe and target remain constant, and the dielectric of the material in the gap (usually air) also remains constant, "any change in capacitance is a result of a change in the distance between the probe and the target." Therefore, the equation above can be simplified to:

Where α indicates a proportional relationship. Due to this proportional relationship, a capacitive sensing system is able to measure changes in capacitance and translate these changes in distance measurements.

The operation of the sensor for measuring thickness of non-conductive materials can be thought of as two capacitors in series, with each having a different dielectric (and dielectric constant). The sum of the thicknesses of the two dielectric materials remains constant but the thickness of each can vary. The thickness of the material to be measured displaces the other dielectric. The gap is often an air gap, (dielectric constant = 1) and the material has a higher dielectric. As the material gets thicker, the capacitance increases and is sensed by the system.

A sensor for measuring fluid levels works as two capacitors in parallel with constant total area. Again the difference in the dielectric constant of the fluid and the dielectric constant of air results in detectable changes in the capacitance between the conductive probes or plates.

VELOCITY SENSORS

A velocity transducer/sensor consists of a moving coil suspended in the magnetic field of a permanent magnet. The velocity is given as the input, which causes the movement of the coil in the magnetic field. This causes an emf to be generated in the coil. This induced emf will be proportional to the input velocity and thus, is a measure of the velocity. The instantaneous voltage produced is given by the equation

$v=N(d\phi/dt)$

N – Number of turns of the coil

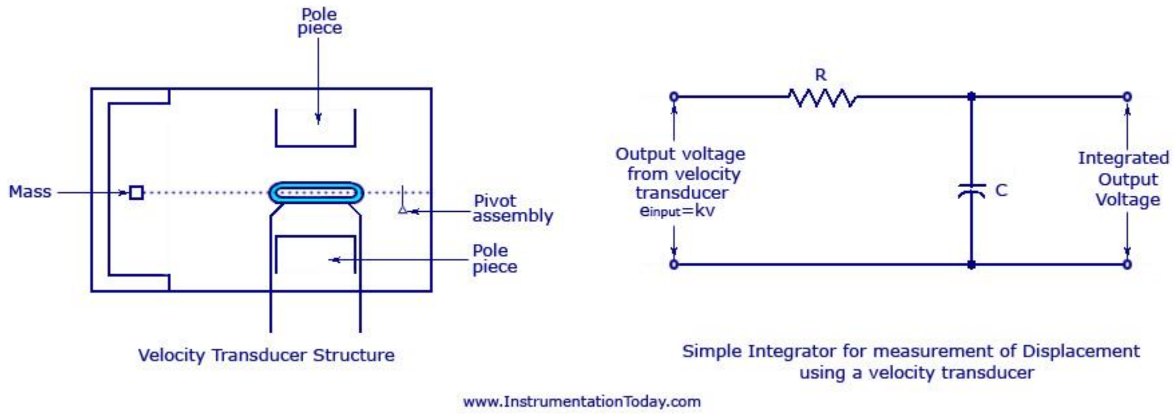
dØ/dt – Rate of change of flux in the coil

The voltage produced will be proportional to any type of velocities like linear, sinusoidal or random.

The damping is obtained electrically. Thus, we can assume a very high stability under temperature conditions. The basic arrangement of a velocity sensor is shown below.

Velocity Transducer Arrangement

The figure shows a moving coil kept under the influence of two pole pieces. The output voltage is taken across the moving coil. The moving coil is kept balanced for a linear motion with the help of a pivot assembly.



Velocity Transducer

Measurement of Displacement Using Velocity Transducer

We know that velocity is the derivative of displacement with respect to time. Similarly, displacement is the time integral of velocity. Thus, a velocity transducer can be used to find the displacement of an object. All we have to do is add an integrating circuit to the velocity transducer arrangement. This is shown in the figure above.

AccelerationTransducer

The output voltage (einput) of the transducer can be represented as the product of a constant k and the instantaneous velocity v. If the velocity varies sinusoidally according to its frequency f, and has a peak value V, then the output voltage can be written as

einput=kV2πft

Capacitor Reactance Xc = 1/2πfc

When the value of frequency f is too low, the value of Xc will be very large. So, the integrated output voltage, eoutput will be proportional to einput and so will also be proportional to the velocity v. When the value of frequency becomes high, the value of Xc will become small. Thus, the integrated output voltage can be written as

eoutput=einput/JwCR

eoutput = KV/wCR Sin(wt-90°)

This shows that the value of integrator output lags behind the value of the input voltage by 90 degrees. For a given value of velocity amplitude V, the integrator output is inversely proportional to frequency w.

MODULE 5

Condition Monitoring

Condition monitoring is the process of monitoring a parameter of condition in machinery, such that a significant change is indicative of a developing failure.
It is a major component of predictive maintenance. The use of conditional monitoring allows maintenance to be scheduled, or other actions to be taken to avoid the consequences of failure, before the failure occurs.
Nevertheless, a deviation from a reference value (e.g. temperature or vibration behavior) must occur to identify impeding damages
Predictive Maintenance does not predict failure.
Machines with defects are more at risk of failure than defect free machines. Once a defect has been identified, the failure process has already commenced and CM systems can only measure the deterioration of the condition.
Intervention in the early stages of deterioration is usually much more cost effective than allowing the machinery to fail. Condition monitoring has a unique benefit in that the actual load, and subsequent heat dissipation that represents normal service can be seen and conditions that would shorten normal lifespan can be addressed before repeated failures occur.
Serviceable machinery includes rotating equipment and stationary plant such as boilers and heat exchangers.

Methods Of Condition Monitoring

1. Screen monitoring records video or static images detailing the contents, or screen capture, of the entire [video display] or the content of the screen activity within a particular program or computer application. Monitoring tools may collect real time video, accelerated or [time-lapse] video or screen shots, or may take video or still image captures at regular intervals (e.g., once every 4 minutes). They may collect images constantly or only collect information while the user is interacting with the equipment (e.g., capturing screens when the mouse or keyboard is active).

2. Data monitoring tracks the content of and changes to files stored on the local [hard drive] or in the user's "private" network share.

3. Keystroke monitoring (e.g., number of keystrokes per minute) may track the performance of keyboard-intensive work such as word processing or data entry. Keystroke logging

captures all keyboard input to enable the employer to monitor anything typed into the monitored machine.

4. Idle time monitoring keeps track of time when the employee is away from the computer or the computer is not being actively used.

Benefits

- o Screen monitoring records video or static images detailing the contents, or screen capture, of the entire [video display] or the content of the screen activity within a particular program or computer application.

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Idle time monitoring keeps track of time when the employee is away from the computer or the computer is not being actively used.

Load Testing

- Load testing is the process of putting demand on a system or device and measuring its response.

- Load testing is performed to determine a system's behavior under both normal and anticipated peak load conditions.

- It helps to identify the maximum operating capacity of an application as well as any bottlenecks and determine which element is causing degradation.

- When the load placed on the system is raised beyond normal usage patterns, in order to test the system's response at unusually high or peak loads, it is known as stress testing.

- The load is usually so great that error conditions are the expected result, although no clear boundary exists when an activity ceases to be a load test and becomes a stress test.

- There is little agreement on what the specific goals of load testing are.
- The term is often used synonymously with concurrency testing, software performance testing, reliability testing, and volume testing.

Load testing is a type of non-functional testing.

Types Of Condition Monitoring Systems

Condition monitoring systems are of two types: periodic and permanent. In a *periodic monitoring system* (also called an *off-line condition monitoring system*), machinery vibration is measured (or recorded and later analyzed) at selected time intervals in the field; then an analysis is made either in the field or in the laboratory.
Advanced analysis techniques usually are required for fault diagnosis and trend analysis. Intermittent monitoring provides information at a very early stage about incipient failure and usually is used where (1) very early warning of faults is required, (2) advanced diagnostics are required, (3) measurements must be made at many locations on a machine, and (4) machines are complex.
In a *permanent monitoring system* (also called an *on-line condition monitoring system*), machinery vibration is measured continuously at selected points of the machine and is constantly compared with acceptable levels of vibration.The principal function of a permanent condition monitoring system is to protect one or more machines by providing a warning that the machine is operating improperly and/or to shut the machine down when a preset safety limit is exceeded, thereby avoiding catastrophic failure and destruction. The measurement system may be permanent (as in parallel acquisition systems where one transducer and one measurement chain are used for each measurement point), or it may be quasi-permanent (as in multiplexed systems where one transducer is used for each measurement point but the rest of the measurement chain is shared between a few points with a multiplexing interval of a few seconds).

In a permanent monitoring system, transducers are mounted permanently at each selected measurement point. For this reason, such a system can be very costly, so it is usually used only in critical applications where: (1) no personnel are available to perform measurements (offshore, remote pumping stations, etc.), (2) it is necessary to stop the machine before a breakdown occurs in order to avoid a catastrophic accident, (3) an instantaneous fault may occur that requires machine shutdown, and (4) the environment (explosive, toxic, or high-temperature) does not permit the human involvement required by intermittent measurements.

Before a permanent monitoring system is selected, preliminary measurements should be made periodically over a period of time to become acquainted with the vibration characteristics of the machine. This procedure will make it possible to select the most appropriate vibration measurement parameter, frequency range, and normal alarm and trip levels.

Establishing A Condition Monitoring Program

A condition monitoring program may be established to check the satisfactory operation of a single machine or, more usually, it is established to check the operation of a number of machines, perhaps all the machines in an entire plant. The following steps are usually considered in the establishment of such a program, depending on the type of machine and impact of failure of operation machines might have.

Step 1. *Determine the type of condition monitoring system,* described in the preceding section, that best meets the needs of the plant.

Step 2. *Make a list of all of the machines to be monitored* (see, for example,Table 16.1), based on the importance of these machines in the production line.

Step 3. *Tabulate the characteristics of the machines* that are important in conducting vibration analyses of the machines of step 2.These characteristics are associated with machine construction such as the natural frequencies of shafts, casings, and pedestals, and operational and defect responses.A tabulation of machine frequencies is important because fault analysis is conducted (Table 16.2) by matching machine frequencies to measured frequencies appearing in a spectrum. The following machine characteristics provide the necessary information for fault analysis.

_ Shaft rotational speeds, bearing defect frequencies, number of teeth in gears, number of vanes and blades in pumps and fans, number of motor poles, and number of stator slots and rotor bars. Vibratory forces such as misalignment, mass unbalance, and reciprocating masses.

_ Vibration responses due to process changes, such as temperature and pressure.

_ Fault responses associated with specific machine types, such as motors, pumps, and fans.

_ Sensitivity to instability in components, such as fluid film bearings and seals due to wear and clearance.

_ Loads or changes in operating conditions.

_ Effects of mass unbalance, misalignment, distortion, and other malfunction/defect excitations on vibration response.

Condition Monitoring Of Machinery

Machinery classification Result of failure
Critical Unexpected shutdown or failure causes significant production loss.
Interrupts production Unexpected shutdown or failure causes minor interruptions in production.
Causes inconvenience Inconvenience in operation, but no interruption in production. Noncritical Production is not affected by failure.

Step 4. *Select the most appropriate vibration measurement parameter*. When an accelerometer is employed as the sensing device in a condition monitoring system, the resulting *acceleration* signal can be electronically integrated to obtain *velocity* or *displacement*, so any one of these three parameters may be used in measurements.

The appropriate parameter may be selected by application of the following simple rule: *Use the parameter which provides the "flattest" spectrum.* The flattest spectrum requires the least dynamic range from the instrumentation which follows the transducer.

For example,Fig. 16.1 shows a velocity spectrum and a displacement spectrum obtained under identical conditions. The dynamic range (i.e., the range from the highest to the lowest signal level) required to measure the displacement spectrum is much larger than the range for the velocity spectrum; it may even exceed the available dynamic range of the instrumentation.Therefore, according to this rule, velocity measurements should be selected.

The *flattest spectrum* rule applies only to the frequency range of interest. Therefore, the parameter selection, to some extent, depends on the type of machine and the type of faults considered.

Step 5. *Select one of the following vibration pickups that will best meet the requirements of step 4.*

Displacement Transducer. A displacement transducer is a transducer that converts an input mechanical displacement into an electrical output that is proportional to the input displacement. Displacement transducer of the eddy-current type (described in Chap. 12), which have noncontacting probes, are commonly used to measure the relative motion between a shaft and its bearings. This information can be related directly to physical values such as mechanical clearance or oil-film thickness, e.g., it can give an indication of incipient rubbing. Shaft vibration provides information about the current condition of a machine and is principally used in permanent monitoring systems, which immediately shut the machine down in the event of trouble. The use of displacement transducers is essential in machinery having journal bearings. However, proximity probe transducers (1) usually are difficult to calibrate absolutely, (2) have limited dynamic range because of the influence of electrical and mechanical runout on the shaft, and (3) have a limited high-frequency range.

Accelerometers and Velocity Pickup. Pickups of this type are usually lightweight and rugged. They are always used for detecting faults which occur at high frequencies (say, above 1000 Hz), for example, to detect rolling element bearing deterioration or gearbox wear. Acceleration measurements of bearing vibration will provide very early warning of incipient faults in a machine. **Figure 16.1** Displacement and velocity spectra obtained under identical conditions. The velocity spectrum requires a smaller dynamic range of the equipment which follows the transducer.Therefore, it is preferable.

Step 6. *Select the measurement locations.* When a periodic (off-line) monitoring System is employed, the number of points at which measurements are made is limited only by the requirement for keeping measurement time to a minimum. As a general rule, bearing vibration measurements are made in the radial direction on each accessible bearing, and in the axial direction on thrust bearings. It is not usually necessary to measure bearing vibration in both the horizontal *and* the vertical direction, since both measurements give the same information regarding the forces within the machine; this information is merely transmitted through two different transmission paths. This applies for *detecting* developing faults. It will later be seen, however, that in order subsequently to *diagnose* the origin of the impending fault, measurements in both the horizontal and the vertical direction may give valuable information.When measuring shaft vibrations with permanently mounted proximity transducers, it is convenient to use two probes on each bearing, located at 90 from each other, thereby providing an indication of the orbit of the shaft within the bearing.

Axial displacement transducers, programmed to shut the machine down on preset levels, are mounted where a thrust measurement will protect the machine rotating parts, such as blades, from rubbing the stationary casing due to faultinduced axial forces.

When a permanent (on-line) monitoring system is employed using a seismic pickup, the number of measurement points usually is minimized for reasons of economy. Selection must be made following a study of the vibration spectra of different bearings in order to locate those points where all significant components related to the different expected faults are transmitted at measurable vibration levels if full spectrum comparison is performed. If only broadband measurements are monitored, then a further requirement is that all frequency components related to the expected faults must be of approximately the same level within the selected frequency range. Otherwise, measurements must be made in selected frequency bands.

Step 7. *Select the time interval between measurements.* The selection of the time interval between measurements requires knowledge of the specific machine. Some machines develop faults quickly, and others run trouble-free for years. A compromise must be found between the safety of the system and the time taken for measurements and analysis. Measurements should be made frequently in the initial stages of a condition monitoring program to ensure that the vibration levels measured are stable and that no fault is already developing.When a significant change is detected, the time interval between measurements should be reduced sufficiently so as not to risk a breakdown before the next measurement.The trend curve will help in determining when the next measurement should be performed.

Step 8. *Establish an optimum sequence of data acquisition.* The sequence in which data acquired in a condition monitoring program must be planned so that the data are acquired efficiently. For example, the data collection may be planned on the basis of plant layout, on the type of data required, or on the sequence of components in the machine train, from driver to driven components.

Principles And Methods

As a starting point for any discussion on condition monitoring it is useful to define what is meant by the term, and to describe how it relates to other techniques used in the operation and maintenance of machines, such as alarm and shut down systems or methods for failure and problem investigation.

The crudest method for operating machines is to run them until they fail, and then to try and repair them in order to make them fit for further service. This method of operation can be very expensive in terms of lost output and machine destruction, and in addition can involve hazards to personnel. It is now well recognised that, particularly in the case of large and expensive plant, it is more economical and operationally satisfactory to carry out regular maintenance. This involves the maintenance of the machine or its various components at regular intervals, to reduce the likelihood of failure during a time when the machine is required to be available for use.

The problem in planning this type of maintenance lies in the choice of an appropriate maintenance interval for the machine, because the actual running time before maintenance is really needed is not constant, but varies from one occasion to another, due to differences in the operation of the machine in the behaviour of its components.

Fig. 1 shows how the running time to failure of a typical machine would be likely to vary if no preventive maintenance were carried out. The vertical line in this diagram represents the safe time interval between preventive maintenance work which could catch all the failures before they occurred. If this safe overhaul interval is chosen, however, there will be many occasions when the machinery will be overhauled long before it is really necessary,such as in those cases at the right hand side of the curve where it could have run on for much longer without failing.

This situation wastes production time, and by increasing the frequency of maintenance operations increases the incidence of human errors on reassembly of the machine.

A more satisfactory compromise in terms of maintenance strategy is to carry out preventive maintenance at what may be irregular intervals, but to determine these intervals by the actual condition of the machine at the time. For such condition-based maintenance to be possible,it is essential to have knowledge of the machine condition and its rate of change with time. The main function of condition monitoring is to provide this knowledge.

There are two main methods used for condition monitoring, and these are trend monitoring and condition checking. Trend monitoring is the continuous or regular measurement and interpretation of data, collected during machine operation, to indicate variations in the condition of the machine or its components, in the interests of safe and economical operation.

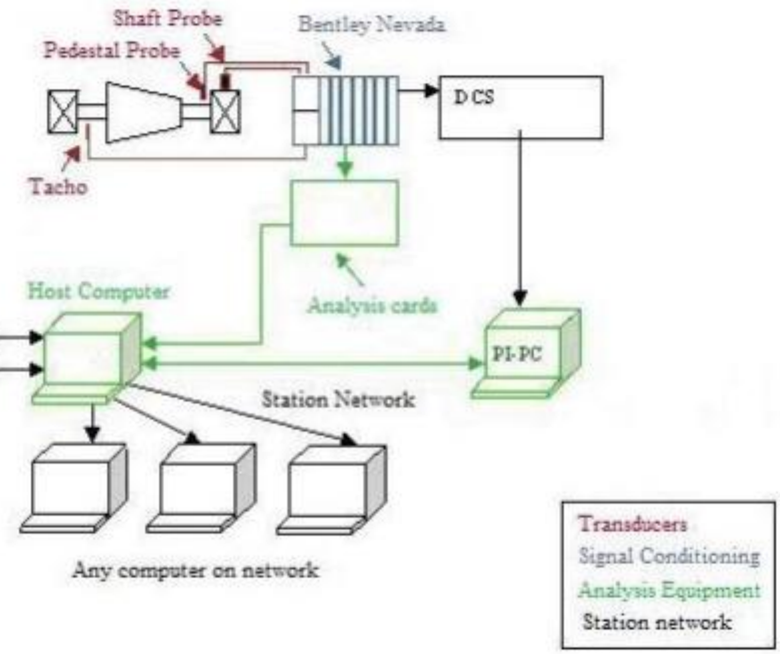
This involves the selection of some suitable and measurable indication of machine or component deterioration, such as one of those listed in Fig.2, and the study of the trend in this measurement with running time to indicate when deterioration is exceeding a critical rate.

The principle involved is illustrated in Fig.3, which shows the way in which such trend monitoring can give a lead time before the deterioration reaches a level at which the machine would have to be shut down.

This lead time is one of the main advantages of using trend monitoring rather than simple alarms or automatic shut down devices.

Vibration Monitoring System (VMS) Specification

To identify potential turbine generator fault mechanisms and so enable informed operational decisions, sophisticated vibration data analysis is required. To do this a modern dedicated vibration monitoring system (VMS) is required. Vibration Diagnostics can provide vibration specification and commissioning services.



Acoustic emission sensor is a device that transforms a local dynamic material displacement produced by a stress wave to an electrical signal. AE sensors are typically piezoelectric sensors with elements maid of special ceramic elements like lead zirconate titanate (PZT). These elements generate electric signals when mechanically strained. Other types of sensors include capacitive transducers, laser interferometers.

Selection of a specific sensor depends on the application, type of flaws to be revealed, noise characteristics and other factors. Typical frequency range in AE applications varies between 20 kHz and 1 MHz. There are two qualitative types of sensors according to their frequency responds: resonant and wideband sensors. Thickness of piezoelectric element defines the resonance frequency of sensor. Diameter defines the area over which the sensor averages surface motion. Another important property of AE sensors is a Curie Point, the temperature under which piezoelectric element loses permanently its piezoelectric properties. Curie temperature varies for different ceramics from 120 to 400C^0. There are ceramics with over 1200C^0 Curie temperature

ACOUSTIC EMISSION SYSTEM

A typical acoustic emission system consists of:

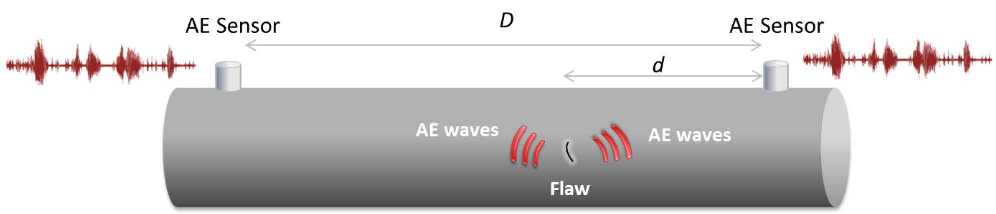
- Sensors used to detect AE events.
- Preamplifiers that amplify initial signal. Typical amplification gains are 40 or 60 dB.
- Cables that transfer signals on distances up to 300m to AE devices. Cables are typically of coaxial type.
- Data acquisition device that performs analog-to-digital conversion of signals, filtration, hits (useful signals) detection and it parameters evaluation, data analysis and charting.

Detection of acoustic emission

The most commonly used method for detection of acoustic emission signals is based on threshold discrimination. When signals exceed a preset fixed or a float amplitude threshold level, a hit measurement and processing is triggered. In addition to threshold based hit detection techniques there are other methods based on a statistical analysis or spectrum characteristics.

Location of acoustic emission sources

There is a verity of different location methods for different structural geometries and applications. Most of location methods are based on evaluation of time difference between wave arrivals to different sensors. In cases when time of arrivals is difficult or impractical to detect, other methods are applied. These include cross correlation methods for location of continuous acoustic emission signals or different zone location method based on effect of signal parameters attenuation with a distance. Linear location of AE source on a pipe is demonstrated in Figure 2.



$$d = \frac{1}{2}\left(D - \Delta T \cdot V\right)$$

d = distance from first hit sensor

D = distance between sensors

V = wave velocity

Figure 2. Calculation of AE source location based on the detected time difference between wave arrivals to sensors and known wave velocity

APPLICATION

The range of modern applications of acoustic emission method is huge. It is used in petro-chemical, power, nuclear power, gas-treatment, military, aerospace, medical, pharmaceutical and automotive industries and of course in academic and industrial research institutions. Applications can be divided on three categories: examination of structures, material study and control over manufacturing processes.

EXAMINATION OF STRUCTURES

Metal pressure vessel inspection is the most common application of acoustic emission method. Thousands of pressure vessels and storage tanks are inspected annually over the world. Tests performed during approval of new pressure vessels and tanks, periodic inspection of pressure vessels and tanks that were in service and in some cases continuously during operation.

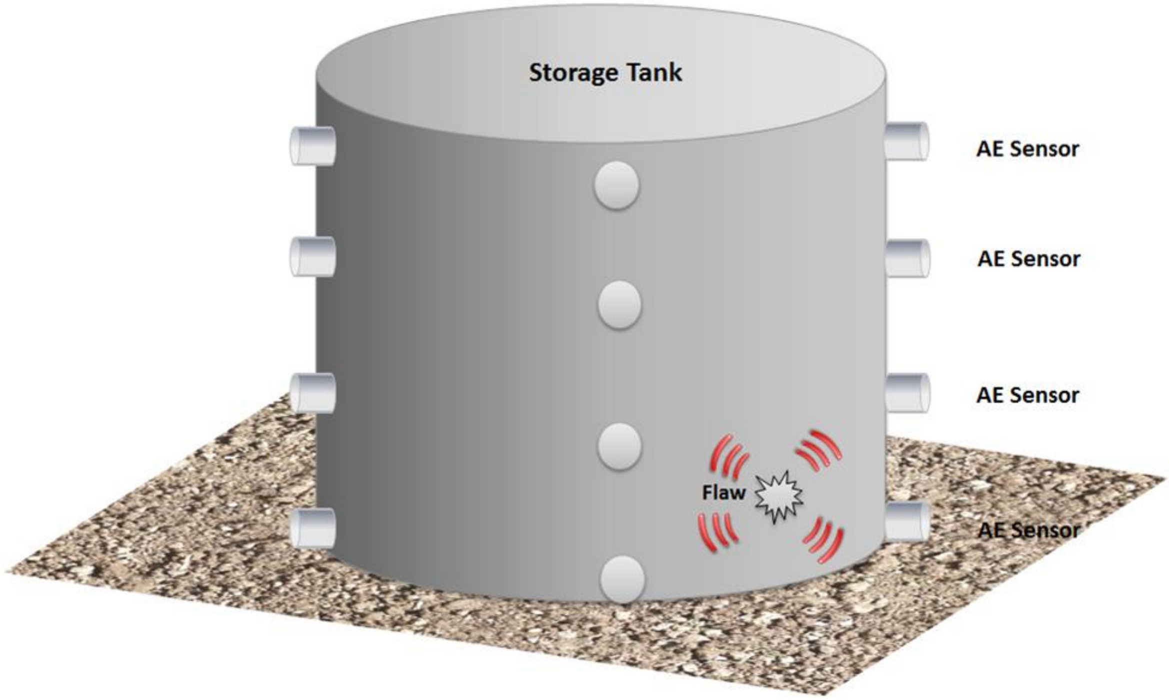


Figure 3. A storage tank under test.

Piping inspection is another common application. Acoustic emission is used efficiently and fast for detection of cracks, corrosion damage and leaks. There are multiple advantages of the method in case of piping inspection. For example in case of buried or insulated pipelines (Figure 4), there is no need to open the entire surface of the pipe but just a small opening for installation of sensors, while a distance between sensors can be from few meters to 100 meters. Acoustic emission testing is applied also for inspection of high pressure and temperature piping systems during their normal operation.

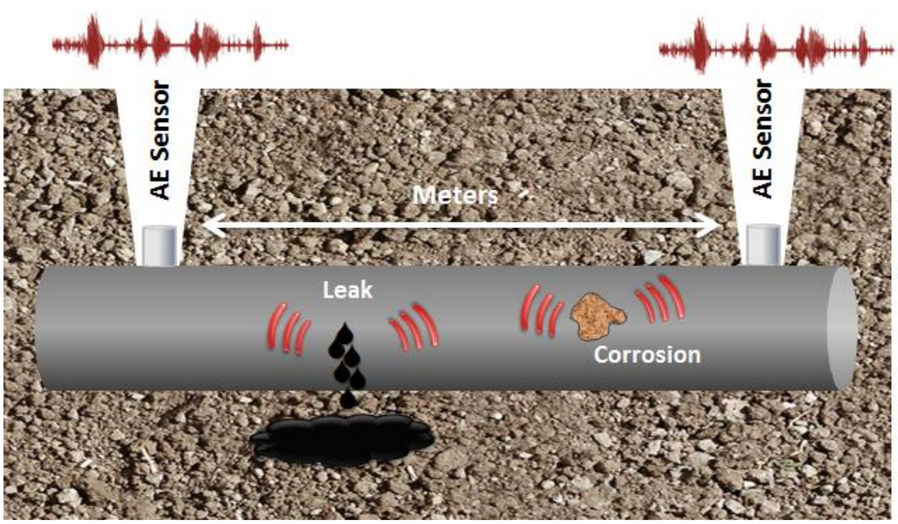


Figure 4. AE sources related to corrosion development and a leak in an underground pipeline.

Inspection of concrete and reinforced concrete bridges are applications where acoustic emission is used for detection of cracks, other concrete flaws, rebar corrosion, failure of cables and other. The method allows an overall inspection of a structure and long term condition monitoring when necessary providing an important information for bridge maintenance.

Examination of structures made of composite materials by acoustic emission method is increasing in aerospace industries. This includes evaluation of different airplane, helicopter and rocket components. There is a great potential for development of in flight monitoring systems based on the acoustic emission technology.

MATERIAL STUDY

Material study is another field of acoustic emission application. Particularly acoustic emission is used for studies of:

- Environmental cracking including stress corrosion cracking, hydrogen embrittlement.
- Fatigue and creep crack growth.
- Material properties including material ductility or embrittlement, inclusions content.
- Plastic deformation development.
- Phase transformation.

and many other.

CONTROL OVER MANUFACTURING PROCESSES

Acoustic emission method is used for control over manufacturing processes. Examples are monitoring of welding, metal crystallization, forming, crimping and other. The method allows detection of defective components prior they leave the manufacturer. There many applications where acoustic emission is the only effective and applicable non-destructive test method. Examples are proof test of components for detection of micro-structural damage, test of composite overlap pressure vessels or engines

STANDARDIZATION

Standardization is an important and natural development of every non-destructive test method. Standardization allows to increase quality and reliability of acoustic emission examinations by specifying test procedures, test methods with assessment criteria, requirements for equipment, methods sensors calibration, necessary personnel qualification and terminology. Since early 1970s there were developed several dozens of standards related to acoustic emission worldwide and in different languages. The leading organization developing acoustic emission standards today is American Society for Testing Materials (ASTM). Organized in 1972, the ASTM E07.04 Subcommittee on Acoustic Emission in the ASTM E07 Committee on Nondestructive Testing, created over 20 standards [2]. Other organizations developed acoustic emission standards are American Society of Mechanical Engineers (ASME), American Society of Nondestructive Testing (ASNT), Association of American Railroads, Compressed Gas Association, European Committee on Standardization, Institute of Electrical and Electronics Engineers (IEEE), International Organization for Standardization (ISO), Japanese Institute for Standardization, Japanese Society for Nondestructive Inspection, USSR State Committee on Standards and other

TOOL WEARING AND ITS MONITORING

Tool wear monitoring system can be effectively applied to machining operation like turning, boring, drilling, facing, forming, milling and shaping. Tools can be classified into two categories single point tool which have one cutting part (turning, shaping), multi point tool (drilling, milling) which have more than one cutting part [6]. This paper deals with recent advancement in tool wear monitoring systems during hard turning.
There are several types of observed cutting tool wear which are listed below:
1. Crater wears which occurs on rake surface. Crater wear can increase the working rake angle and reduce the cutting force, but it will also weaken the strength of cutting edge.
2. Flank wear which occurs on the flank face due to friction between machined surface of workpiece and tool flank. Flank wear is mainly caused by the rubbing action of the tool on the machined surface.
3. Notch wears is special type of combined flank and rake face wear which occurs adjacent to the point where the major cutting edge intersects the work surface.

There are various methods used for measurement of tool wear by researchers. Commonly used tool wear sensing methods can be classified in to two main categories: Direct sensing method and Indirect sensing method. Direct methods are based upon direct measurements of the tool wear using optical, radioactive, electrical resistance proximity sensors or vision system etc. The direct tool wear methods have the advantages of capturing actual geometric changes arising from the wear of tool. However, direct measurements are less beneficial because of the cutting area is largely inaccessible and continuous contact between the tool and the workpiece. This method is almost impossible in the presence of coolant fluids. Indirect methods are based on parameters measured during the cutting operation that can be correlated to wear state. In indirect method, tool condition is not captured directly but achieved from the measurable parameters (cutting force, vibration, acoustic emission, motor current and temperature) through sensor signal output to predict the condition of cutting tool.

TOOL WEAR MONITORING SYSTEM

Tool wear is the most undesirable characteristics of machining process as it's adversely affect the tool life, which also has impact on dimensional accuracy, surface quality and consequently, the economics of machining operations. Hence, tool wear monitoring is necessary. With effective monitoring system, warn tool can be change in time to avoid production time and scrapped components. Analysis of the monitoring signals is most crucial factor in development of tool wear monitoring during hard turning, because it helps to achieve effective results
Indirect sensor based tool wear monitoring system works in three steps i) data or signal acquisition ii) signal processing and analysing and iii) resulted tool condition. In this, signal processing is an important step. In signal processing there are two steps, pre-processing and post processing. Different hardware such as, model like amplifiers, filters etc. are considered in pre-processing of signal. In post processing comparative method like Root Mean Square (RMS), Fast

Fourier Transformation (FFT), time– frequency domain, statistical analysis etc. have been used to signal processing

MEASUREMENT OF PROCESS PAERAMETERS

There are number of process parameters used to measure tool wear in TCMS. Most commonly used parameters are cutting forces, vibration signals, surface roughness, tool wear. The brief review of this process parameter is given below.

3.1. Cutting Force Measurement

It has been observed that variation in the cutting force can be correlated to tool wear. Gradual increase in tool wear during the cutting process causes the cutting forces to increase therefore the cutting forces is generally considered one of the most significant indicators of tool wear in the metal cutting process. Dynamometer is used for the measurement of cutting forces. Many researchers have investigated the effect of cutting force on tool wear during hard turning. Ghani et al. studied that effect of tool wear on tool life, surface quality and production time and developed online tool wear measurement and monitoring system, using a low-cost sensor technique and user friendly GUI. MATLAB software was used develop a user-friendly graphical user interface (GUI) for online monitoring purposes. In experimental process two-channel strain gauge at tool holder was used to measure deflections in both tangential and feed direction. Result shows that developed online monitoring system, using the strain gauge signal, is an effective method of detecting the progression of flank wear width during machining. This is an efficient and low-cost method which can be used in then real machining industry to predict the level of wear in the cutting tool. Bartarya and Choudhury studied the effect of cutting parameters and cutting force during hard turning of AISI 52100 grade steel. To test the quality of fit of data, they used ANOVA analysis method. They used AISI 52100 material of harness 60±2 HRC. Due to high hardness uncoated CBN tool was used for turning operation. The results revealed that depth of cut was found to be the most influential parameter affecting the three cutting forces followed by the feed rate. Fnides et al. [16] works on hard steel with grade X38CrMoV5-1. The machining was carried out on grade X38CrMoV5-1 steel. It has hardness value of 50 HRC. Mixed ceramic (CC650) was used as cutting tool insert and studied the effect of cutting speed, feed rate and depth of cut on cutting forces and surface roughness. Observed that tangential force is very sensitive for tool wear and depth of cut was most crucial parameter for tool wear progression.

3.2. Measurement of Vibration Signals

Vibration signals are also one of the most important parameter for measurement of tool wear because they provide thorough insight in metal cutting process. Many researchers have worked on vibration signals induced during machining of hard material. Accelerometers are used to measure vibration signals. Researchers used tri-axial accelerometer to measure vibration signals in all three mutually perpendicular directions (feed, radial and thrust). Dimla et al. measure vibration signals in three mutually perpendicular directions using Kistler mini accelerometers (type 8730A). Investigation showed that vertical component (z-direction) of both cutting forces and the vibration signals were the most sensitive to tool wear. The results indicated that the magnitudes of the static cutting forces were enormously dependent on the cutting conditions especially the DOC and feed-rate. Abouelatta and Madl studied correlation between surface roughness and cutting vibration in turning process. Surtronic 3+ surface roughness tester was used to measure surface roughness and FFT Spectrum Analyser were used to measure vibration signals in radial and feed direction by using 3D accelerometer sensors. Finally the measured results were analysed by commercial software MATALAB, BC++, SPSS. Wang et al. monitored vibration signals and used them using v support vector machine to develop tool condition monitoring system.

3.3. Surface Roughness Measurement

Surface roughness and dimensional accuracy play very important role while performing machining operation. Poor surface finish may affect the performance of machining process. High cutting forces and high localized temperatures may dramatically affect the surface roughness. Cutting conditions has a considerable effect on surface roughness. Cemal et al. studied effect of cutting parameters (cutting speed, feed rate and depth of cut) on surface roughness. Mathematical model was developed by using the data gathered from a series of turning experiments performed. Experiments were carried out on cold-work tool steel AISI P20 with CNMG 120408 coated carbide inserts. A result indicates that feed rate has greatest influence, followed by cutting speed on finishing of workpiece. Higher feed rates lead to higher surface roughness values. Asilturk and Akkus studied the effect of cutting parameters on surface roughness in hard turning using the Taguchi method. Experiments have been conducted on AISI 4140 (51 HRC) using the L9 orthogonal array in a CNC turning machine under dry cutting condition. Coated carbide cutting tools were used as cutting tool inserts. Analysis of variance (ANOVA) was applied to investigate effects of cutting speed, feed rate and depth of cut on surface roughness. Results indicated that the feed rate has the most significant effect on Ra and Rz. According to the ANOVA analysis, the feed rate has an effect on Ra and Rz at a reliability level of 95%. Fnides et al. observed that surface roughness is very sensitive to the variation of feed rate and that flank wear has a great influence on the evolution of cutting force components and on the criteria of surface roughness. Ozel and Karpat measured surface roughness and tool flank wear of hard turning. The result shows that a decrease in the feed rate resulted in better surface roughness but slightly faster tool wear development, and increasing cutting speed resulted in significant increase in tool wear development but resulted in better surface roughness. Increase in the workpiece hardness resulted in better surface roughness but higher tool wear.

3.4. Measurement of Tool Wear

Carrying on the machining process with a worn tool, increases the friction between the tool and the work piece, also causes poor surface finish therefore progression of tool wear is need to be monitored. Chinchanikar and Choudhury [20] studied effect of work material hardness and cutting parameters on performance of coated carbide tool when machining of AISI 4340 steel and observed the effect of cutting conditions on cutting forces, surface roughness and tool life by multiple linear regression models. Correlation coefficients were found close to 0.9. Highly significant parameters were determined by performing an Analysis of Variance (ANOVA). Analysis of the results concluded that the use of lower feed value, lower depth of cut and by limiting the cutting speed to 235 and 144 m/min; while turning 35 HRC and 45 HRC work material, respectively, ensures minimum cutting forces, surface roughness and better tool life. Experimental observations indicate that all the three components of cutting forces are higher for harder work material. Grzesik and Zalisz investigated the wear phenomenon of hard material using ceramic tool. AISI 5140 steel (60 HRC) was used as a workpiece material. Cutting condition used for performing finishing cuts are constant cutting speed of 100 m/min with varying feed rate and small depth of cut of 0.2 mm. Experimental observations indicate that depending on the mechanical and thermal conditions generated on the wear zones, the wear mechanisms involve abrasion, fracture, plastic flow, material transfer and tribochemical. Dogra, Sharma et al. compared CBN cutting tool insert with coated carbide cutting tool insert and cryogenically treated coated carbide cutting tool insert during machining of hardened AISI H11 steel (48-49 HRC). Results concluded that the flank wear of CBN cutting tool insert is lower as compared to other inserts.

MODULE 6

Material Requirements Planning (MRP)

What Is Material Requirements Planning (MRP)?

Material requirements planning (MRP) is a computer-based inventory management system designed to improve productivity for businesses. Companies use material requirements-planning systems to estimate quantities of raw materials and schedule their deliveries.

How MRP Works
MRP is designed to answer three questions: *What* is needed? *How much* is needed? *When* is it needed?" MRP works backward from a production plan for finished goods, which is converted into a list of requirements for the subassemblies, component parts, and raw materials that are needed to produce the final product within the established schedule.

By parsing raw data—like bills of lading and shelf life of stored materials—this technology provides meaningful information to managers about their need for labor and supplies, which can help companies improve their production efficiency.

MRP Systems: Background
Material requirements planning was the earliest of the integrated information technology (IT) systems that aimed to improve productivity for businesses by using computers and software technology. The first MRP systems of inventory management evolved in the 1940s and 1950s. They used mainframe computers to extrapolate information from a bill of materials for a specific finished product into a production and purchasing plan. Soon, MRP systems expanded to include information feedback loops so that production managers could change and update the system inputs as needed.

The next generation of MRP, manufacturing resources planning (MRP II), also incorporated marketing, finance, accounting, engineering, and human resources aspects into the planning process. A related concept that expands on MRP is enterprise resources planning (ERP), which uses computer technology to link the various functional areas across an entire business enterprise. As data analysis and technology became more sophisticated, more comprehensive systems were developed to integrate MRP with other aspects of the manufacturing process.

KEY TAKEAWAYS

- Material requirements planning (MRP) is the earliest computer-based inventory management system.
- Businesses use MRP to improve their productivity.
- MRP works backward from a production plan for finished goods to develop inventory requirements for components and raw materials.

MRP in Manufacturing

A critical input for material requirements planning is a bill of materials (BOM)—an extensive list of raw materials, components, and assemblies required to construct, manufacture or repair a product or service. BOM specifies the relationship between the end product (independent demand) and the components (dependent demand). Independent demand originates outside the plant or production system, and dependent demand refers to components.

Companies need to manage the types and quantities of materials they purchase strategically; plan which products to manufacture and in what quantities; and ensure that they are able to meet current and future customer demand—all at the lowest possible cost. MRP helps companies maintain low inventory levels. Making a bad decision in any area of the production cycle will cause the company to lose money. By maintaining appropriate levels of inventory, manufacturers can better align their production with rising and falling demand.

Types of Data Considered by MRP

The data that must be considered in an MRP scheme include:

- Name of the final product that's being created. This is sometimes called independent demand or Level "0" on BOM.
- What and when info. How much quantity is required to meet demand? When is it needed?
- The shelf life of stored materials.
- Inventory status records. Records of net materials available for use that are already in stock (on hand) and materials on order from suppliers.
- Bills of materials. Details of the materials, components, and sub-assemblies required to make each product.
- Planning data. This includes all the restraints and directions to produce such items as routing, labor and machine standards, quality and testing standards, lot sizing techniques, and other inputs.

MANUFACTURING RESOURCE PLANNING (MRP II)

What Is Manufacturing Resource Planning?

Manufacturing Resource Planning (MRP II) is an integrated information system used by businesses. Manufacturing Resource Planning (MRP II) evolved from early Materials Requirement Planning (MRP) systems by including the integration of additional data, such as employee and financial needs.

The system is designed to centralize, integrate, and process information for effective decision making in scheduling, design engineering, inventory management, and cost control in manufacturing.

Both MRP and MRP II are seen as predecessors to Enterprise resource planning (ERP), which is a process whereby a company, often a manufacturer, manages and integrates the important parts of its business.

An ERP management information system integrates areas such as planning, purchasing, inventory, sales, marketing, finance, and human resources. ERP is most frequently used in the context of software, with many large applications having been developed to help companies implement ERP.

Understanding Manufacturing Resource Planning (MRP II)
MRP II is a computer-based system that can create detailed production schedules using real-time data to coordinate the arrival of component materials with machine and labor availability. MRP II is used widely by itself, but it's also used as a module of more extensive enterprise resource planning (ERP) systems.

KEY TAKEAWAYS

- Manufacturing Resource Planning (MRP II) is an integrated information system used by businesses.
- MRP II is an extension of materials requirement planning (MRP).
- Both MRP and MRP II are seen as predecessors to Enterprise resource planning (ERP).

MRP II is an extension of the original materials requirements planning (MRP I) system. Materials requirements planning (MRP) is one of the first software-based integrated information systems designed to improve productivity for businesses.

A materials requirements planning information system is a sales forecast-based system used to schedule raw material deliveries and quantities, given assumptions of machine and labor units required to fulfill a sales forecast.

By the 1980s, manufacturers realized they needed software that could also tie into their accounting systems and forecast inventory requirements. MRP II was provided as a solution, which included this functionality in addition to all the capabilities offered by MRP I.

Real-World Examples of MRP II Software

The following are a small sampling of some popular MRP II software providers, as of early 2020:

- IQMS
- Fishbowl
- FactoryEdge
- Prodsmart
- abas
- Oracle Netsuite Manufacturing Edition
- Epicor

- S2K Enterprise

MRP I vs. MRP II

For all intents and purposes, MRP II has effectively replaced MRP I software. Most MRP II systems deliver all of the functionality of an MRP system. But in addition to offering master production scheduling, bill of materials (BOM), and inventory tracking, MRP II provides functionality within logistics, marketing, and general finance.

For example, MRP II is able to account for variables that MRP is not—including machine and personnel capacity—providing a more realistic and holistic representation of a company's operating capabilities. Many MRP II solutions also offer simulation features that allow operators to enter variables and see the downstream effect. Because of its ability to provide feedback on a given operation, MRP II is sometimes referred to as a closed-loop system.

MRP I included the following three major functionalities:

- master production scheduling
- bill of materials
- inventory tracking

MRP II includes those three, plus the following:

- machine capacity scheduling
- demand forecasting
- quality assurance
- general accounting

MRP II systems are still in wide use by manufacturing companies today and can either be found as stand-alone solutions or as part of an enterprise resource planning (ERP) system. Enterprise Resources Planning (ERP) software systems are regarded as the successors of MRP II software.

ERP suites include applications well outside the scope of manufacturing. These can include everything from human resources and customer relationship management to enterprise asset management.

SHOP FLOOR CONTROL

Shop floor planning and control is the process of using methods and tools to track, schedule, and report the status of work-in-progress (WIP) manufacturing from your floor-level, giving you a clear channel of communication between your operators and managers on the production line.

Shop floor activity control is an essential tool for the effective implementation of your:

— Master production schedule;

— Controlling priorities in production; and

— Minimizing WIP and finished goods inventories.

The Three Phases of Shop Floor Control

Shop floor planning concerns the management of your operations, inventory, equipment, and workers.

And your shop floor planning and control will go through these three phases:

— Order release;

— Order scheduling; and

— Order progress.

Phase 1 – Order Release

Using shop floor applications, the master production schedule will inform which manufacturing order needs to be generated.

Then from there, the order release document will inform the shop floor management boards of the resources and manufacturing processes needed to complete the order.

Phase 2 – Order Scheduling

Once the order release has been generated, shop floor applications will schedule the production of the order, while providing you with a detailed workflow of the manufacturing route the order will pass through.

The order scheduling phase will explain:

— The work stations the order passes through; and

— The materials and quantity needed for the order.

This allows managers and employees to understand what needs to be done, who needs to do it, and how it needs to be done.

Phase 3 – Order Progress

The shop floor scheduling boards monitor the progress of the manufacturing order and various other operations within your manufacturing business.

Giving you breakdowns of:

— The entire overview of in-waiting, WIP, and finished manufacturing orders;

— Individual orders along the production line; and

— The employees who are working, about to work, or have worked on an order.

ADVANTAGES OF SHOP FLOOR CONTROL

1. Real-Time Information

Shop floor planning and control software give you real-time updates immediately, allowing managers and operators to understand the progress of manufacturing orders passing through the factory.

This up-to-minute information from your shop floor planning software enables you to identify problems on your production line and make changes to your production schedule on the fly.

2. Reduced Costs

Shop floor management lean practices will help you locate areas along your production line that needs improvement, such as areas that's prone to bottlenecks in manufacturing.

Improving the efficiency of your manufacturing will allow you to:

— Reduce your manufacturing lead time;

— Reduce your manufacturing overheads; and

— Increase your profit margin by avoiding delays from unexpected problems emerging.

3. Resource Planning

One of the other advantages of shop floor control is how easy it is to allocate resources to other tasks as the software can handle the production process efficiently.

Not only will shop floor planning software help you automate your resource allocation and workflow but because it helps you perform these tasks quicker, you remove the need to have a team member stuck in inefficient spreadsheets developing the master production schedule.

4. Problems and Variations Become Transparent

Shop floor management boards give managers and operators an overview of any relevant information, open topics, and manufacturing orders in production, so everyone can be on the same page, and work toward a shared goal.

This means everyone can start their workday with a complete understanding of what is happening along the production line.

5. Direct Support of Management

Everyone within the business can communicate with each other quickly and efficiently, which will allow them to solve issues faster, and keep production going without delays.

Having your shop floor data in one place, and easily accessible, means you don't have to waste time trying to explain issues or waste time giving feedback to other departments when trying to address an issue.

6. Key Performance Indicators (KPI)

It probably goes without saying, but a skilled and experienced team with be crucial for a successful production run.

Using shop floor applications will allow you to communicate back to your team on performance levels, and help provide more training for those underperforming, boosting productivity.

7. Quality Control

Shop floor control software gives your managers the ability to trace:

— Batch failures;

— Material waste; and

— Separate repairable batch failures from the main inventory.

While your operators will be easily able to measure and report material waste, while identifying batch failures as recoverable or not.

8. Price Products Fairly

As already mentioned under KPI's, improved analytics and reporting means you can gather data on:

— Operators (working hours, break times, downtime);

— Manufacturing costs;

— Production lead time estimations; and

— The workload a workstation can take and it's capacity.

This information will help you better understand how many products you can produce at any given time and the value of those products.

9. Project-Based Purchasing

Perfect for businesses that practice bespoke manufacturing.

Although shop floor manufacturing software does support both make to order (MTO) and make to stock (MTS), the software will help you with material procurement for:

— Custom projects;

— MTO; or

— Assemble to order (ATO) jobs.

However, it doesn't have to be one or the other, shop floor planning software can help you switch between workflows for individual projects.

10. Paperless Manufacturing

The latest trends and predictions show that customers are more informed than ever before, and want to purchase goods with businesses who practice eco-friendly manufacturing.

Adopting shop floor planning on your production lines allows you to achieve a paperless manufacturing workflow, by giving you the tools to:

— Schedule production;

— Track progress; and

— Manage your entire business from a smartphone, tablet, or computer.

Factory Data Collection System

FDC system is used to collect data for monitoring order progress in SFC. The following are important data collected by the FDC system.

- Number of products (piece counts) completed at a certain machine.
- Number of parts scrapped (or) Number of parts reworked.
- Direct labor time spent
- Equipment breakdown.

Purpose of data collection system;

The purpose of the data collection system in shop floor control is to provide basic data for monitoring order progress.

In computerized SFC system the data are submitted to the order progress module for analysis and generation of work order status reports and exception reports.

Types of data collection systems;

- On-line data collection systems
- Off-line data collection systems

Types of data collected from the shop floor;

- Machine data,
- Operator data,
- Tooling data,
- Data relating to jobs to be done,
- Materials data,
- Materials handling data,
- Scheduling data,
- Process planning data, and
- Inspection data.
- Data collection techniques in shop floor control?
- Job traveler
- Employee time sheet
- Operation tear strips or punched cards included with shop packet
- Centralized shop floor terminals
- Individual work centre terminals

Computer process monitoring (Computer assisted data collection systems);

Computer process monitoring is a data collection system in which the computer is directly connected to the workstation and associated equipment for the purpose of observing the operation.

Components used to build a computer process monitoring system

- Transducers and sensors,
- Analog to digital converters (ADC),
- Multiplexers,
- Real time clocks, and
- Other electronic devices
- Configurations of computer assisted data collection systems
- Or (Automated data collection system)?
- Data logging systems
- Data acquisition systems
- Multilevel scanning

Types of data collection systems;

- On-line data collection systems
- Off-line data collection systems

Factory Data Collection System

- On-line versus batch systems
- Data input techniques
- Job traveler
- Employee time sheets
- Operation tear strips
- Prepunched cards
- Providing key board based terminals
- One centralized terminal
- Satellite terminals
- Workstation terminals

Data acquisition system (DAS);

The data acquisition system that collects data from the various production operations for direct communication to a central computer. Hence it is called as online system.

Automatic identification methods

Automatic identification is a term that refers to various technologies used in automatic or semi automatic acquisition of product data for entry into a computer system.

Automatic identification methods

§ Bar codes

§ Radio frequency systems

§ Magnetic stripe

§ Optical character recognition

§ Machine vision

Classifications of bar codes according to the dimensions of width

High density : X dimension is 0.010 in. or less.

Medium density : X dimension is between 0.010 and 0.030 in.

Low density : X dimension is 0.030 in. or greater.

Barcode Technology in automatic data collection system

A bar code (often seen as a single word, *barcode*) is the small image of lines (bars) and spaces that is affixed to retail store items, identification cards, and postal mail to identify a particular product number, person, or location. The code uses a sequence of vertical bars and spaces to represent numbers and other symbols. A bar code symbol typically consists of five parts: a quiet zone, a start character, data characters (including an optional check character), a stop character, and another quiet zone.

0 36000 29145 2

barcode symbol

A barcode is an optical machine-readable representation of data relating to the object to which it is attached. Originally barcodes systematically represented data by varying the widths and spacings of parallel lines, and may be referred to as linear or one-dimensional (1D). Later they evolved into rectangles, dots, hexagons and other geometric patterns in two dimensions (2D). Although 2D systems use a variety of symbols, they are generally referred to as barcodes as well. Barcodes originally were scanned by special optical scanners called barcode readers. Later, scanners and interpretive software became available on devices including desktop printers and smartphones.

An early use of one type of barcode in an industrial context was sponsored by the Association of American Railroads in the late 1960s. Developed by General Telephone and Electronics (GTE) and called KarTrak ACI (Automatic Car Identification), this scheme involved placing colored stripes in various combinations on steel plates which were affixed to the sides of railroad rolling stock. Two plates were used per car, one on each side, with the arrangement of the colored stripes representing things such as ownership, type of equipment, and identification number. The plates were "read" by a trackside scanner located, for instance, at the entrance to a classification yard while the car was moving past The project was abandoned after about ten years because the system proved unreliable after long-term use in the field.

Barcodes became commercially successful when they were used to automate supermarket checkout systems, a task for which they have become almost universal. Their use has spread to many other tasks that are generically referred to as automatic identification and data capture (AIDC). The very first scanning of the now ubiquitous Universal Product Code (UPC) barcode was on a pack of Wrigley Company chewing gum in June 1974.

Other systems have made inroads in the AIDC market, but the simplicity, universality and low cost of barcodes has limited the role of these other systems until the 2000s (decade), over 40 years after the introduction of the commercial barcode, with the introduction of technologies such as radio frequency identification, or RFID.

Barcode Reader

A barcode reader is used to read the code. The reader uses a laser beam that is sensitive to the reflections from the line and space thickness and variation. The reader translates the reflected light into digital data that is transferred to a computer for immediate action or storage. Bar codes and readers are most often seen in supermarkets and retail stores, but a large number of different uses have been found for them. They are also used to take inventory in retail stores; to check out books from a library; to track manufacturing and shipping movement; to sign in on a job; to identify hospital patients; and to tabulate the results of direct mail marketing returns.

Very small bar codes have been used to tag honey bees used in research. Readers may be attached to a computer (as they often are in retail store settings) or separate and portable, in which case they store the data they read until it can be fed into a computer.

There is no one standard bar code; instead, there are several different bar code standards called symbologies that serve different uses, industries, or geographic needs. Since 1973, the Uniform Product Code (UPC), regulated by the Uniform Code Council, an industry organization, has provided a standard bar code used by most retail stores. The European Article Numbering system (EAN), developed by Joe Woodland, the inventor of the first bar code system, allows for an extra pair of digits and is becoming widely used. POSTNET is the standard bar code used in the United States for ZIP codes in bulk mailing. The following table summarizes the most common bar code standards.

Barcode Scanning Technology

Scanning technology is constantly evolving and providing industries with more choices in data capture solutions. Two competing data capture devices: the laser scanner and the digital imager have many businesses facing a tough decision.

Deciding which scanning technology is right for your application can be a difficult task. Knowing the advantages and applications in which these two technologies are used is the first step to success.

The key to deciding between these two technologies is determining which fits the requirements and budget of your business most accurately.

2D Data Matrix Code

2D Data Matrix Code

Both laser scanners and digital images are programmed to decode specific symbologies, or the "language," of barcodes. The symbology used in the application can

help determine which scanning technology will provide the most benefit. The use of 2-

dimensional (2D) symbologies is on the rise in many markets, making digital imagers a better choice. However, for applications that don't require reading 2D barcodes, laser

scanners are a cost-effective option.

Types of bar code readers;

- Fixed beam reader,
- Moving beam reader.
- Smart cards
- Smart cards are made of plastic.

They are of the size of a credit card and are embedded with one or more microchips.

These have a 8 bit or higher level microprocessors and a storage capacity of about 8kB-256kB. Personal identification numbers prevent their unauthorized use.

AGILE MANUFACTURING

Agile manufacturing is a term applied to an organization that has created the processes, tools, and training to enable it to respond quickly to customer needs and market changes while still controlling costs and quality. It's mostly related to lean manufacturing.

An enabling factor in becoming an agile manufacturer has been the development of manufacturing support technology that allows the marketers, the designers and the production personnel to share a common database of parts and products, to share data on production capacities and problems—particularly where small initial problems may have larger *downstream* effects. It is a general proposition of manufacturing that the cost of correcting quality issues increases as the problem moves downstream, so that it is cheaper to correct quality problems at the earliest possible point in the process.

Agile manufacturing is seen as the next step after lean manufacturing in the evolution of production methodology. The key difference between the two is like between a thin and an athletic person, agile being the latter. One can be neither, one or both. In manufacturing theory, being both is often referred to as leagile. According to Martin Christopher, when companies have to decide what to be, they have to look at the customer order cycle (COC) (the time the customers are willing to wait) and the leadtime for getting supplies. If the supplier has a short lead time, lean production is possible. If the COC is short, agile production is beneficial.

Agile manufacturing is an approach to manufacturing which is focused on meeting the needs of customers while maintaining high standards of quality and controlling the overall costs involved in the production of a particular product. This approach is geared towards companies working in a highly competitive environment, where small variations in performance and product delivery can make a huge difference in the long term to a company's survival and reputation among consumers.

This concept is closely related to lean manufacturing, in which the goal is to reduce waste as much as possible. In lean manufacturing, the company aims to cut all costs which are not directly related to the production of a product for the consumer. Agile manufacturing can include this concept, but it also adds an additional dimension, the idea that customer demands need to be met rapidly and effectively. In situations where companies integrate both approaches, they are sometimes said to be using "agile and lean manufacturing". Companies which utilize an agile manufacturing approach tend to have very strong networks with suppliers and related companies, along with numerous cooperative teams which work within the company to deliver products effectively. They can retool facilities quickly, negotiate new agreements with suppliers and other partners in response to changing market forces, and take other steps to meet customer demands. This means that the company can increase production on products with a high consumer demand, as well as redesign products to respond to issues which have emerged on the open market.

Markets can change very quickly, especially in the global economy. A company which cannot adapt quickly to change may find itself left behind, and once a company starts to lose market share, it can fall rapidly. The goal of agile manufacturing is to keep a company ahead of the competition so that consumers think of that company first, which allows it to continue innovating and introducing new products, because it is financially stable and it has a strong customer support base.

Companies that want to switch to the use of agile manufacturing can take advantage of consultants who specialize in helping companies convert and improve existing systems. Consultants can offer advice and assistance which is tailored to the industry a company is involved in, and they usually focus on making companies competitive as quickly as possible with proved agile techniques. There are also a number of textbooks and manuals available with additional information on agile manufacturing techniques and approaches.

Another approach was developed combining the attributes of agility together with leanness across one supply chain is the hybrid lean-agile strategy. This blended lean-agile strategy hybridizes attributes of leanness (cost minimization, waste reduction, continuous improvement), agility (speed, flexibility, responsiveness) and leagility (mass customization, postponement) in one supply network. The significance of the hybridized lean aspect is higher upstream the supply chain than the agility dimension in the same supplier node, compared to downstream the supply chain at the distributor node closer to the customers, which operates in a more agile manner.

FLEXIBLE MANUFACTURING SYSTEM(FMS)

A flexible manufacturing system (FMS) is a highly automated OT machine cell. consisting of a group of processing workstations (usually CNC machine tools), interconnected by an automated material handling and storage system, and controlled by a distributed computer system. The reason the FMS is *called flexible* is that it is capable of processing a variety of different part styles simultaneously at the various orkstations, and the mix of part styles and quantities of production can be adjusted in response to changing demand patterns. The FMS is most suited for the mid-variety, mid-volume production range (refer to Figure 1.7).

The initials FMS are sometimes used to denote the *term flexible machining system.* The machining process is presently the largest application area for FMS technology. However, it seems appropriate to interpret *FMS* in its broader meaning, allowing for a wide range of possible applications beyond machining.

An FMS relies on the principles of group technology. No manufacturing system can be completely flexible. There are limits to the range of parts or products that can be made in an FMS. Accordingly, an FMS is designed to produce parts (or products) within a defined range of styles.

sizes. and processes. In other words. an FMS is capable of producing a single part family or a limited range of part families,

A more appropriate term for an FMS would be *flexible automated manufacturing system.* The use of the word "automated" would distinguish this type of production technology from other manufacturing systems that arc flexible but not automated, such as a manned GT machine cell. On the other hand, tile word "flexible" would distinguish it from other manufacturing systems that are highly automated but not flexible, such as a conventional transfer line. However, the existing terminology is well established

What Makes It Flexible?

The issue of manufacturing system flexibility was discussed previously in Section 13.2.4. In that discussion, we identified three capabilities that a manufacturing system must possess to be flexible: (I) the ability to identify and distinguish among the different part or product styles processed by the system, (2) quick changeover of operating instructions, and (1) quick changeover of physical setup. Flexibility is an attribute that applies to both manual and automated systems. In manual systems, the human workers are often the enablers of the system's flexibility.

To develop the concept of flexibility in an automated manufacturing system, consider a machine cell consisting of two CNC machine tools that are loaded and unloaded by an industrial robot from a parts carousel, perhaps in the arrangement depicted in Figure 16.1. The cell operates unattended for extended periods of time. Periodically, a worker must unload completed parts from the carousel and replace them with new work parts. By any definition, this is an automated manufacturing cell, but is it a flexible manufacturing cell? One might argue that yes, it is flexible, since the cell consists of CNC machine tools, and CNC machines are flexible because they can be programmed to machine different

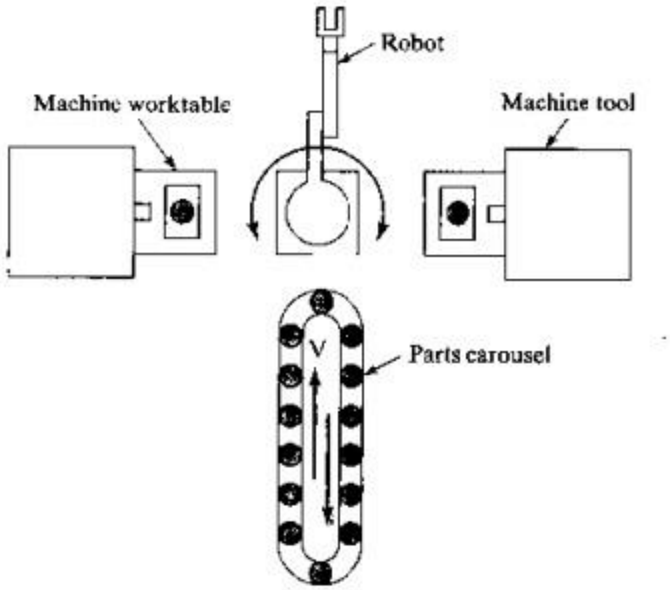


Figure 16.1 Automated manufacturing cell with two machine tools and robot. Is it a flexible cell?

part configurations. However, if the cell only operates in a batch mode, in which the same part style is produced by both machines in lots of several dozen (or several hundred) units, then this does not qualify as flexible manufacturing,

'lb qualify as being flexible, a manufacturing system should satisfy several criteria. The following ale four reasonable tests of flexibility in an automated manufacturing system:

Part variety test. Can the system process different part styles in a non-batch mode?

Schedule change test. Can the system readily accept changes in production schedule, and changes in either part mix or production quantities?

Error recovery test. Can the system recover gracefully from equipment malfunctions and breakdowns, so that production is not completely disrupted'!

New part test. Can new part designs be introduced into the existing product mix with relative ease'!

If the answer to all of these questions is "yes" for a given manufacturing system, then the system can be considered flexible. The most important criteria are (1) and (2). Criteria (3) and (4) are softer and can be implemented at various levels. In fact, introduction of new part designs is not a consideration in some FMSs; such systems are designed to produce a part family whose member are all known in advance.

if the automated system does not meet at least the first three tests, it should not be classified as an FMS. Getting back to our illustration, the robotic work cell satisfies the criteria if it: (1) can machine different part configurations in a mix rather than in batches;

(2) permits changes in production schedule and part mix; (3) is capable of continuing to operate even though one machine experiences a breakdown (e.g., while repairs are being made on the broken machine, its work is temporarily reassigned to the other machine); and (4) as new part designs arc developed, NC part programs are written offline and then downloaded to the system for execution. This fourth capability requires that the new part is within the part family intended for the FMS, so that the tooling used by the CNC machines as well as the end effector of the robot are suited to the new part design.

Over the years, researchers and practitioners have attempted to define manufacturing flexibility. These attempts are documented in several of our references,

and. The result of these efforts IS the conclusion that flexibility in manufacturing has multiple dimensions; there are various types of flexibility. Table 16.1 defines these flexibility types and lists the kinds of factors on which they depend.

To a significant degree, the types of flexibility in Table 16.1 are alternative ways of stating our preceding list of flexibility tests for a manufacturing system. The correlations are indicated in Table 16.2.

Types of FMS

Having considered the issue of flexibility and the different types of flexibility that are exhibited by manufacturing systems, let us now. consider the various types of FMSs. Each FMS is designed for a specific application, that is, a specific family of parts and processes Therefore, each FMS is custom engineered; each FMS is unique. Given these circumstances, one would expect to find a great variety of system designs to satisfy a wide variety of application requirements.

TABLE 16.1 Types of Flexibility in Manufacturing. These Concepts of Flexibility Are Not Limited to Flexible Manufacturing Systems. They Apply to Both Manned and Automated Systems. Sources: [3], [7], [23], [26]

Flexibility Type	*Definition*	*Depends on Factors Such As:*
Machine flexibility	Capability to adapt a given machine (workstation) in the system to a wide range of production operations and part styles. The greater the range of operations and part styles, the greater the machine flexibility.	Setup or changeover time. Ease of machine reprogramming (ease with which part programs can be downloaded to machines). Tool storage capacity of machines. Skill and versatility of workers in the system.
Production flexibility	The range or universe of part styles that can be produced on the system.	Machine flexibility of individual stations. Range of machine flexibilities of all stations in the system.
Mix flexibility	Ability to change the product mix while maintaining the same total production quantity; that is, producing the same parts only in different proportions.	Similarity of parts in the mix. Relative work content times of parts produced. Machine flexibility.
Product flexibility	Ease with which design changes can be accommodated. Ease with which new products can be introduced.	How closely the new part design matches the existing part family. Off-line part program preparation. Machine flexibility.
Routing flexibility	Capacity to produce parts through alternative workstation sequences in response to equipment breakdowns, tool failures, and other interruptions at individual stations.	Similarity of parts in the mix. Similarity of workstations. Duplication of workstations. Cross-training of manual workers. Common tooling.
Volume flexibility	Ability to economically produce parts in high and low total quantities of production, given the fixed investment in the system.	Level of manual labor performing production. Amount invested in capital equipment.
Expansion flexibility	Ease with which the system can be expanded to increase total production quantities.	Expense of adding workstations. Ease with which layout can be expanded. Type of part handling system used. Ease with which properly trained workers can be added.

Flexible manufacturing systems can be distinguished according to the kinds of operations they perform:(l) *processing operations* or (2) *assembly operations* (Section 2.2.1). An FMS is usually designed to perform one or the other but rarely both. A difference that is applicable to machining systems is whether the system will process *rotational parts* or *non-rotational parts* (Section 13.2.1). Flexible machining systems with multiple stations that process rotational parts are much less common than systems that process non-rotational parts. Two other ways to classify FMSs are by: (1) number of machines and (2) level of flexibility

TABLE 16.2 Comparison of Four Criteria of Flexibility in a Manufacturing System and the Seven Types of Flexibility

Flexibility Tests or Criteria	Type of Flexibility (Table 16.1)
1. ***Part variety test.*** Can the system process different part styles in a non-batch mode?	Machine flexibility Production flexibility
2. ***Schedule change test.*** Can the system readily accept changes in production schedule, changes in either part mix or production quantities?	Mix flexibility Volume flexibility Expansion flexibility
3. ***Error recovery test.*** Can the system recover gracefully from equipment malfunctions and breakdowns, so that production is not completely disrupted?	Routing flexibility
4. ***New part test.*** Can new part designs be introduced into the existing product mix with relative ease?	Product flexibility

Number of Machines. Flexible manufacturing systems can be distinguished according to the number of machines in the system. The following are typical categories:

single machine cell (type I A in our classification scheme of Section]3.2)

flexible manufacturing cell (usually type II A, sometimes type III A, in our classification scheme of Section 13.2)

flexible manufacturing system (usually type II A, sometimes type III A, in our classification scheme of Section 13.2)

A *single machine cell* (SMC) consists of one CNC machining center combined with a parts storage system for unattended operation (Section 14.2), as in Figure 16.2. Completed parts are periodically unloaded from the parts storage unit, and raw work-parts are loaded into it. The cell can be designed to operate in either a batch mode or a flexible mode or in combinations of the two. When operated in a batch mode, the machine processes parts of a single style in specified lot sizes and is then changed over to process a batch of the next part s.tyle. When operated in a flexible mode, the system satisfies three of the four f1exibili1y tests (Section 16.1.1). It is capable of (1) processing different part styles, (2) responding to changes in production schedule, and (4) accepting new part introductions.

Criterion (3),error recovery, cannot be satisfied because if the single machine breaks down, production stops.

A flexible manufacturing all (FMC) consists of two or three processing workstations (typically CNC machining centers or turning centers) plus a part handling system. The part handling system is connected to a load/unload station. In addition, the handling system usually includes a limited parts storage capacity. One possible FMC is illustrated in Figure

A flexible manufacturing cell satisfies the four flexibility tests discussed previously. *A flexible manufacturing system* (FMS) has four or more processing workstations connected mechanically by a common part handling system and electronically by a distributed computer system. Thus, an important distinction between an FMS and an FMC is

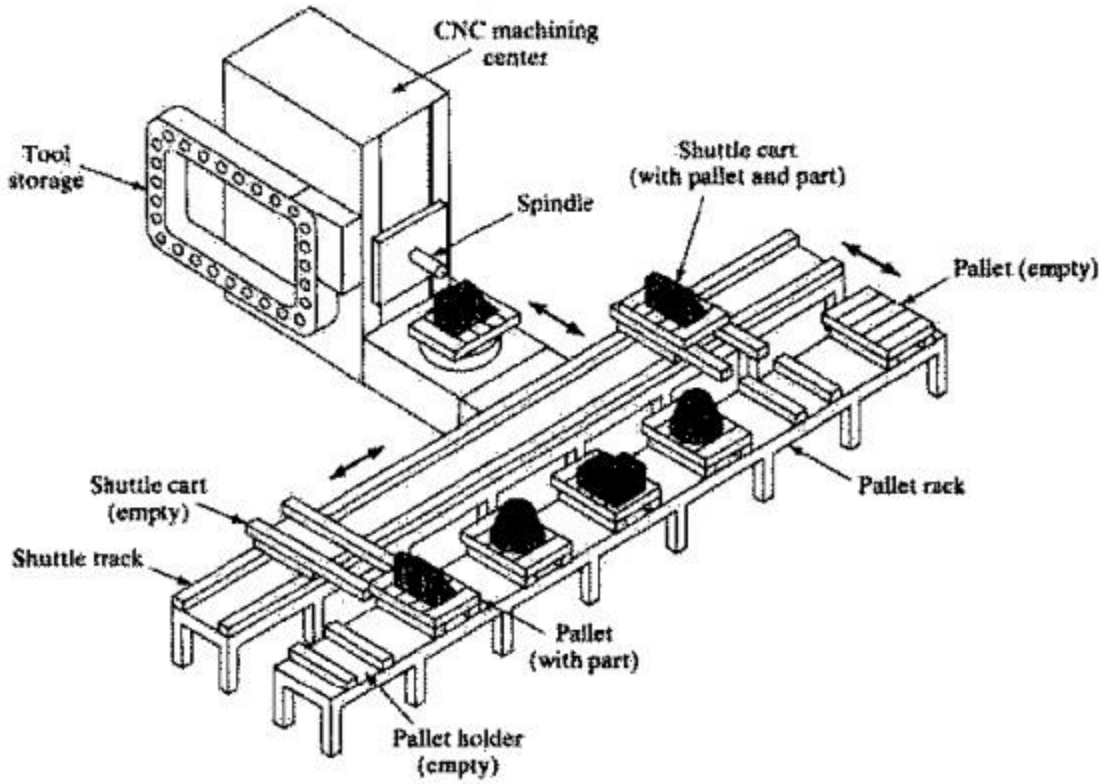


Figure 16.2 Single machine cell consisting of one CNC machining center and parts storage unit.

the number of machines: an FMC has two or three machines, while an FMS has four or more." *A* second difference is that the FMS generally includes non-processing workstations that support production but do not directly participate in it. These other stations include part/pallet washing stations, coordinate measuring machines, and so on. A third difference is that the computer control system of an FMS is generally larger and more sophisticated, often including functions not always found in a cell, such as diagnostics and tool monitoring. These additional functions are needed more in an FMS than in an FMC because the FMS is more complex.

Some of the distinguishing characteristics of the three categories of flexible manufacturing cells and systems are summarized in Figure 16.4. Table 16.3 compares the three systems in terms of the four flexibility tests.

Level of *Flexibility*. Another classification of FMS is according to the level of flexibility designed into the system. This method of classification can be applied to systems with any number of workstations, but its application seems most common with FMCs and FMSs. two categories are distinguished here:

dedicated FMS

random-order FMS

A *dedicated FMS* is designed to produce a limited variety of part styles, and the complete universe of parts to be made on the system is known in advance. The term *special manufacturing system* has also been used in reference to this FMS type (c.g., [24». The part family is likely to be based on product commonality rather than geometric similarity. The product design is considered stable, and so the system can be designed with a certain amount of process specialization to make the operations more efficient. Instead of using general-purpose machines, the machines can be designed for the specific processes required to make the limited part family, thus increasing the production rate of the system. In some instances, the machine sequence may be identical or nearly identical for all parts processed and so a transfer line may be appropriate. in which the workstations possess the necessary flexibility to process the different parts in the mix. Indeed, the term *flexible transfer lint* is sometimes used for this case.

A *random-order EMS* is more appropriate when the part family is large, there are substantial variations in part configurations, there will be new part designs introduced into the system and engineering changes in parts currently produced, and the production schedule is subject to change from day-to-day, To accommodate these variations, the random-order FMS must be more flexible than the dedicated FMS. It is equipped with general-purpose machines to deal with the variations in product and is capable of processing parts in various sequences (random-order). A more sophisticated computer control system is required for this FMS type.

We see in these two system types the tradeoff between flexibility and productivity. The dedicated FMS is less flexible but more capable of higher production rates. The random-order FMS is more flexible but at the price of lower production rates. A comparison of the features of these two FMS types is presented in Figure 16.5. Table 16.4 presents a comparison of the dedicated FMS and random-order FMS in terms of the four flexibility tests