Mechatronics and Manufacturing Automation

NPTEL Phase 2

Dr. S. N. Joshi
Assistant Professor
Department of Mechanical Engineering
Indian Institute of Technology Guwahati,
Guwahati - 781 039
Assam, INDIA.

Email: snj@iitg.ernet.in
Phone: 0361 258 2678

Module 1 Introduction

Lecture 1
Introduction

Objectives of this course:

1. To study the definition and elements of mechatronics system.
2. To learn how to apply the principles of mechatronics and automation for the development of productive and efficient manufacturing systems.
3. To study the hydraulic and pneumatic systems employed in manufacturing industry.
4. To learn the CNC technology and industrial robotics as applications of Mechatronics in manufacturing automation.

1. What is "Mechatronics"?

Mechatronics is a concept of *Japanese* origin (1970's) and can be defined as the application of electronics and computer technology to control the motions of mechanical systems (figure 1.1.1).

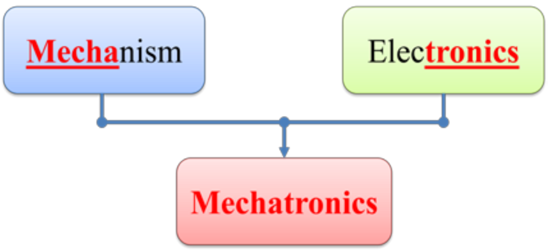

Figure 1.1.1 Definition of Mechatronics

It is a multidisciplinary approach to product and manufacturing system design (Figure 1.1.2). It involves application of electrical, mechanical, control and computer engineering to develop products, processes and systems with greater flexibility, ease in redesign and ability of reprogramming. It concurrently includes all these disciplines.

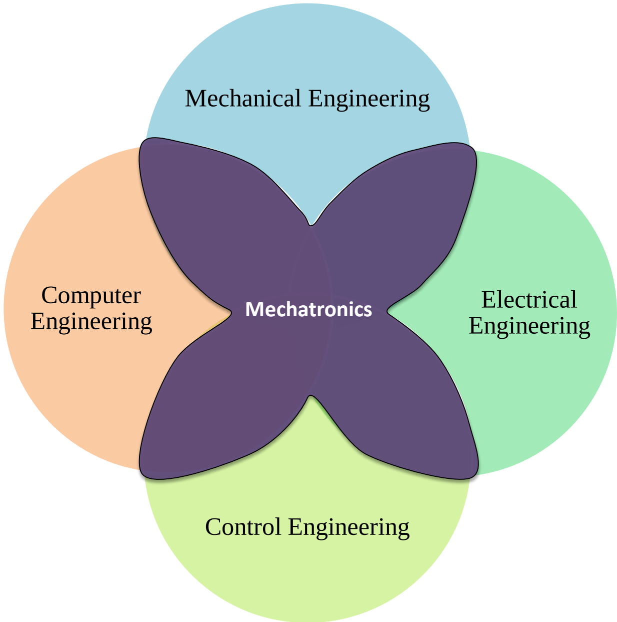

Figure 1.1.2 Mechatronics: a multi-disciplinary approach

Mechatronics can also be termed as replacement of mechanics with electronics or enhance mechanics with electronics. For example, in modern automobiles, mechanical fuel injection systems are now replaced with electronic fuel injection systems. This replacement made the automobiles more efficient and less pollutant.

With the help of microelectronics and sensor technology, mechatronics systems are providing high levels of precision and reliability. It is now possible to move (in x – y plane) the work table of a modern production machine tool in a step of 0.0001 mm.

By employment of reprogrammable microcontrollers/microcomputers, it is now easy to add new functions and capabilities to a product or a system. Today's domestic washing machines are "intelligent" and four-wheel passenger automobiles are equipped with safety installations such as air-bags, parking (proximity) sensors, anti-theft electronic keys etc.

2. *Importance of Mechatronics in automation*

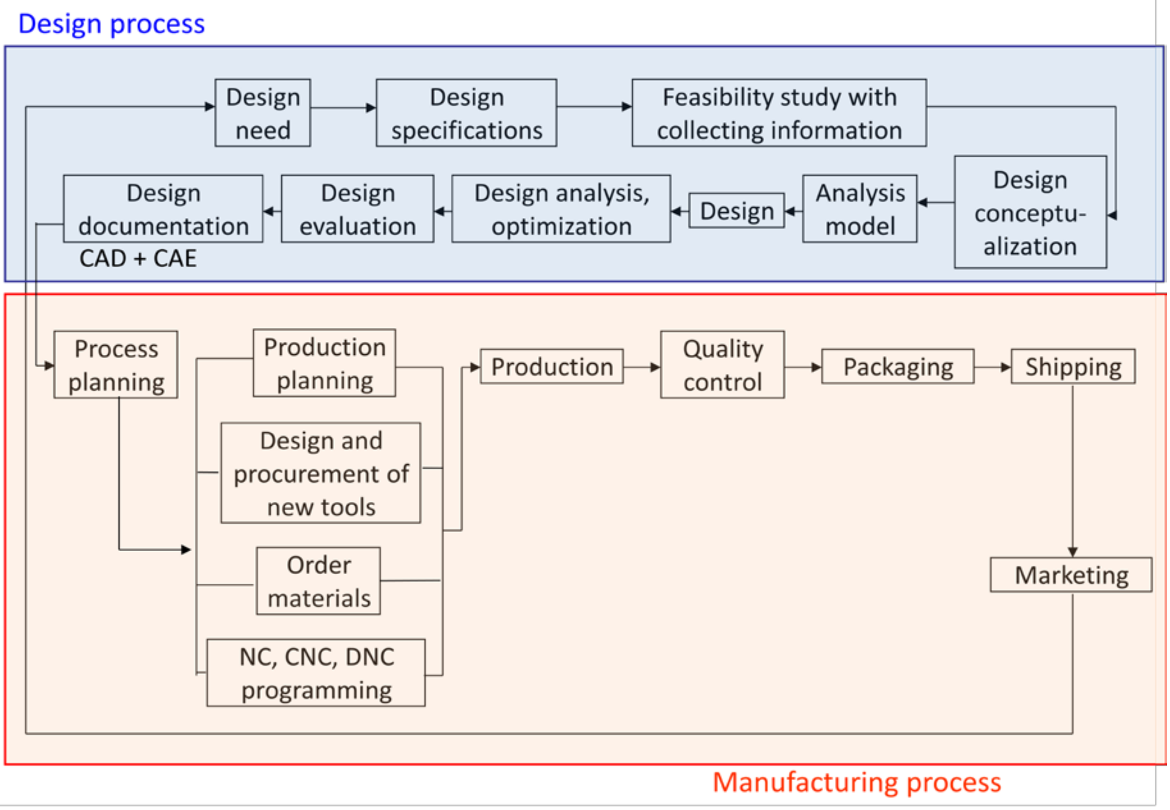

Figure 1.1.3 Operations involved in design and manufacturing of a product

Today's customers are demanding more variety and higher levels of flexibility in the products. Due to these demands and competition in the market, manufacturers are thriving to launch new/modified products to survive. It is reducing the product life as well as lead-time to manufacture a product. It is therefore essential to automate the manufacturing and assembly operations of a product. There are various activities involved in the product manufacturing process. These are shown in figure 1.1.3. These activities can be classified into two groups viz. design and manufacturing activities.

Mechatronics concurrently employs the disciplines of mechanical, electrical, control and computer engineering at the stage of design itself. Mechanical discipline is employed in terms of various machines and mechanisms, where as electrical engineering as various electric prime movers viz. AC/DC, servo motors and other systems is used. Control engineering helps in the development of various electronics-based control systems to enhance or replace the mechanics of the mechanical systems. Computers are widely used to write various softwares to control the control systems; product design and development activities; materials and manufacturing resource planning, record keeping, market survey, and other sales related activities.

Using computer aided design (CAD) / computer aided analysis (CAE) tools, three-dimensional models of products can easily be developed. These models can then be analyzed and can be simulated to study their performances using numerical tools. These numerical tools are being continuously updated or enriched with the real-life performances of the similar kind of products. These exercises provide an approximate idea about performance of the product/system to the design team at the early stage of the product development. Based on the simulation studies, the designs can be modified to achieve better performances. During the conventional design-manufacturing process, the design assessment is generally carried out after the production of first lot of the products. This consumes a lot of time, which leads to longer (in months/years) product development lead-time. Use of CAD–CAE tools saves significant time in comparison with that required in the conventional sequential design process.

CAD-CAE generated final designs are then sent to the production and process planning section. Mechatronics based systems such as computer aided manufacturing (CAM): automatic process planning, automatic part programming, manufacturing resource planning, etc. uses the design data provided by the design team. Based these inputs, various activities will then be planned to achieve the manufacturing targets in terms of quality and quantity with in a stipulated time frame.

Mechatronics based automated systems such as automatic inspection and quality assurance, automatic packaging, record making, and automatic dispatch help to expedite the entire manufacturing operation. These systems certainly ensure a supply better quality, well packed and reliable products in the market. Automation in the machine tools has reduced the human intervention in the machining operation and improved the process efficiency and product quality. Therefore it is important to study the principles of mechatronics and to learn how to apply them in the automation of a manufacturing system.

3. Mechatronics system

A system can be thought of as a box or a bounded whole which has input and output elements, and a set of relationships between these elements. Figure 1.1.4 shows a typical spring system. It has 'force' as an input which produces an 'extension'. The input and output of this system follows the Hooke's law $F = -kx$, where F is force in N, x is distance in m and k is stiffness of the spring.

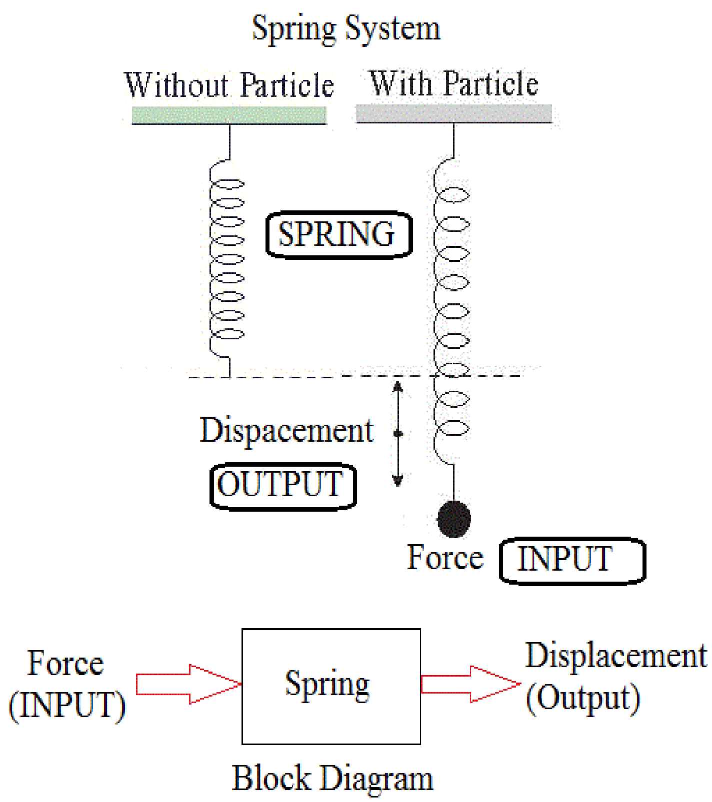

Figure 1.1.4 A spring-force system

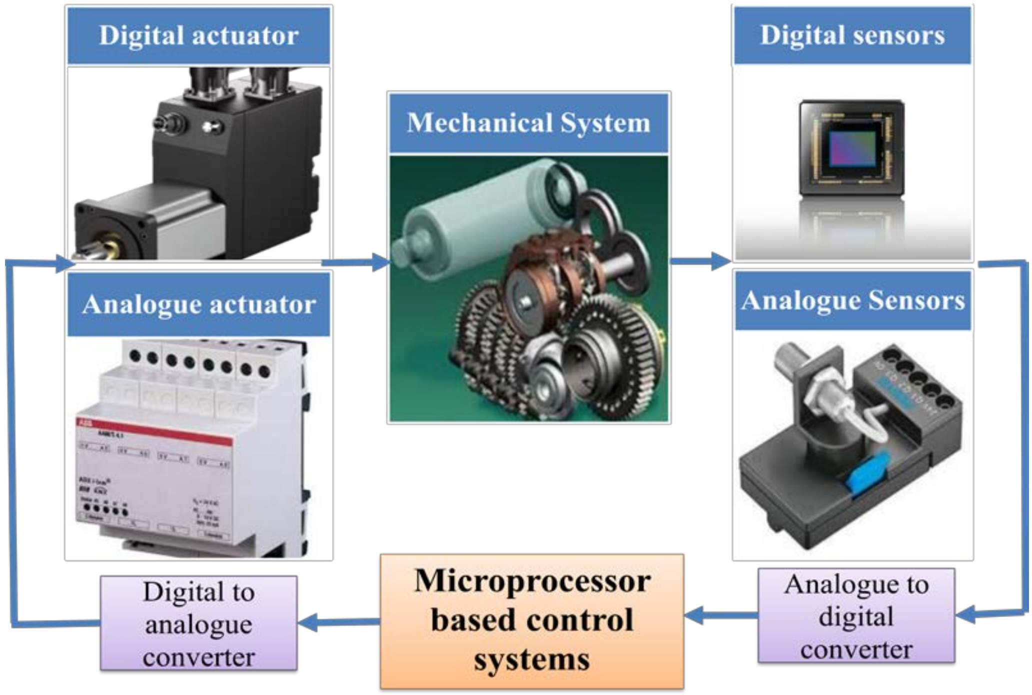

Figure 1.1.5 Constituents of a mechatronics system

A Mechatronics system integrates various technologies involving sensors, measurement systems, drives, actuation systems, microprocessor systems and software engineering. Figure 1.1.5 shows the basic elements of a mechatronics system. Consider the example of a simple spring-mass system as shown in figure 1.1.4. To replace the mechanics of this mechanical system with an equivalent mechatronics based system, we need to have the basic controlling element, a *microprocessor*. Microprocessor processes or utilizes the information gathered from the sensor system and generates the signals of appropriate level and suitable kind (current or voltage) which will be used to actuate the required actuator viz. a hydraulic piston-cylinder device for extension of piston rod in this case. The microprocessor is programmed on the basis of the principle of Hooks' Law. The schematic of microprocessor based equivalent spring mass system is shown in figure 1.1.6.

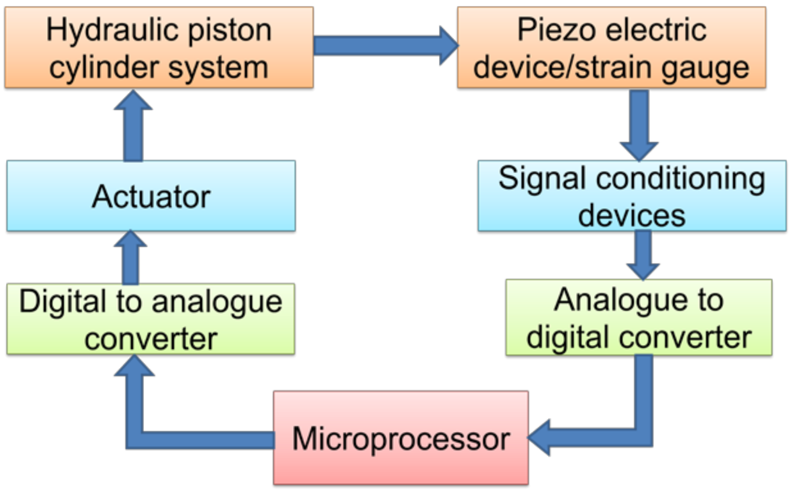

Figure 1.1.6 Microprocessor based equivalent spring mass system

The input to the system is a force which can be sensed by suitable electro-mechanical sensors viz. piezo-electric device or strain gauges. These sensors generate either digital signals (0 or 1) or analogue signals (milli-volts or milli-amperes). These signals are then converted into right form and are attenuated to a right level which can properly be used by the microprocessor to take generate the actuation signals. Various electronics based auxiliary devices viz. Analogue-to-Digital Converter (ADC), Digital-to-Analogue Converter (DAC), Op-amps, Modulators, Linearization circuits, etc. are used to condition the signals which are either received by the microprocessor from the sensors or are sent to the actuators from the microprocessor. This mechatronics based spring-mass system has the input signals in the digital form which are received from the ADC and Piezo-electric sensor. The digital actuation signals generated by the microprocessors are converted into appropriate analogues signals. These analogue signals operate the hydraulic pump and control valves to achieve the desired displacement of the piston-rod.

In this course we will be studying in detail the various elements of a Mechtronics system (shown in figure 1.1.5) and their applications to manufacturing automation.

In the next lecture we will study the applications of Mechatronics in manufacturing engineering and in the subsequent lectures; above-mentioned elements will be discussed in detail.

Assignment 1: Study the product life cycle diagram and elaborate the various design and manufacturing activities for a product: four-wheel automobile (a passenger car) or a mobile cell phone.

Assignment 2: Identify a mechatronics system being used by you in your daily routine. Analyze its elements and state its importance in the functioning of that system.

References:

1. HMT Ltd. Mechatronics, Tata McGraw-Hill, New Delhi, 1988.

2. Boltan, W., Mechatronics: electronic control systems in mechanical and electrical engineering, Longman, Singapore, 1999.

Module 1 Introduction

Lecture 2
Mechatronics: products and systems in manufacturing

Mechatronics has a variety of applications as products and systems in the area of ‘manufacturing automation’. Some of these applications are as follows:

1. Computer numerical control (CNC) machines
2. Tool monitoring systems
3. Advanced manufacturing systems
    a. Flexible manufacturing system (FMS)
    b. Computer integrated manufacturing (CIM)
4. Industrial robots
5. Automatic inspection systems: machine vision systems
6. Automatic packaging systems

Now, let us know in brief about these applications one by one.

1. *Computer numerical control (CNC) machines*

CNC machine is the best and basic example of application of Mechatronics in manufacturing automation. Efficient operation of conventional machine tools such as Lathes, milling machines, drilling machine is dependent on operator skill and training. Also a lot of time is consumed in workpart setting, tool setting and controlling the process parameters viz. feed, speed, depth of cut. Thus conventional machining is slow and expensive to meet the challenges of frequently changing product/part shape and size.

Conventional Milling Machine　　　　CNC Machine Tool

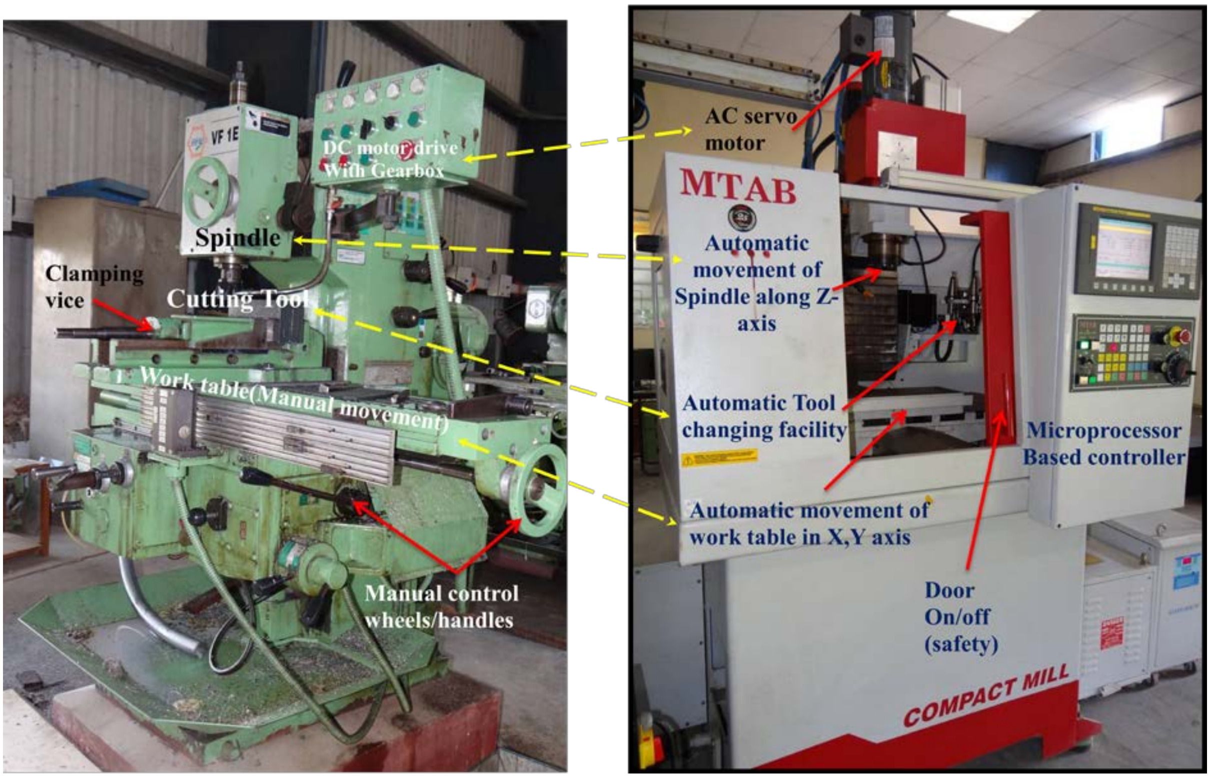

Figure 1.2.1 Comparison between a conventional machine tool and a CNC machine tool

Computer numerical control (CNC) machines are now widely used in small to large scale industries. CNC machine tools are integral part of Computer Aided Manufacturing (CAM) or Computer Integrated Manufacturing (CIM) system. CNC means operating a machine tool by a series of coded instructions consisting of numbers, letters of the alphabets, and symbols which the machine control unit (MCU) can understand. These instructions are converted into electrical pulses of current which the machine's motors and controls follow to carry out machining operations on a workpiece. Numbers, letters, and symbols are the coded instructions which refer to specific distances, positions, functions or motions which the machine tool can understand.

CNC automatically guides the axial movements of machine tools with the help of computers. The auxiliary operations such as coolant on-off, tool change, door open-close are automated with the help of micro-controllers. Figure 1.2.1 shows the fundamental differences between a conventional and a CNC machine tool. Manual operation of table and spindle movements is automated by using a CNC controllers and servo motors. The spindle speed and work feed can precisely be controlled and maintained at programmed level by the controller. The controller has self diagnostics facility which regularly alarms the operator in case of any safety norm violation viz. door open during machining, tool wear/breakage etc. Modern machine tools are now equipped with friction-less drives such as re-circulating ball screw drives, Linear motors etc. The detail study of various elements of such a Mechatronics based system is the primary aim of this course and these are described at length in the next modules.

2. Tool monitoring systems

Uninterrupted machining is one of the challenges in front manufacturers to meet the production goals and customer satisfaction in terms of product quality. Tool wear is a critical factor which affects the productivity of a machining operation. Complete automation of a machining process realizes when there is a successful prediction of tool (wear) state during the course of machining operation. Mechatronics based cutting tool-wear condition monitoring system is an integral part of automated tool rooms and unmanned factories. These systems predict the tool wear and give alarms to the system operator to prevent any damage to the machine tool and workpiece. Therefore it is essential to know how the mechatronics is helping in monitoring the tool wear. Tool wear can be observed in a variety of ways. These can be classified in two groups (Table 1.2.1).

Table 1.2.1 Tool monitoring systems [2]

Direct methods	**Indirect methods**
Electrical resistance	Torque and power
Optical measurements	Temperature
Machining hours	Vibration & acoustic emission
Contact sensing	Cutting forces & strain measurements

Direct methods deal with the application of various sensing and measurement instruments such as micro-scope, machine/camera vision; radioactive techniques to measure the tool wear. The *used or worn-out* cutting tools will be taken to the metrology or inspection section of the tool room or shop floor where they will be examined by using one of direct methods. However, these methods can easily be applied in practice when the cutting tool is not in contact with the work piece. Therefore they are called as offline tool monitoring system. Figure 1.2.2 shows a schematic of tool edge grinding or replacement scheme based on the measurement carried out using offline tool monitoring system. Offline methods are time consuming and difficult to employ during the course of an actual machining operation at the shop floor.

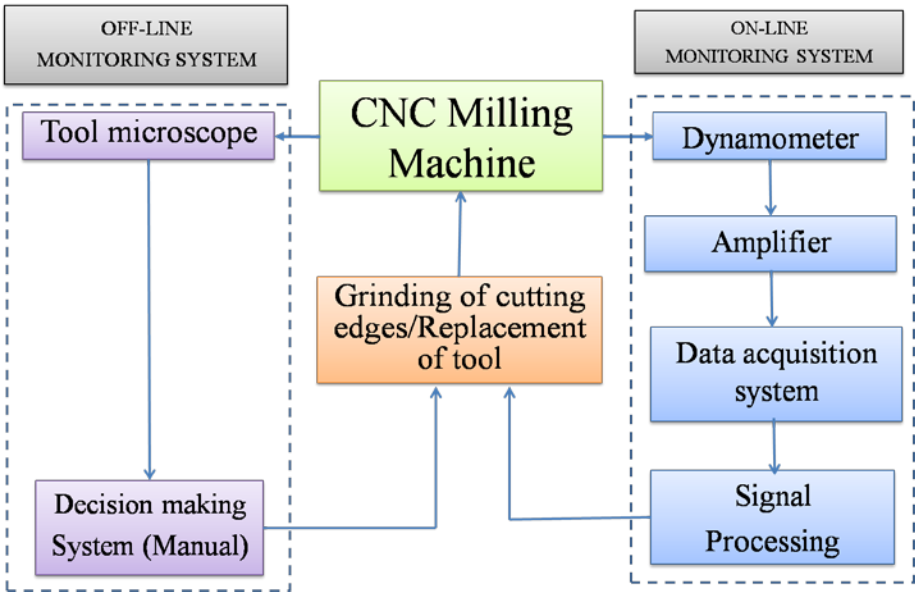

Figure 1.2.2 Off-line and on-line tool monitoring system for tool edge grinding

Indirect methods predict the condition of the cutting tool by analyzing the relationship between cutting conditions and response of machining process as a measurable quantity through sensor signals output such as force, acoustic emission, vibration, or current.

Figure 1.2.2 shows a typical example of an on-line tool monitoring system. It employs the cutting forces recoded during the real-time cutting operation to predict the tool-wear. The cutting forces can be sensed by using either piezo-electric or strain gauge based force transducer. A micro-processor based control system continuously monitors 'conditioned' signals received from the Data Acquisition System (DAS). It is generally programmed/trained with the past recorded empirical data for a wide range of process conditions for a variety of materials. Artificial Intelligence (AI) tools such as Artificial Neural Network (ANN), Genetic Algorithm (GA) are used to train the microprocessor based system on a regular basis. Based on this training the control system takes the decision to change the tool or gives an alarm to the operator. Various steps followed in On-line approach to measure the tool wear and to take the appropriate action are shown in Figure 1.2.3.

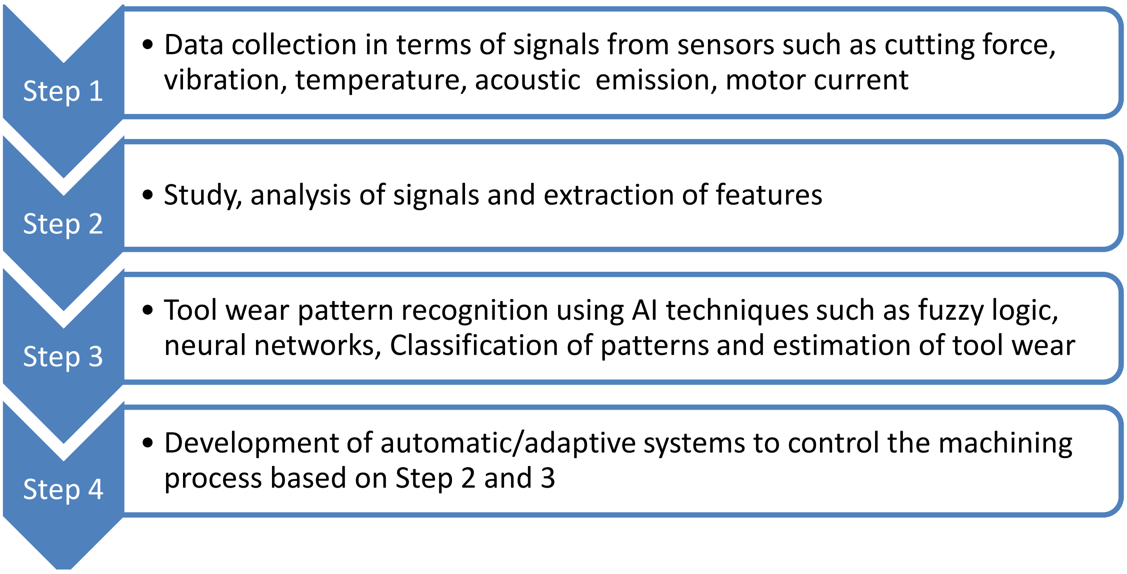

Figure 1.2.3 Steps followed in an indirect tool monitoring system

A lot of academic as well as industrial research has been carried out on numerical and experimental studies of design, development and analysis of 'Tool Condition Monitoring Systems'. Readers are suggested to browse various international journals such as International Journal of Advanced Manufacturing Technology (Springer), International Journal of Machine Tool and Manufacture; International Journal of Materials Processing Technology (Elsevier), etc. to learn more about these techniques.

3. Advanced Manufacturing Systems

3.1Flexible Manufacturing System

Nowadays customers are demanding a wide variety of products. To satisfy this demand, the manufacturers' "production" concept has moved away from "mass" to small "batch" type of production. Batch production offers more flexibility in product manufacturing. To cater this need, Flexible Manufacturing Systems (FMS) have been evolved.

As per Rao, P. N. [3], *FMS combines microelectronics and mechanical engineering to bring the economies of the scale to batch work. A central online computer controls the machine tools, other work stations, and the transfer of components and tooling. The computer also provides monitoring and information control. This combination of flexibility and overall control makes possible the production of a wide range of products in small numbers.*

FMS is a manufacturing cell or system consisting of one or more CNC machines, connected by automated material handling system, pick-and-place robots and all operated under the control of a central computer. It also has auxiliary sub-systems like component load/unload station, automatic tool handling system, tool pre-setter, component measuring station, wash station etc. Figure 1.2.4 shows a typical arrangement of FMS system and its constituents. Each of these will have further elements depending upon the requirement as given below,

A. Workstations
- CNC machine tools
- Assembly equipment
- Measuring Equipment
- Washing stations

B. Material handing Equipment
- Load unload stations (Palletizing)
- Robotics
- Automated Guided Vehicles (AGVs)
- Automated Storage and retrieval Systems (AS/RS)

C. Tool systems
- Tool setting stations
- Tool transport systems

D. Control system
- Monitoring equipments
- Networks

It can be noticed that the FMS is shown with two machining centers viz. milling center and turning center. Besides it has the load/unload stations, AS/RS for part and raw material storage, and a wire guided AGV for transporting the parts between various elements of the FMS. This system is fully automatic means it has automatic tool changing (ATC) and automatic pallet changing (APC) facilities. The central computer controls the overall operation and coordination amongst the various constituents of the FMS system.

Video attached herewith gives an overview of a FMS system

Figure 1.2.4 A FMS Setup

The characteristic features of an FMS system are as follows,

1. FMS solves the mid-variety and mid-volume production problems for which neither the high production rate transfer lines nor the highly flexible stand-alone CNC machines are suitable.
2. Several types of a defined mix can be processed simultaneously.
3. Tool change-over time is negligible.
4. Part handling from machine to machine is easier and faster due to employment of computer controlled material handling system.

Benefits of an FMS

- Flexibility to change part variety
- Higher productivity
- Higher machine utilization
- Less rejections
- High product quality
- Reduced work-in-process and inventory
- Better control over production
- Just-in-time manufacturing
- Minimally manned operation
- Easier to expand

3.2Computer Integrated Manufacturing (CIM)

In the last lecture, we have seen that a number of activities and operations viz. designing, analyzing, testing, manufacturing, packaging, quality control, etc. are involved in the life cycle of a *product* or a *system* (*see* Figure 1.1.4). Application of principles of automation to each of these activities enhances the productivity only at the individual level. These are termed as '*islands of automation'*. Integrating all these islands of automation into a single system enhances the overall productivity. Such a system is called as "*Computer Integrated Manufacturing* (CIM)".

The Society of Manufacturing Engineers (SME) defined CIM as *'CIM is the integration of the total manufacturing enterprise through the use of integrated systems and data communications coupled with new managerial philosophies that improve organizational and personal efficiency'*.

CIM basically involves the integration of advanced technologies such as computer aided design (CAD), computer aided manufacturing (CAM), computer numerical control (CNC), robots, automated material handling systems, etc. Today CIM has moved a step ahead by including and integrating the business improvement activities such as customer satisfaction, total quality and continuous improvement. These activities are now managed by computers. Business and marketing teams continuously feed the customer feedback to the design and production teams by using the networking systems. Based on the customer requirements, design and manufacturing teams can immediately improve the existing product design or can develop an entirely new product. Thus, the use of computers and automation technologies made the manufacturing industry capable to provide rapid response to the changing needs of customers.

4. *Industrial robots*

Industrial robots are general-purpose, re-programmable machines which respond to the sensory signals received from the system environment. Based on these signals, robots carry out programmed work or activity. They also take simple independent decisions and communicate/interact with the other machines and the central computer. Robots are widely employed in the following applications in manufacturing [3]:

A. Parts handling: it involves various activities such as:
    - Recognizing, sorting/separating the parts
    - Picking and placing parts at desired locations
    - Palletizing and de-palletizing
    - Loading and unloading of the parts on required machines

B. Parts processing: this may involves many manufacturing operations such as:
    - Routing
    - Drilling
    - Riveting
    - Arc welding
    - Grinding
    - Flame cutting
    - Deburring
    - Spray painting
    - Coating
    - Sand blasting
    - Dip coating
    - Gluing
    - Polishing
    - Heat treatment

C. Product building: this involves development and building of various products such as:
    - Electrical motors
    - Car bodies
    - Solenoids
    - Circuit boards and operations like
        - Bolting
        - Riveting
        - Spot welding
        - Seam welding
        - Inserting
        - Nailing
        - Fitting
        - Adhesive bonding
        - Inspection

Further detail discussion on various aspects of industrial robots such as its configuration, building blocks, sensors, and languages has been carried out in the last module of this course.

5. Automatic quality control and inspection systems

Supply of a good quality product or a system to the market is the basic aim of the manufacturing industry. The product should satisfy the needs of the customers and it must be reliable. To achieve this important product-parameter during a short lead time is really a challenge to the manufacturing industry. This can be achieved by building up the 'quality' right from the product design stage; and maintaining the standards during the 'production stages' till the product-delivery to the market.

A number of sensors and systems have been developed that can monitor quality continuously with or without the assistance of the operator. These technologies include various sensors and data acquisition systems, machine vision systems, metrology instruments such as co-ordinate measuring machine (CMM), optical profilometers, digital calipers and screw gauges etc. Now days the quality control activities are being carried out right from the design stage of product development. Various physics based simulation software is used to predict the performance of the product or the system to be developed. In the manufacture of products such as spacecrafts or airplanes, all the components are being critically monitored by using the digital imaging systems throughout their development.

In the next module we will study the various sensors, signal conditioning devices and data conversion devices which are commonly used in mechatronics and manufacturing automation.

Assignment 1 Visit to your nearby tool room or CNC work shop and prepare a case study on a real life example on tool wear monitoring system employed in the same.

Assignment 2 Differentiate between an FMS and a CIM system. Prepare a report on how automation can enhance the productivity of a mold-making tool room to cater the changing customer demands in terms of shape, size and quality of molds.

References:

1. HMT Ltd. Mechatronics, Tata McGraw-Hill, New Delhi, 1988.
2. H. Chelladurai, V. K. Jain and N. S. Vyas, Development of a cutting tool condition monitoring system for high speed turning operation by vibration and strain analysis, Int. J. Adv. Manuf. Technol. 2008, 37:471–485.
3. P. N. Rao, CAD/CAM Principles and Applications, Tata McGraw Hill, 2011.