8. Computer-Aided Manufacturing

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Design and Engineering Applications
Introduction

- The primary goal of engineering is to transform ideas into products that are economical and reliable.
- The process of designing and introducing a part to manufacturing involves a sizable investment and draws on various disciplines and resources.
- Engineering is an important key to product design, product manufacturing flow, and the ability of a company to produce good products.

**Product design** determines
- the function
- appearance
- cost of production
- the ability to plan and control manufacturing operations.

It is known that about 70-80 percent of the resources and cost required to produce a part are committed at its design phase. The further the part in its production, the more costly it is for any design change, as shown in Fig.
Engineering design has been influenced heavily by the CAD technology and tools available to designers. Similarly, manufacturing has undergone major changes with the introduction of numerically controlled (NC) and computer numerically controlled (CNC) machine tools. These replace conventional machines, thus offering increased flexibility, superior accuracy, and shorter production cycles. Machining of complex (sculptured) surfaces with conventional machining is neither economical nor accurate. These surfaces are found in a wide range of components including those for aircrafts, automobiles, construction and agricultural equipments, machine tools themselves, appliances, cameras, and instrument cases.

The potential benefits of integrating engineering and manufacturing are well recognized. More specifically, full integration of CAD and CAM is an important aspect of factory automation. Factory automation is a vast and complex subject. Achieving automation in a given company depends on the company corporate strategy, which includes such aspects as product improvements, manufacturing efficiency, quality improvements, market development, the organization, and the people.
- Design <> CAD technology and tools
- Manufacturing <> numerically controlled (NC) and computer numerically controlled (CNC) machine tools.
- NC and CNC replace conventional machines, thus offering increased flexibility, superior accuracy, and shorter production cycles.
- The integration of CAD and CAM is an important aspect of factory automation.
Historically, CAD/CAM integration began with the development of the NC technology. NC machine tools have been improving steadily in both areas of hardware control and software developments. NC part programming and interactive computer graphics have contributed heavily to these developments. The integration of CAD and CAM places increasing emphasis on tools and paths for NC machines. It is interesting to note how independent developments (CAD and CAM) which began at completely opposite ends of the CAD/CAM spectrum during evolution of CAD/CAM systems have gradually approached each other.

In an attempt to show the influence of engineering design on the manufacturing process (as shown in previous Fig.), to help designers overcome their isolation from the manufacturing process, and to appreciate the subtleties facing CAD/CAM integration, this chapter is organized in two parts.

- a quick overview of manufacturing-specifically part production cycles and manufacturing systems and processes.
- focus on process planning, NC part programming, and tool path generation and verification from geometric models.
Part Production Cycle (after part design)

- **Part classification and identification.** Parts are classified, numbered, and coded to enable them to be identified, permit easy storage and retrieval, and facilitate their production (if they are similar to other existing parts). Group technology (GT) plays an important role in producing a part. If a part has been classified using a GT part coding systems (such as OPTIZ, CODE, KK-3, MICLASS, and DCLASS systems) and its process plan has been coded. New parts with similar features can be produced by using and/or modifying the existing process plan. Process planning typically consumes considerable engineering time.
**Process planning.** This is the planning strategy for manufacturing the part. This step involves identifying the sequence of processes to manufacture the part, identifying proper jigs and fixtures, planning and, or ordering of material, ordering and/or design of tools, and scheduling part production and inspection. In short, process planning is a complete time schedule that begins with a part design on paper and ends with a real product.

**Design and procurement of new tools.** A part process plan may reveal that new tools are needed to produce the part. If this is the case, the process planner (a person who develops the process plan) initiates a request for design or purchase of new tools so that the new tools become available at the time of manufacturing.
Planning and ordering of material. The process planner ensures that all the materials shown on the bill of material, developed by the part designer at the design phase, are in stock for part production. Other accepted uses of a bill of material include product definition, service-parts control, liability and warranty protection, and part costing. Material handling systems such as MRPII [material resource (or requirement) planning] helps a great deal in this step.

NC programming. If NC machine tools are used to machine the part, an NC programmer must develop the program needed to machine the part. The integration between CAD and CAM facilitates the program generation and verification a great deal.
**Production scheduling.** Part production must be scheduled within the capacity and schedule of shops involved in producing the part as well as the availability of materials, tools, jigs or fixtures, and other items needed to produce the part. In addition, existing inventory, anticipated orders and shipments, and future market needs play a decisive factor in the additional production of existing parts.

**Manufacturing.** The culmination of all the above activities is the manufacturing of the part. Various manufacturing processes exist and one or more of them would have been identified during process planning to manufacture the part. This identification is based on the tolerance and surface finish requirements specified by the designer.

**Inspection.** Inspections of produced parts are required by internal (the company producing the part) quality control and outside customers such as the government. Quality control inspects parts for dimensional accuracy (tolerance), finish, material, and other physical properties. Typically, statistical concepts of quality control are used to eliminate the need for inspection of every individual part.
**Other Activities.** Parts that survive inspection and quality control requirements may follow different paths depending on various factors. If the company that produces a given part also produces the product the part belongs to, the next step after inspection is to assemble the part with others to form the product. If not, the part is packaged and shipped to prospective customers who assemble the parts into their products.
Manufacturing System Classification

The classification of the manufacturing system of a company should identify the activities in the three major process segments (i.e., design, manufacturing control and planning, and production) in CIM wheel.
Types of Manufacturing Systems

- Project
- Job Shop
- Repetitive
- Line
- Continuous

Project: most distinguishing characteristics of this category is that the products are complex, with many parts, but are often one of a kind. Example: aircraft and ship builders.
- **Job Shop**: characterized by low volume and quantities (i.e., lot sizes). Parts are moved around fixed production work cells. Example: classic machine shops

- **Repetitive**: orders are repetitive, blanket contracts for multiple years, moderately high volume, fixed routings for production machines. Example: automotive subcontractors
**Line:** delivery time (i.e., lead time) required by customers is often shorter than total time to build product, product has many options or models, inventory of subassemblies is normally present. Example: auto manufacturing.

**Continuous:** manufacturing lead time is greater than lead time quoted to customer, product demand is predictable, product inventory is held, volume is high, and products have few options. Always uses product flow layout with production line limited to a few different products. Example: nylon carpet yarn, breakfast cereal, petroleum and chemical products.
## Comparison Table of Manufacturing Systems

<table>
<thead>
<tr>
<th></th>
<th>Project</th>
<th>Job shop</th>
<th>Repetitive</th>
<th>Line</th>
<th>Continuous</th>
</tr>
</thead>
<tbody>
<tr>
<td>Process speed</td>
<td>Varies</td>
<td>Slow</td>
<td>Moderate</td>
<td>Fast</td>
<td>Very fast</td>
</tr>
<tr>
<td>Labor content</td>
<td>High</td>
<td>High</td>
<td>Medium</td>
<td>Low</td>
<td>Very low</td>
</tr>
<tr>
<td>Labor skill level</td>
<td>High</td>
<td>High</td>
<td>Moderate</td>
<td>Low</td>
<td>Varies</td>
</tr>
<tr>
<td>Order quantity</td>
<td>Very small</td>
<td>Low</td>
<td>Varies</td>
<td>High</td>
<td>Very high</td>
</tr>
<tr>
<td>Unit quantity cost</td>
<td>Very large</td>
<td>Large</td>
<td>Moderate</td>
<td>Low</td>
<td>Very low</td>
</tr>
<tr>
<td>Routing variations</td>
<td>Very high</td>
<td>High</td>
<td>None</td>
<td>Low</td>
<td>Very low</td>
</tr>
<tr>
<td>Product options</td>
<td>Low</td>
<td>Low</td>
<td>None</td>
<td>Very high</td>
<td>Very low</td>
</tr>
<tr>
<td>Design component</td>
<td>Very large</td>
<td>Large</td>
<td>Very small</td>
<td>Moderate</td>
<td>Small</td>
</tr>
</tbody>
</table>

All manufacturing falls on this continuum.  
Manufacturing characteristics.
Manufacturing Processes

The notion of considering manufacturing issues at the design phase is known as design for manufacturing (DFM).

The design engineers should understand the nature of materials and the rationale for their physical and mechanical properties so that they can predict the most favorable shaping, forming, cutting, and finishing processes to transform their designs into products of high quality and least cost. The materials used to produce the majority of discrete goods can be classified into ferrous, nonferrous, plastics, ceramics, powdered metals, and composites.

The manufacturing processes can be classified in four groups as:

- Casting/Molding Processes
- Forming Processes; Forging, Extrusion, Rolling, Sheet metal working, Thread rolling, Explosive forming, Electromagnetic forming
- Machining Processes
- Joining Processes
Integration Requirements

The need for increasing productivity and surviving in an increasingly competitive market has found the importance of integrating CAD and CAM, and has prompted the notion of **CIM**.

The original idea of CIM is to establish a common database to hold the great bulk of data necessary to run a company.

Based on a typical product cycle, a CIM database must support all of the design and manufacturing activities, and related information. The CIM wheel shown on the right shows typical interactivities in manufacturing enterprise (continue to next page).
Thus, the CIM database acts as a central data-bank for the company. The information in the database would be accessed by any element in the CIM environment, to either extract or enter data. Therefore, the database would always contain the most recent information.
- Part numerical data must be accurate.
- Part data should be tolerated properly.
- Drawing tolerances should match manufacturing practice.
- Separate drawing annotation (notes and dimensions) from drawing data (geometrical entities). If such information is on the same layer as geometry, the NC package might reject the part data file.
- Establish standards for layer assignments. Layer in most CAD/CAM software can be effectively used to isolate geometry for NC part programming in an easy and rapid manner.
- Profile entities must connect. A typical CNC machine tool will cut continuously only within 0.0001 in. It is, therefore, imperative that CAD databases meet or exceed machine tool accuracy.
- Avoid overlapping drawing entities. If an arc or line is copied over an existing one, the resulting tool path will be unusable.
- Dimensionality requirement must be specified. If a design calls for milling operations which require Z-axis motion, the CAD package used to create the part database must have three-dimensional capabilities. However, two-dimensional only packages would be sufficient for some applications such as routing.
- Input part geometry in manufacturing order. Geometric entities should be input in the order in which they are connected to each other so that they form a continuous unidirectional (clockwise or counterclockwise) path that the cutting tool might follow. However, requiring designers to enter geometry in manufacturing order could severely curtail creativity and design productivity. Therefore, most existing NC packages reorder geometry automatically or semi-automatically.
Process Planning

Process planning is a common task in discrete part manufacturing. It is the manufacturing activity responsible for the conversion of design data to manufacturing or work instructions. More specifically, process planning is defined as the activity that translates part design specifications from an engineering drawing data to the manufacturing operation instructions required to convert a part from a rough to a finished state.

- **Manual Approach:** The traditional manual approach involves examining an engineering part drawing and developing manufacturing process plans and instructions based on knowledge of manufacturing such as process and machine capabilities, tooling, materials, related costs, and shop practices.

- **Variant Approach:** The variant approach (also called the retrieval approach), one of the two existing CAPP approaches to process planning, is a computer assisted extension of the manual approach. The two major functions of a variant CAPP system are the creation of a new plan and the modification of an existing one.

- **Generative Approach:** The generative process planning approach is viewed as the automated approach to process planning. Unlike the variant approach, the generative approach does not require assistance from the user to generate a process plan. It usually accepts part geometrical and manufacturing data from the user, and utilizes computerized searches and decision logics to develop the part process plan automatically.

- **Hybrid Approach:** One can combine some of the characteristics of the variant and generative approaches to develop useful and successful hybrid process planning systems.
Geometric Modeling for Process Planning: In the context of process planning covered in this chapter and geometric modeling covered, it is obvious that geometric information as required by process planning (identifying machinable surfaces or features and tolerances) is not readily available in the CAD database. Additional algorithms to identify machined surfaces from a CAD model are needed and may not exist. This leaves the option of user intervention and the human-computer interactive system as the solution to identify these surfaces. Solid modeling theory has the promise to meet this need. Feature-based modeling offers an attractive geometric modeling approach for process planning and other machining activities.
Part Programming

One of the outcomes of process planning is the *method sheet* which lists the manufacturing instructions for various machines to produce the finished part. By producing these sheets, we imply that machine operators are humans who read the instructions and operate the machines accordingly. In an attempt to automate part production, the information in these sheets can be utilized directly to program machine tools to machine the part. Various attempts have been made to automate manufacturing to meet the increasing demand for accuracy and production.

Modern manufacturing systems utilize computers as an integral part of their control. The concept of an automatically controlled factory represents the central goal of the automation revolution. Simple production machines and mechanization that were introduced in the late 1700s were replaced by fixed automatic mechanisms and transfer lines around the 1900s. Next came machine tools with simple automatic control.
The introduction of machine tools was not enough to enable discrete part manufacturing to cope with the requirements facing it. Highly skilled operators were required to operate these machine tools to produce parts. Manual operations were not fast or accurate enough, and therefore prompted the need to automate part machining. The premise was that if the machining steps of a part could be captured in a program (called part program) and the control system of the machine tool could read it, then the part can be machined automatically without the need for human operators. Part programming is considered the turning point of the metal-cutting industry to meet the demands of intricate designs, with tight tolerances, which could never have been machined using the manual approach.

The premise of part programming was seriously considered during the Second World War. The aircraft and missile demands of the U.S. Air-Force, combined with the demands for commercial jets, were not possible to meet by conventional manufacturing. A U.S. government study in 1947 showed that the entire U.S. metal-cutting industry could not produce the parts needed by the Air-Force alone. As a result, the U.S. Air-Force has contracted the Parsons Corporation to develop a dynamic and accurate manufacturing system that both meets the accuracy requirements and allows design changes easily and inexpensively. The Parsons Corporation subcontracted the development of the control system to the MIT in 1951. In 1952, the MIT developed and demonstrated a machine tool (Cincinnati Hydrotel Milling Machine) with the new technology which was named numerical control (NC).
Numerical Control (NC)

Process planning > the method sheet > (to automate part production) utilize directly to program machine tools to increase accuracy and production

The central goal of the automation revolution > the concept of an automatically controlled factory

- simple production machines and mechanization in the late 1700s
- fixed automatic mechanisms and transfer lines around the 1900s.
- machine tools with simple automatic control

- the need to automate part machining > capture machining steps in a program (called part program) and read it in the control system of the machine tool > machined automatically without the need for human operators. Part programming is considered the turning point of the metal-cutting industry to meet the demands of intricate designs, with tight tolerances.

- The premise of part programming during the Second World War > U.S. Air-Force > the Parsons Corporation > MIT in 1951 > MIT developed and demonstrated a machine tool (Cincinnati Hydrotel Milling Machine) with the new technology which was named numerical control (NC) in 1952
The **NC technology**: based on controlling the motion of the drives of the machine tool as well as the motion of the cutting tool via an NC part program.

The **NC part program**: a set of statements which can be interpreted by the machine control system and converted into signals that move the machine spindles and drives.

- First generation of NC machine tools: used vacuum tube technology and the machine controller read part programs from punched tape.

- Second generation of NC machine tools: used improved electronic tubes and later solid-state circuits and the machine controller read part programs from punched tape.

**NC machine has a punched-tape reader to read instructions to controller that has no memory to store instructions. This machine has hardwired control, whereby control functions such as motion interpolation is accomplished through the use of inflexible physical electronics components. NC depends on continuous reading of instructions of the tape reader.**
Third generation of NC machine tools: used much improved integrated circuits and the ROM (read-only memory) technology in the machine controller. This led to CNC (computer numerical control) machine tools and the display monitors was added later for visual editing of part programs.

CNC has microprocessor as an integral part of MCU. A program can be loaded into MCU so that the dependence on tape reader is eliminated. The program in the memory can be edited by operator. Also, it has preprogrammed cycles of machining commands (i.e., canned cycles) for common operations such as drilling and hole tapping that are greatly simplified through the use of canned cycles.

Fourth generation of NC machine tools: has better storage capabilities (using bubble memory technology), faster memory access, and macro capabilities. This generation sets the stage for DNC (direct numerical control) machines. With local area network this is also called distributed numerical control (DNC).

DNC has an off-site host computer that holds tool motion commands for all the parts. This information is downloaded only when the machine that will do the work is determined. Thus, control information is distributed to machines in most efficient way possible.
While the NC hardware technology has been improving steadily, the NC software has been advancing as well. NC programming has benefited a great deal from the CAD technology and the advancements in geometric modeling. NC software permits NC programmers to generate tool paths for complex parts using part geometry and to verify these paths visually on graphics displays. NC tool path generation and verification have eliminated manual programming and have allowed machining sculptured surfaces which were not possible to machine before.
Economics of Manufacturing and NC

The simple economics per piece in manufacturing can be expressed as:

\[ \text{Profit} = \text{selling price} - \text{marketing cost} - \text{manufacturing cost} - \text{overhead} \]

Of course, there are many other factors that affect the details, but in this book the manufacturing cost is the concern. Some of major direct cost of manufacturing can be found in:

- cost to buy raw materials and inspect, store, and move them
- cost of manufacturing equipment
- cost to set up and operate the equipment
- cost to assemble, package, store the final products
- cost of utilities, transportation, and disposal
Time Value of Money

\[ R = P \frac{i(1+i)^n}{(1+i)^n - 1} \]

the capital recovery amount

\[ P = R \frac{(1+i)^n - 1}{i(1+i)^n} \]

the uniform annual series

present worth amount
Facts on NC Machines

A part can be machined by various machine tools, but certain factors render some machines unacceptable. One of the major factors in selecting machine tools for a particular job is economics. For example, a few simple pieces can be easily machined by a skilled machinist in less time on a conventional machine tool, but with intricate parts the NC machine can cut it more effectively in terms of time, money, and quality.

Some of the factors to consider in selecting NC machines include:

- NC machines cost 1.5 to 5 times more than conventional machines.
- Maintenance requires trained, skilled personnel as well as experienced programmer for NC programs.
- Idle time is minimum, fatigue is non-existent, there are fewer rejects, human mistakes are avoided, and all planning is carried out before a job is started on NC machine.
- Tool life is greater in NC machines due to continuously maintained speed and depth of the cuts.
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- Tool life is greater in NC machines due to continuously maintained speed and depth of the cuts.
- There is at least 25% reduction in scrap and rework using NC machines.
- There is at least 20-25% reduction in material handling.
- There is at least 30-40% reduction in inspection and quality control time.
- The floor space required for NC machine is less because NC machine can perform multiple operations and replace several conventional machines.
- Tooling costs, storage costs, and setup costs for intricate parts are considerably less in NC machines.
Example 1 (annual lot size)

Ex. Determine the minimum number of parts required to produce to make the NC machine more profitable in a year. The conventional machine costs $45,000 that produces 20 parts per hour. The annual maintenance cost is $2,600 and the labor cost is $12.50/h and other labor-associated overhead rates amount to 25%. The NC machine costs $115,000 that can produce 55 parts per hour. The annual maintenance cost is $5,400 and the labor cost and labor-associated cost amounts to one-third of the cost of the conventional machine.

Solution: Let’s the number of parts per year to produce be Q. Then, the total costs for conventional machine and NC machine are

\[ T_c = 45,000 + \left\{ \frac{2,600 + \left[ \frac{12.50}{h} \times (1 + 25\%) \right]}{20 \text{ parts/h}} \times Q \right\} \times 1 \text{ yr} \]

\[ T_{nc} = 115,000 + \left\{ \frac{5,400 + \left[ \frac{12.50}{h} \times (1 + 25\%) \right] \times \frac{1}{3}}{55 \text{ parts/h}} \times Q \right\} \times 1 \text{ yr} \]

The solution is obtained by setting \( T_c = T_{nc} \) and solving for Q.

Q. What will be done solution if it is to be profitable in three years?
Ex-8.1 NC Economics

\[ T_c(Q) := 45000 + 2600 + \frac{12.5 \cdot (1 + .25)}{20} \cdot Q \]

\[ T_{nc}(Q) := 115000 + 5400 + \frac{12.5 \cdot (1 + .25) \cdot \frac{1}{3}}{55} \cdot Q \]

Given

\[ T_c(Q) = T_{nc}(Q) \]

Find \( Q \rightarrow 106036.96551724137931 \)
Effect of Lot Size to Part Cost

Now, consider another example below with some assumptions introduced as:

1. one normal 8 hour shift consists of 1,800 production hours per year
2. the machine will fail after making a million parts
Example 2

Example 8.9.2. **Economics** Consider three different machines in the table below.

<table>
<thead>
<tr>
<th>Machine Type</th>
<th>Price ($)</th>
<th>Production Rate/ Hour</th>
<th>Annual Maintenance ($)</th>
<th>Labor + Overhead Cost ($) / Piece</th>
</tr>
</thead>
<tbody>
<tr>
<td>Manual Milling</td>
<td>10,000</td>
<td>6</td>
<td>400</td>
<td>20</td>
</tr>
<tr>
<td>NC Milling</td>
<td>45,000</td>
<td>35</td>
<td>2,000</td>
<td>2</td>
</tr>
<tr>
<td>NC Milling with automatic load and unload</td>
<td>100,000</td>
<td>35</td>
<td>3,500</td>
<td>0</td>
</tr>
</tbody>
</table>

A manufacturing company is considering to borrow money from a bank at annual rate of 10% to buy a milling machine. It wants to pay back all money in 10 years. When the material and tool cost per piece is 60 cents, determine the cost per part for each machine at various annual production lot sizes of 100, 10,000, and $10^6$. 
**Solution.** First, the money borrowed to buy the machine must be paid back in ten years. The annual payment \( R \) can be calculated by the above formula. For example, for manual milling machine it becomes
\[
R = 10,000 \times \frac{0.1 \times (1 + 0.1)^{10}}{(1 + 0.1)^{10} - 1} = 1627.45.
\]
This is the amount the company must pay annually.

For lot size of 100 for the same machine, the cost per part can be calculated by
\[
\left[ \frac{R + 400}{100} + 20 + 0.6 \right] = 40.87
\]

<table>
<thead>
<tr>
<th>Machine Type</th>
<th>Annual Payment ($)</th>
<th>Annual Maintenance ($)</th>
<th>Labor + Overhead Cost ($) / Part</th>
<th>Material + Tool Cost / Part</th>
<th>Cost/Part at Various Annual Lot Sizes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Manual Milling</td>
<td>1627.45</td>
<td>400</td>
<td>5</td>
<td>0.6</td>
<td>100: 25.87, 10^4: 5.80, 10^6: beyond capacity</td>
</tr>
<tr>
<td>NC Milling</td>
<td>2,000</td>
<td>0.5</td>
<td>0.6</td>
<td></td>
<td></td>
</tr>
<tr>
<td>NC Milling with automatic load and unload</td>
<td>3,500</td>
<td>0</td>
<td>0.6</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

The rest of entries can be calculated in the same way. Try it.
Fundamentals of NC

A part program is a combination of machine tool code and machine specific instructions. It contains geometric information about part geometry and motion information to move the cutting tool as well as other related information such as cutting speed, feedrate, and auxiliary functions (coolant on and off, spindle direction, etc.) that are programmed according to surface finish and tolerance requirements.

In conventional machining, the handwheels of the machine tool are operated by the expert machine operator. The NC system replaces the manual actions of the operator.

Part programmers who prepare part programs for NC machine tools must have knowledge of manufacturing requirements such as tools, cutting fluids, fixture design techniques, use of machinability data, and process engineering. In addition, they must be familiar with the function of NC machine tools and machining processes.
Description of Machine Tools:

- **NC machine tool** = **MCU** (machine control unit) + the machine tool itself
- **MCU** = **DPU** (data processing unit) + **CLU** (control loop unit),
  - DPU reads and decodes the part program, processes the decoded information, and provides data to the CLU
  - CLU controls the machine tool and the drives attached to the leadscrews, and receives feedback signals on the actual position and velocity of the axes of the machine.
**MOTIONS OF MACHINE TOOLS:** A workpiece is machined to the finished shape by providing a relative motion between the workpiece and the tool. Each motion adds to the versatility of the machine tool and requires its own axis of motion.

In NC machine tools, each axis of motion is equipped with a driving device to replace the handwheel of the conventional machine. The type of driving device is selected mainly by the power requirements of the machine. A driving device may be a dc motor, a hydraulic actuator, or a stepper motor.
An axis of motion is defined as an axis where relative motion between the cutting tool and workpiece occurs. The primary three axes of motion are referred to as the X, Y, and Z axes and form the machine tool coordinate system. The XYZ system is a right-hand system and the location of its origin may be fixed or adjustable. The positive directions of the axes are usually defined by the manufacturer of the machine tool. However, it is a convention that the positive direction of the Z axis moves the cutting tool away from the workpiece.

In addition to the primary slide motions in the X, Y, and Z directions, secondary slide motions may exist and be labeled U, V, and W. Rotary motions around axes parallel to X, Y, and Z may also exist and are designated a, b, and c respectively. These notations are EIA standards. It is conventional that machine tools are designated by the number of axes of motion they can provide to control the tool position and orientation such as 2 1/2-axis, 3-axis, or 5-axis milling machines. These axes refer to the possible axes of motion the machine tool can control simultaneously. (continue to next page)
Observe the planes on which the motion lies.
Various Axes of Motion

(a) 2- (or 3-) axis, (b) 4-axis, and (c) 5-axis motions
Motion Axes of Machine Tools

(a) 3-axis,
(b) 4-axis with rotary head,
(c) 4-axis with rotary table
(d) 5-axis with rotary head and rotary table,
(e) 5-axis with dual rotary heads,
(f) 5-axis with dual rotary tables

Various Axes of FADAL VMC 15 CNC 32MP
Various Axes of HAAS VF8 and NIIGATA HN50A – FANUC 15MA-B TABLE
Figure 10.4.3-3  4-axis horizontal milling machine with a rotary table and its axis orientations
Lathe

- Headstock
- Spindle
- Tool Rest
- Tailstock
- Bed
- Tool Holder with Cutting Tools
Cutting Tool and Tool Holder
Spindle Taper and Headstock

Figure. Cam-lock type spindle nose showing taper, adapter, and headstock center in place.
Workpiece and Spindle Head

Unless a workpiece has a taper machined onto it which perfectly matches the internal taper in the spindle, or has threads which perfectly match the external threads on the spindle (two things which almost never happen), an accessory must be used to mount a workpiece to the spindle.

- A workpiece may be bolted or screwed to a faceplate, a large flat disk that mounts to the spindle. Alternatively faceplate dogs may be used to secure the work to the faceplate.
- A workpiece may be clamped in a three- or four-jaw chuck, which mounts directly to the spindle or mounted on a mandrel.

In precision work (and in some classes of repetition work), cylindrical workpieces are invariably held in a collet inserted into the spindle and secured either by a drawbar, or by a collet closing cap on the spindle. Suitable collets may also be used to mount square or hexagonal workpieces.
Spindle Taper Problems

There are four major spindle taper problems with which all manufacturers need to be concerned.

The first taper problem is bellmouthing. Bellmouthing takes place naturally as the spindle taper wears during continued use. It usually occurs at the large diameter of the taper, leaving contact only at the small diameter portion, which may account for fifty percent or even less of the total spindle taper contact area. This reduced contact leads to increased tool movement and greater tool runout. Because bellmouthing happens very gradually over a long period of time, it often goes unnoticed. The drawing (figure 1) below shows the area of wear (or bellmouthing) on the spindle taper.
This lack of contact between the tool holder and the spindle will first begin to show on the machine spindle taper (and tool holder) as fretting. This is easily seen by the eyes of the operator as rust colored areas, or spots (Figure 2). The machine operator will begin to observe such symptoms as tool chatter on workpiece surfaces, carbide inserts chipping at the cutting edge and inconsistent bore sizes.
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The second taper problem is **machine malfunction or operator error**.

This can cause a tool holder to spin inside the spindle taper. This condition leads to a buildup of galled material, which completely eliminates contact of the tool with the taper surface. Although attempts to grind away the material buildup by hand can increase taper contact, the increase is usually not sufficient to achieve satisfactory work piece quality. Furthermore, such grinding can irreparably damage (Figure 3) an otherwise repairable spindle.
The third taper problem is **weak tool retention.** This problem can cause tool chatter, even though the spindle taper is acceptable. Unchecked, the condition inevitably leads to premature taper wear of the machine spindle and of the tool holder.

The fourth taper problem is the use of **worn tool holders.** Using worn tool holders in a new, rebuilt, or reground spindle will cause premature spindle taper wear, due to inefficient contact between the tool and the taper. Tool holder condition is as important as spindle condition.
Milling Machines

Bed Type Milling Machine
Workpiece and Spindle Head

Unless a workpiece has a taper machined onto it which perfectly matches the internal taper in the spindle, or has threads which perfectly match the external threads on the spindle (two things which almost never happen), an accessory must be used to mount a workpiece to the spindle.

- A workpiece may be bolted or screwed to a [faceplate](#), a large flat disk that mounts to the spindle. Alternatively, faceplate dogs may be used to secure the work to the faceplate.
- A workpiece may be clamped in a [three- or four-jaw chuck](#), which mounts directly to the spindle or mounted on a [mandrel](#).

In precision work (and in some classes of repetition work), cylindrical workpieces are invariably held in a [collet](#) inserted into the spindle and secured either by a drawbar, or by a collet closing cap on the spindle. Suitable collets may also be used to mount square or hexagonal workpieces.
Tool Materials

- Cutting Tool
- Carbide Insert
- Cubic Boron Nitride or Polycrystalline Diamond
- Workpiece
Milling Cutters
End Mills

Face and Side Mills

Face Mill Cutter

Side Mill Cutter
## Multiple Flute End Mills

<table>
<thead>
<tr>
<th>Flutes</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>2 Flutes Square End mills (Center Cut)</td>
</tr>
<tr>
<td>3</td>
<td>3 Flutes Square End mills (Center Cut)</td>
</tr>
<tr>
<td>4</td>
<td>4 Flutes Square End mills (Center Cut)</td>
</tr>
<tr>
<td>5</td>
<td>5 Flutes Square End mills (Center Cut)</td>
</tr>
<tr>
<td>6</td>
<td>6 Flutes Square End mills (Center Cut)</td>
</tr>
<tr>
<td>4</td>
<td>4 Flutes Square End mills (with Center Hole)</td>
</tr>
<tr>
<td>5</td>
<td>5 Flutes Square End mills (with Center Hole)</td>
</tr>
</tbody>
</table>
RobbJack recommends **Climb Milling** (as opposed to Conventional Milling) for most applications (assuming back-lash control in the machine).

**Climb Milling** generally allows better flute engagement in the material, resulting in more efficient machining and superior part finishes. **Conventional Milling** can lead to work hardening in some ferrous materials.
Application Guidelines of Milling Tools

• **Rough Slotting/Pocketing**
  Two and three flute end mills can be used in non-ferrous and ferrous materials with depth of cuts not exceeding one diameter per pass.

  Three and four flute carbide Ruffers can be used for rough pocketing and profiling operations in many ferrous materials with radial depths of cuts not exceeding 25% of the diameter.

• **Finish Slotting/Peripheral/Pocketing**
  Three, four and six flute end mills offer greater stability with increased feed rates for finishing.
Chip Formation in Manufacturing

Schematics of cutting and types of developed
Nomenclature of a Cutting Tool

standard terminology for single-point cutting tools

Angles for HSS on Aluminum
NC Programming Languages

1. Manual part programming (g-codes)
2. APT (automatically programmed tools) part programming
3. Computer-assisted part programming (CAPP) in CAM system
4. Computer integrated part programming (CIPP)

The statements of a part programming language can be divided into eight groups:

- **Language features.** Define variables (symbolic names) and subscripted scalar variables and geometric entities in a part program.

- **Geometric statements.** Analytic representations (points, lines, conics, planes, quadric surfaces, etc.), Z-surface representation for coordinate assignments (used for synthetic surfaces), and nesting statements are available. In a CAD environment, geometric information required by these statements are generated interactively when the user digitizes the surface to be machined when using NC software.

- **Tool statements.** Tool shape (geometry), tool axis orientation, and tool-to-part tolerance.

- **Motion statements.** Provide information for type of machining (PIP or continuous path), direction of cutting, speed and feedrate, etc.
- **Arithmetic statements.** Addition, subtraction, etc., as well as functions (square root, sine, etc.) are available.

- **Repetitive programming.** Statements that provide looping, branching, coordinate copying, and coordinate transformations are provided. Moreover, macro facilities enable programmers to deal with repetitive programming more effectively.

- **Output facilities.** A part program forms what is called the CL-data, CL meaning cutter location. The CL-data is stored in a file called CL-file. A computer printout of this file is known as the CL-printout. The CL-file is stored in ASCII format. In an attempt to reduce the file size and post processing, the part program can be stored in a binary format. In this case, the file is known as the BCL-file, with the “B” meaning binary.

- **Postprocessor statements.** The CL-file (or BCL-file) is written in the programming language syntax. This syntax is a high level form which the machine tool controller is incapable of reading and interpreting. Therefore, the CL-file must be post processed via a postprocessor.
NC programming begins with part definition (i.e., geometry construction) and is completed by machining plan that relates to how to control the tool motion to remove the material from the part.

These topics will be covered in the following two chapters.
Basics of NC Programming

NC part program should contain information such as:

- **MACHINE TOOL COORDINATE SYSTEM**: Cartesian
- **MATHEMATICS OF TOOL PATHS**: automatic in CAD software
- **MACHINE FORCES**: proper feeds and speeds
- **CUTTER PROGRAMMING**: absolute programming, incremental programming, rapid positioning, linear interpolation, circular interpolation, canned cycles (ie, subroutines)
- **TOOL OFFSET**
Successful NC machining of parts utilizing CAD databases can be achieved by identifying four steps: machined surfaces (feature recognition), tool path generation, tool path verification, and collision detection.

Automatic feature recognition for manufacturing is a crucial step in integrating CAD and CAM. One important feature recognition is collision detection that is concerned with finding if the cutting tool and its assembly (tool, shank, etc.) may collide with other components of the manufacturing environment such as the workpiece itself, jigs, fixtures, spindles, etc. One method to solve the collision problem, using solid modeling, is to find the swept volume generated by the tool motion in space and intersect it with any of the models of the components (jigs, fixtures, etc.). If the intersection is not null, collision occurs and the components would have to be rearranged.
The figure above shows some geometries to consider for tool-path generation. There are various approaches to determine the tool path. For example, the surface normal and tangent vectors at each point.
APT (Automatically Programmed Tool)

The more advanced NC programming languages such as APT employ surface geometry techniques to generate tool paths. APT has the capability to describe, and therefore to generate, tool paths for all analytic curves and surfaces. APT utilizes the nonparametric representation to describe these geometric entities. Each entity has a corresponding geometric statement that takes the required input parameters to define it as described in the following chapters.

NC programming based on APT uses only unoriented, unbounded, single surfaces. APT does not recognize connected surfaces. This is why APT cannot be used directly with solid models that use orientable and bounded surfaces (faces). In an attempt to enhance NC programming capabilities, machining sculptured or free-form surfaces have received wide attention. These capabilities enable machining synthetic surfaces which are usually represented in a parametric form.

In cutting free-form surfaces, one is faced with the problems of cutter offset, accuracy, and cutter interference with the workpiece (tool gouging). Customarily, ball-end (or ball-nosed) cutters are used in these circumstances and the calculation of cutter offsets is achieved by finding the directions of normals on the surface. Having determined the directions of normals, the tool is then offset by the radius of the cutter along the normal vectors over the surface.
NC part programs and the tool paths that are supposed to guide tools during actual machining usually include a lot of coordinate values that are impossible to verify manually. Graphical and visual display of the tool paths are beneficial in the verification process. NC verification software including most CAM software that employ APT can simulate the actual machining process by displaying the cutting tool moving, following its tool path, relative to the stock and jigs and fixtures. The animated tool path is generated by displaying the tool position and orientation, using the NC program data, at various points on the tool path, creating frames, and storing the frames for playback.

The advantages of tool path verification are numerous. Check whether:

1. The cutter removes the necessary material from the stock.
2. The cutter hits any clamps or fixtures on approach.
3. The cutter passes through the floor or side of a pocket, or through a rib.
4. The tool paths are as efficient as they could be.
Other advantages include rapid turnaround of program development, rapid training for potential NC programmers without danger, and freeing machine tools to only cut real parts (no testing of programs or training individuals).

Some machining problems still go undetected even with tool path verification. Such problems as tool chatter and stock warpage (due to heat stresses during machining) are simply beyond the scope of verification.
CAM system with APT generates the toolpath in CL data format that must be post-processed to machine control data (MCD). MCD is the actual part program for a specific machine.