NUMERO: 2351A ANNO: 2018

A P P U N T I

STUDENTE: Sobrero Giovanni

MATERIA: Integrated Manufacturing Systems - Prof. Salmi Taurino

Integrated Manufacturing Systems

Professors: Salmi, Taurino (Production Planning)
Giovanni Sobrero's Schemes
A.A. 2017 – 2018

Prof. Alessandro Salmi:

A1 CNC – Basic concepts

A2 CNC – Machine tools structure

A3 CNC – Tools and workpiece management

A4 CNC – Drives, actuation systems and feedback devices

A5 CNC – Machine control unit

A6 Industrial Robotics

A7 CMM

A8 Additive Manufacturing

A9 Automation in Manufacturing

Prof. Taurino:

(B1 Enterprise Organization) *

(B2 Business Functions)

(B3 Human Resource Management)

(B4 Toyota Kata)

(B5 Team Working)

(B6 Soft Thinking)

() * For another course, not for Mechanical Engineering

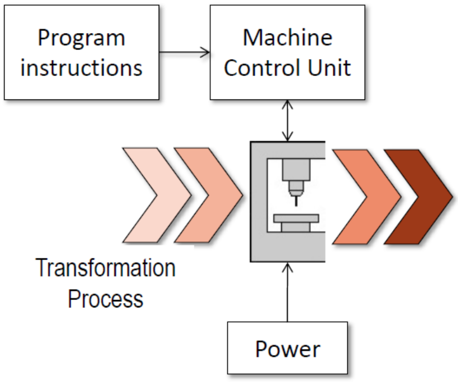
C1 PRODUCTION PLANNING

C2 MATERIAL REQUIRENMENT PLANNING (MRP)

C3 PRODUCTION SCHEDULING

A1 CNC – Basic concepts

What is Numerical Control?



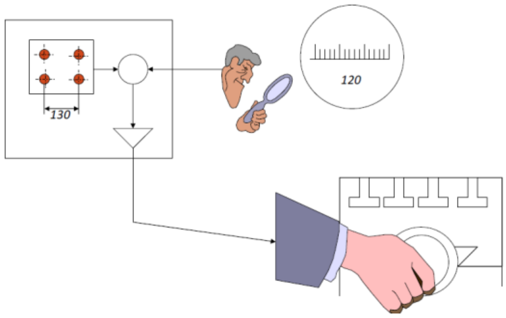
- Numerical Control (NC) is a **method of automatically operating** a manufacturing machine based on a code of letters, numbers and special characters.

- The numerical data required to produce a part is provided to a machine in the form of a program, named "**part program**".

- The program is translated into the appropriate electrical signals for input to motors that run the machine.

- Therefore, NC is the automated control of machine tools by an **electromechanical controller** and a **part program**.

- Before NC, the motions of the machine tool had to be controlled manually or mechanically (for example by means of cams).



The definition of CNC given by the Electronic Industry Association (EIA) is as follows:

"A system in which actions are controlled by the direct insertion of numerical data at some point. The system must automatically interpret at least some portion of this data"

In simple words, a CNC system receives numerical data, interprets the data and then controls the action accordingly.

Numerical Control – History

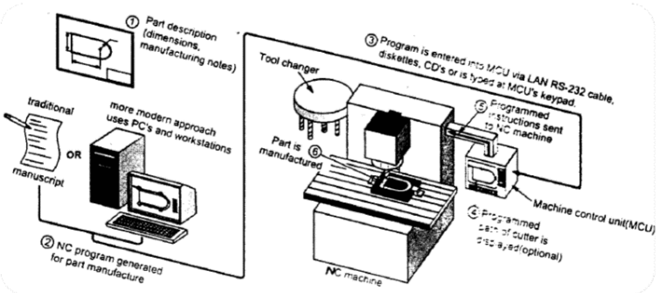
- The concept is credited to John T. Parsons (1947). By means of **punched cards** he was able to control the position of a machine tools in an attempt to cut helicopter blades.
US Air Force teamed up with MIT to develop a programmable milling machine (1949).
- In 1952, a three-axis Cincinnati Hydrotel milling machine was demonstrated. The term **Numerical Control** (NC) was born. The machine had an electromechanical controller and used punched cards.
A new class of machines named *machining centers* and *turning centers,* that could perform multiple machining processes, was developed.
- Modern NC machines have a computer on board, **Computer Numerical Control** (CNC). They can run unattended at over 40,000 rpm (spindle speed) with a feed rate of over 1,500 mm/min and an accuracy of 2.5 µm.

- All numerical control machines manufactured since the Seventies are of CNC type.

NC (hard-wired) to CNC (soft-wired)

Numerical Control (NC) is often referred to as the older generation of numerical control technology. NC systems are ***hard-wired* controls** in which most *functions* are *implemented by* ***Electronic Hardware*** based upon **digital circuit technology**.

Computer numerical control (CNC) is a numerical control system in which a dedicated, stored program computer is built into the control to perform basic and advanced NC functions. CNC controls are also referred to as ***soft-wired* NC systems** because most of their control *functions* are *implemented by* ***Control Software Programs.***



Advantages of CNC over conventional NC

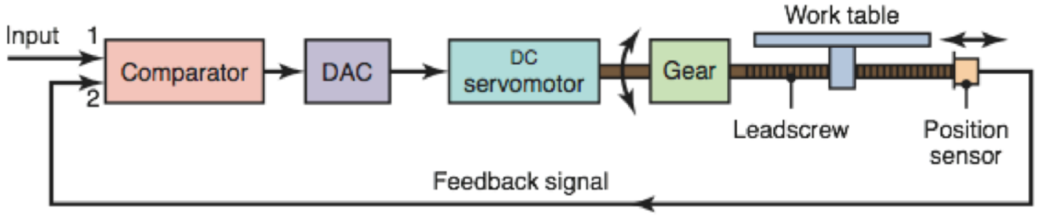
- The use of Control Software rather than hard-wired;
- Increased flexibility (variety of mixed operations and functions);
- Elimination of tape reader (or tape read only once per program);
- Part program storage (computer memory and storage media);
- Display shows instructions being executed and other operational data;
- Greater accuracy (faster control solutions);
- More versatility (e.g., program editing at the machine, reprogramming, tool path plotting, metric conversion, cutter dimension compensation);
- Fixed (subroutine) cycles (e.g., pocket milling, pecking, …);
- Manual data input (MDI), even while another program is running, and remote data transfer;
- System integration capability (connect to robots and other computer or microprocessor-based equipment, creating manufacturing cells);
- **Machine diagnostics (gives error message** or identifies problem).

(Computer) Numerical Control

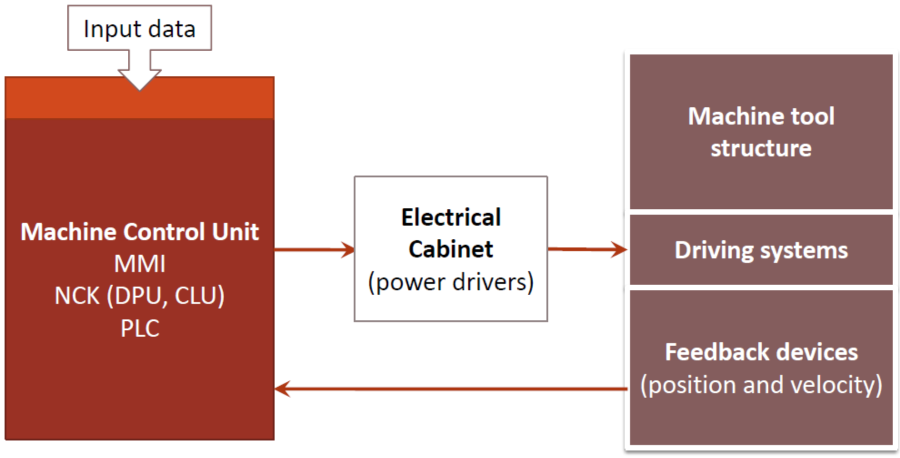
- Today, manual machine tools have been largely replaced by **(Computer) Numerical Control** (CNC) machine tools. Basically, these machines still perform the same functions, but movements of the machine tool are controlled electronically rather than manually.
- CNC machine tools can produce the same parts over and over again with very little variation. **They can run day and night, week after week, without getting tired**. These are obvious advantages over manual machine tools, which need a great deal of human interaction in order to do anything.
- CNC machine tools are **highly productive**. They are also expensive to purchase, set up, and maintain. However, the productivity advantage can easily offset this cost if their use is properly managed.
- This does not mean that **manual machine tools** are obsolete. They are still used extensively for tool and fixture work, maintenance and repair, and small volume production. However, much of the high- and

Computer Numerical Control – Fundamentals

- The computer reads the instructions and sends *electrical signals to a motor*, which then turns a screw to move the machining table.
- A ***sensor*** mounted on the table or on the motor sends positioning information back to the computer. Once the computer determines that the correct location has been reached, the next move will be executed.
- This *cycle repeats itself over and over* until the end of the instructions is reached. This is a simplistic but accurate view of a typical CNC machine tool.



Hardware Configuration of CNC Machine



Hardware Configuration – Machine Tool Structure

- Design and construction of Computer Numerically Controlled (CNC) machines are **entirely different** from those of conventional machines. This difference is due to the **introduction of automation** to get better machining accuracy and higher performance.
- It is important to provide **sufficiently high static stiffness** along with the optimum stiffness to weight ratio during the designing of machine tool structure.
- Besides machine tool structure, the following **structural basic elements** affect machining accuracy:

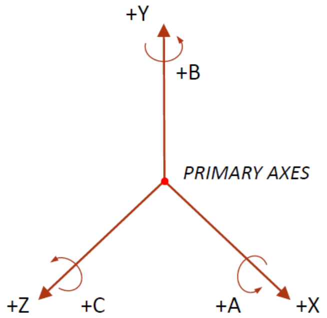
- Slideways;
- Power Screws and their support bearing;
- Transmission elements (gears, belt, …);
- Spindle support;
- Tool holding devices;
- Work holding devices.

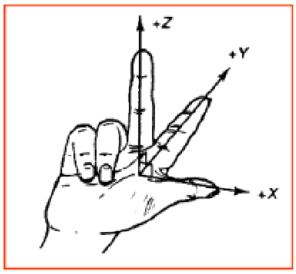
1.2 the Tool Change,
1.3 the Workpiece Change,
1.4 the in/out signal processing.

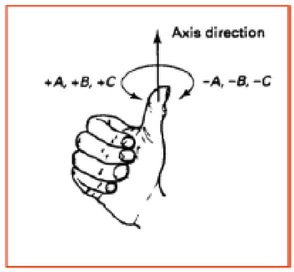
- Therefore, plays the role of controlling **the Machine Behavior with the exception of the servo control**.

Designation of Machine Tool Axes

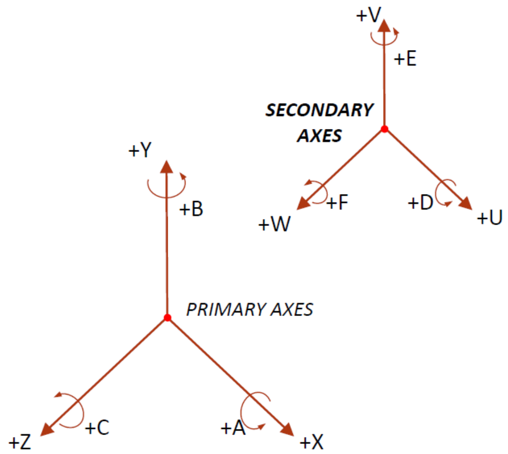
- The standards for machine axes are established according to the industry standard report EIA RS-267A (consistent with UNI ISO 841).
- The **linear axis** that moves parallel to the main spindle centerline is designated Z axis. the longest travel axis is designated X axis. The only axis left is Y axis. If the fingers of your hand are now aligned to X and Z axes according to the right-hand rule, the index finger represents Y axis.
- The three primary **rotary axes** are A, B, and C. Each one is designated by identifying the primary linear axis that its rotary plane is perpendicular to. A axis rotates around X axis, B axis rotates around Y axis, and C axis rotates around Z axis.

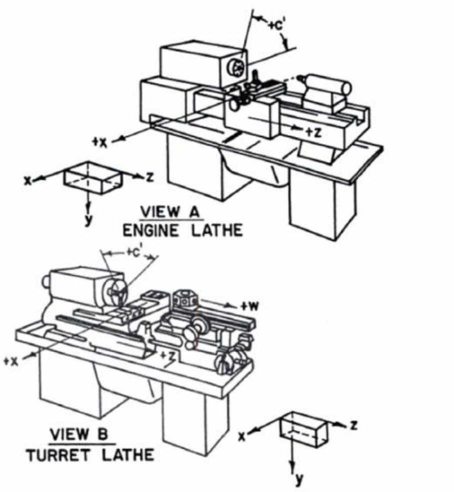


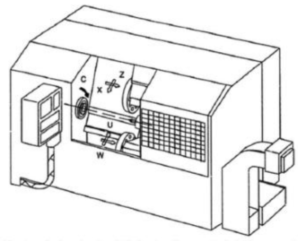




- The **secondary axes** system U, V and W is **independent and parallel** to the primary axes X, Y and Z respectively.
- The characters D, E and F are normally used to designate secondary angular/rotational motion either parallel to A, B and C, or about special axes.
- **When axes designations are assigned, it is assumed that the cutter moves in relation to the workpiece.**
- It is known that this is not always true and on many machines the workpiece moves relative to the cutter. Under such circumstances, it has been stated that each axis should be designated by a prime mark (i.e. X', Y', …)





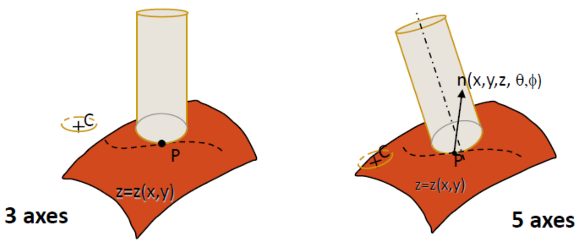


10.29 Axes Designation for CNC Turning Centre with Twin Turrets and Driven Tooling

Multiaxis machine tools

Multiaxis machines offer several improvements over other CNC tools at the cost of increased complexity and price of the machine:

- **Reduced set up work** (most parts, even complex in shape, can be manufactured in one or two set-ups eliminating the need for extra fixturing);
- **Accuracy** (every time you move a workpiece from one fixture to another, there is a risk of misalignment). The use of indexing rotary tables allows precise movement, while the highest levels of accuracy are maintained;
- **Better surface finish** can be obtained **by moving the tool tangentially about the surface**.



Applications of CNC Machines

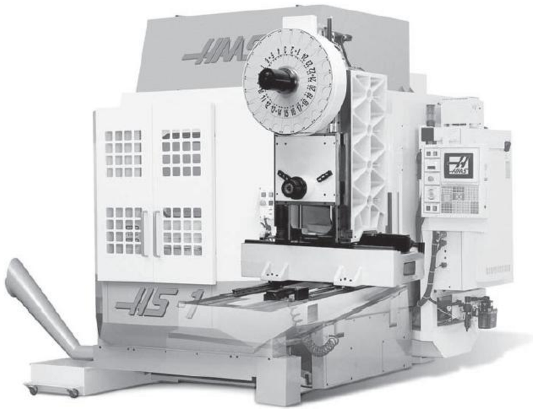
CNC machines are widely used in the metal cutting industry and are best used to produce the following types of products:

- parts with **complicated contours**;
- parts requiring **close tolerance** and/or **good repeatability**;
- parts requiring **expensive jigs** and **fixtures** if produced by conventional machines;
- in cases where **human errors** could be extremely costly;
- parts that may have several engineering changes, such as during the development stage of a prototype;
- small batch lots or short production runs.

Common Types of CNC Machine Tools

Some common types of CNC machines and instruments used in industry are the following:

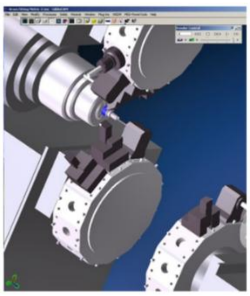
- Usually the **spindle** is mounted on a **stationary** and **extremely rigid base**.
- This rigid construction is ideal for **heavy cutting** and high material-removal rates.

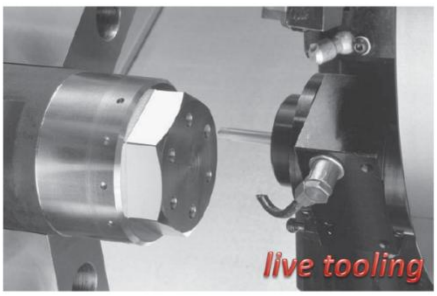


CNC Lathes/Turning Center ("Tornitrice")

CNC lathes have some unique advantages over their conventional counterparts:

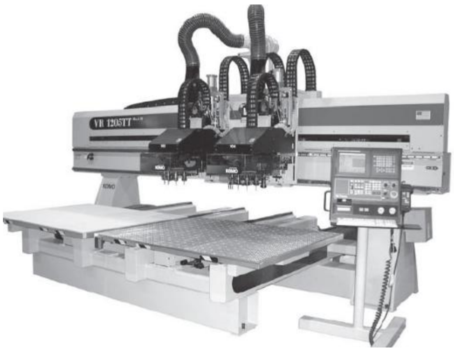
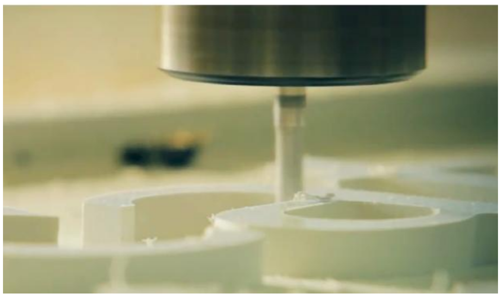
- They can **cut Circular Arcs**;
(that were impossible to cut by means of a conventional lathe without special tooling).
- CNC makes it easy to keep a **constant** surface speed **at the cutting edge as the diameter changes**.
- This leads to an **increased tool life** and consistent **surface finishes**.
- Many CNC turning centers **are also equipped** with some enhanced features to make them more productive:
    - One example is **Multiple Turrets**. CNC turning centers with multiple turrets **can perform two operations at the same time.**
    - Another productivity enhancement is live tooling. This so-called **Live Tooling** is in fact a small, **light-duty milling spindle mounted in the tool holder**.





Routers

- They tend to be **Light-Duty** machines that are fundamentally **very similar to a CNC vertical milling machine**, except that they are for **cutting soft materials at high speeds.**
- They are exceptionally good at cutting **wood, plastic,** and even **aluminum**.
- They are used for furniture and cabinet manufacturing, **model making,** and in the **aerospace industry for cutting shapes out of thin aluminum and composites**.

A2 CNC – Machine tools structure

Design of machine tool structure

The structure of a Conventional machines suffers from some limitations:

- Lack of stiffness;
- Backlash (it is any kind of unexpected play in an axis due to clearance or looseness of mechanical parts);
- Machine tool Resonance;
- Machine tool Chatter ("vibrations").

CNC machine tools should not be characterized by the above undesirable factors. As a matter of fact, the design of CNC machine structure must satisfy the following requirements:

- Geometrical accuracy of the structure has to be kept throughout the design and service;
- Deformation does not exceed the limits of load acting in a machine tool structure;
- Structure should ensure the Working Stress;
- The mating surface of the structure should be machined with a high degree of accuracy.

CNC machine tool structure

The machine tool structure includes the following parts:

- Bed
- Column
- Box type housing
- Carriages
- Tables

EXAMPLE: Horizontal milling machine ("fresatrice") (chain)

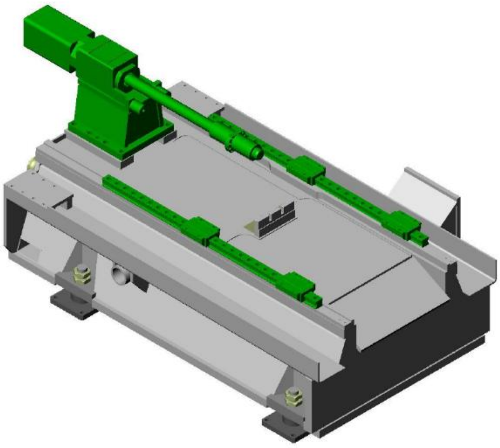
Motor (1) →

Support →

Guides (z) →

Basement →

Bolts →



3) Sled: it is connected to the motor and runs on the **guides in the direction z**;

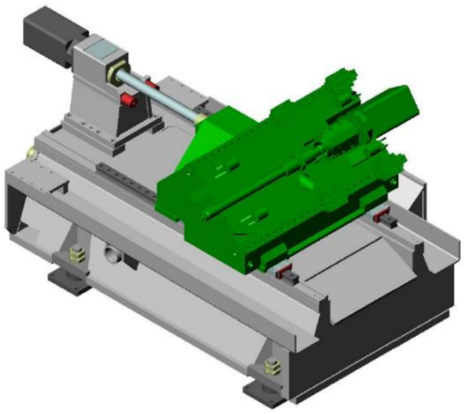
Motor (1) →

Support →

Guides (z) →

Basement →

Bolts →



← Sled

4) Upright ("montante") + Operating Head:

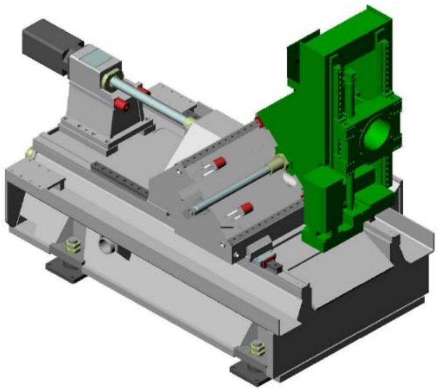
Motor (1) →

Support →

Guides (z) →

Basement →

Bolts →



← Sled

← Upright

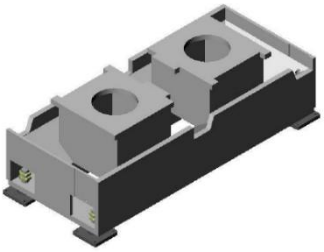
← Operating Head

← Motor (2)

- The Upright moves along the **direction x**;

7) Workpiece ("portapezzo") (Base for the piece):

Workpiece →

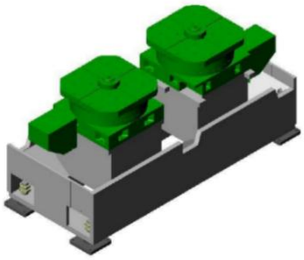


8) Rotary tables:

Workpiece →

Rotary tables →

Motor (3) →



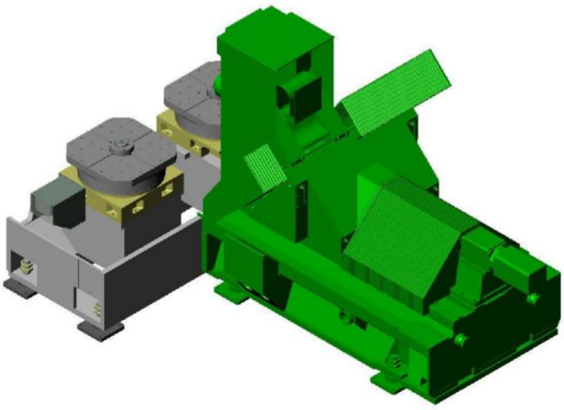
- There is a motor to exchange tables;

9) Complete structure:

Workpiece

Rotary tables

Motor (3)



Motor (1)
Support
Guides (z)
Basement
Bolts
Sled
Upright
Operating Head
Spindle/Mandrel
Motor (2)
External protections

10) Complete tool machine:

- materials, mass, installation.

Materials of machine tool structure

Gray Cast Iron:
- First material (widely used);
- Low cost;
- Good Damping Vibrations capacity;
- Good heat transfer;
- Too heavy for moving parts;

Welded Steel:
- Lighter than iron, high stiffness-to-weight ratio;
- Stability and rigidity;
- Low damping capacity;
- Design flexibility.

Polymer Concrete:
- Mixture of crushed concrete and plastic;
- Low stiffness; (same stiffness of Cast Iron);
- Good damping capacity;
- Poor thermal conductivity: PC does not diffuse heat as well as Cast Iron. Therefore, attention must be paid to the isolation of heat sources to prevent the formation of hot spots;

Ceramic Composites:
- Good strength, stiffness, corrosion resistance, wear resistance, thermal stability, surface finish;
- Used for spindles and bearings (silicon nitride).

Composites - Reinforced materials:
- Expensive;
- Used for high-accuracy, high speed machining applications.

Graphite - Epoxy Composites:
- Good castability;
- High stiffness-to-weight ratio;
- Good damping capacity;
- Thermal stability;
- Resistance to environment degradation.

Cast Iron machine tool structure

- Widely used in machine construction;
- Low cost for moderate sizes;
- Not stable -> not convenient time;
- Stable with thermal anneal, aging, or vibration stress relieve;
- Too heavy for moving parts;
- Good damping vibrations;
- Good heat transfer;
- Integral features can be cast in place;
- Design and manufacturing rules are well-established.

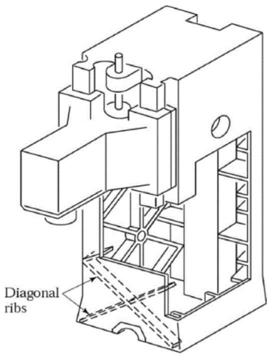
Welded Steel machine tool structure

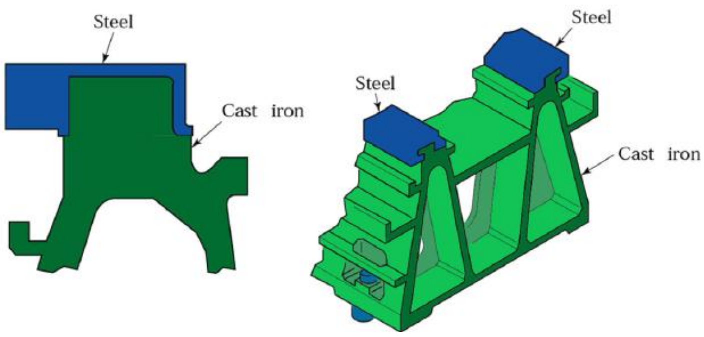
- (Often used for larger structures or small-lot sizes);
- Lighter than Cast Iron;
- Good rigidity and stability;

Static loads – Stiffness improvements

- An example of a machine-tool structure. The box-type, one-piece design with internal diagonal **Ribs**, significantly improves the stiffness of the machine. Or if we have a PC structure: **internal Foam Core**.

- **Steel Slideways integrally-cast on the top of the Cast-Iron bed** of a machining center. Because of its high elastic modulus, the steel provides higher stiffness than cast iron.





Thermal loads

The thermal deformation can be reduced in the following ways:

- designing all parts considering thermal stresses;
- large **heat removing surfaces** can be provided;
- the **motor**, gear **drives** and other drives can be **externally mounted**;
- excellent **Coolants** can be used;
- providing a proper **lubrication** system **to remove frictional heat** from bearings and slideways;
- providing an efficient scrap removal system for dissipating the heat generated in the machining processes;
- thermo-symmetric designing of machine structure;
- reducing ambient temperature by installing air **Conditioning units**;

Dynamics loads

Forced Vibrations (periodic):

- From vibrations transmitted from the environment;
    - shock and vibrations generated in presses, machine tools, internal-combustion engines, compressors, cranes, carts, rail and road vehicles, etc., are transmitted to other machines through the foundation;
- From parts of the machine tools;
    - rotating unbalanced masses;
    - gear, belt, bearing irregularities;
    - unbalanced electromagnetic forces in electric motors; pressure oscillations in hydraulic drives;
- From the variation in the cross-sectional area of the removed material;
    - due to the shape of the machined surface (e.g., in turning of a non-round or slotted part);
    - caused by the configuration of the tool (e.g., in milling and broaching when cutting tools have multiple cutting edges).

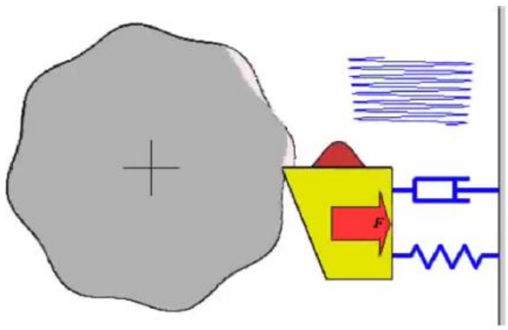
Self-Excited Vibrations (regenerative chatter):

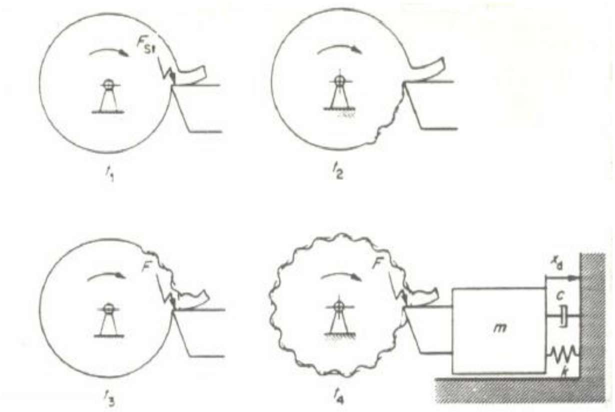
- From the interaction between the Cutting process and the Structure of the machine tool
- Begins with a disturbance in the cutting process;
- Interrupted cutting force from discontinues chips, serrated chips, material strength.

- Dynamics of machine tool system.

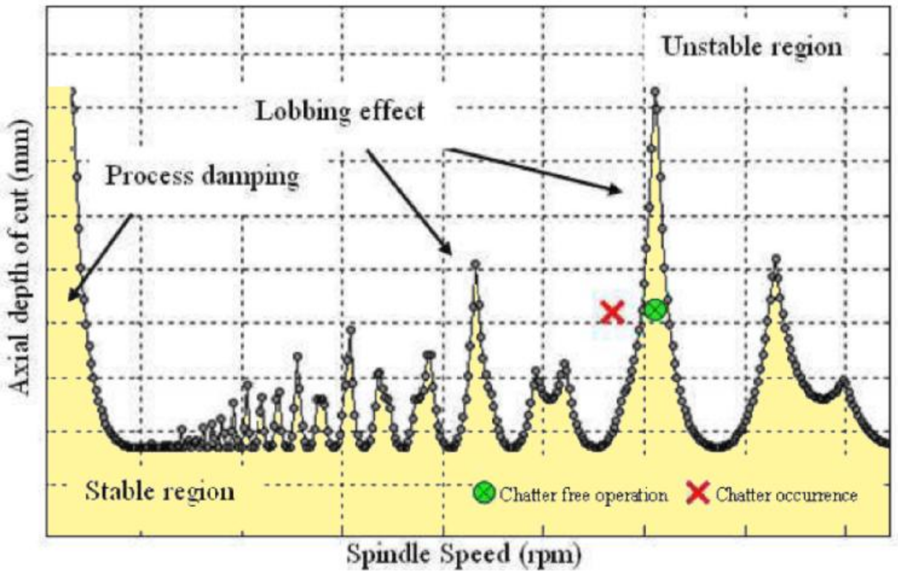
Dynamic loads – Regenerative chatter

Regenerative chatter is the most common form of self-excited vibration. It often occurs because the majority of metal cutting operations involve **overlapping cuts,** which can be a source of **vibrations amplification**. Due to the cutter vibrations, **a wavy surface** is left on the machined surface.
The force on the cutting tool varies due to the phase difference between the waving surface left in the previous revolution and the wave left by the actual one. **This phenomenon can greatly amplify** vibrations becoming dominant and building up chatter.





Machine-tool chatter is essentially a problem of dynamic stability. A machine tool under vibration-free cutting conditions may be regarded as a dynamical system in steady-state motion. **The border between** a **stable cut** (i.e. no chatter) and an **unstable cut** (i.e. with chatter) **can be visualized** in terms of the **Axial Depth of Cut** as a function of the spindle speed. This is a **Stability Lobes Diagram** (SLD).



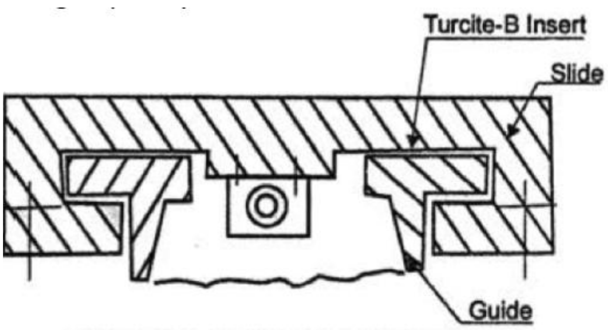
Using these diagrams it is possible to find the specific **combination of Machining Parameters**, which results in the maximum chatter-free material removal rate ("Utilizzando questi diagrammi è possibile trovare la combinazione specifica dei parametri di lavorazione, che si traduce nella massima velocità di rimozione del materiale senza vibrazioni."). The idea is to seek regions of stability within lobes taking advantage of the

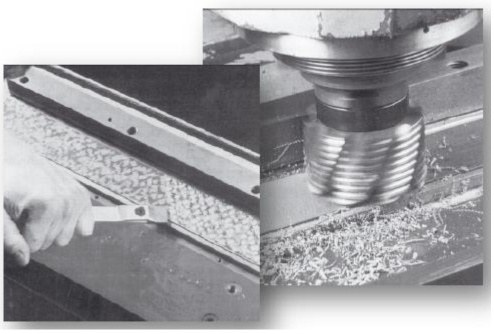
- Sliding Friction Slideways (or Plain Slideways)
- Anti-Friction Slideways: Linear Motion Bearings
    - Roller type;
    - Ball type;
- Pressurized Slideways: Hydrostatic Slideways

Sliding Friction Slideways

- The friction slideways have a **better Damping Capacity** than anti-friction and pressurized slideways.
- But there is a **tendency to stick-slip at low-feed rates**. Prevention of Stick-Slip ph.:

1. If friction slideway is coated with some **anti friction material**, then good damping with low friction can be obtained.
2. We can use **plastic or non-metallic Inserts** bonded to the underside of the sliding members. They can be either of thermoplastic or of thermosetting type. The **static coefficient of friction** for the coated slide ways **is less** than the **dynamic friction coefficient**. **With an increase in speed, the dynamic coefficient of friction increases to a value and remains constant.** This initial slope of the friction velocity curve is responsible for preventing stick-slip.
- The Inserts are made up of **two or more materials**, out of which one **reduce friction coefficient** and the other **increases wear resistance**, strength and load bearing capacity.



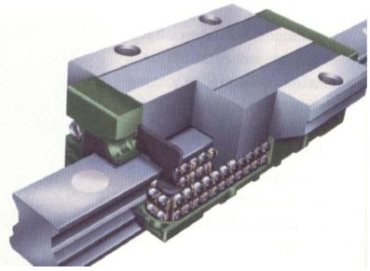


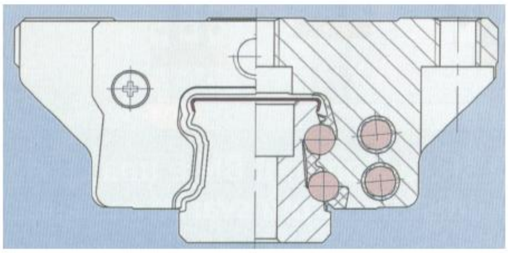
The used material are Turcite-B, Ferobestos-CA 3, SKC-3 and moglice.

Lubrication		Co-efficient of Friction		
		Turcite – B	Ferobestos/CA3	SKC – 3
Trace	Static	0.073	0.152	0.041
	Dynamic	0.068	0.1427	0.040
Flooded	Static	0.062	0.097	0.04
	Dynamic	0.059	0.082	0.031
Bearing pressure N/mm²		Upto 140	Upto 35	Upto 500
Minimum sliding-speed without stickslip mm/min		0.01	—	0.01
Wear co-efficient under clean lubrication condition		0.04	0.06	0.06
Engineering cost involved		Less	Less	High

- These materials are widely used in heavy-duty machine tools due to easy manufacture, less friction, good anti-scoring and anti-corrosive properties.
But they have the following **disadvantages**:

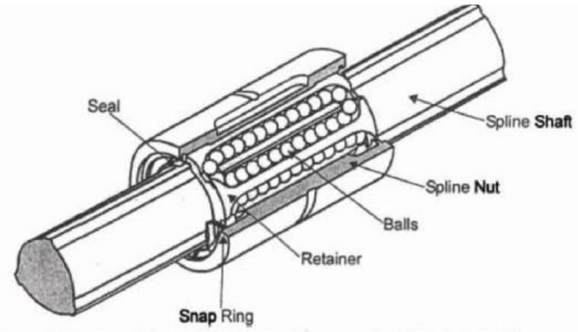
Another type of linear motion device is the use of a ball bush, where the balls are arranged in the track inside of a bush, which can slide along a ground rod to provide the linear motion similar to the round slide ways used in conventional machine tools.

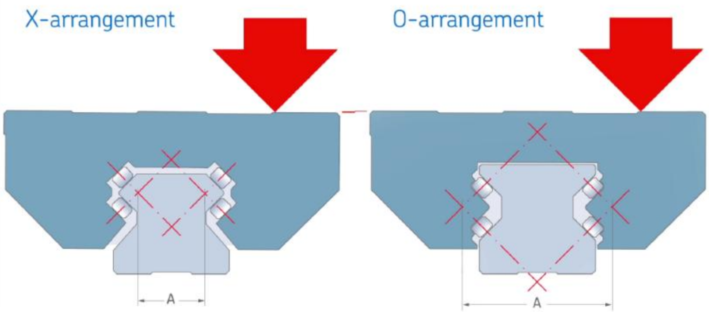




The rolling element provides the following advantages when applied to reciprocating motion:

- **Stick-slip problem is completely eliminated;**
- **Low damping capacity**: even though internal clearance is reduced to zero to absorb machine vibration and shock, the smooth motion is obtained;
- **reduced friction -> reduced drive power (needed):** with rolling element linear motion bearings, there is little difference between dynamic friction and static friction. This means that it is possible to reduce the drive power to be used and also makes the drive equipment more compact;
- **machine weight, overall costs and maintenance costs can be reduced;**
- lubrication of metal to metal contact slideways is different at low speed. So a high degree of wear results in conventional slides. But rolling element slide (linear motion system) requiring only a small quantity of lubricant shows little wear and last long.



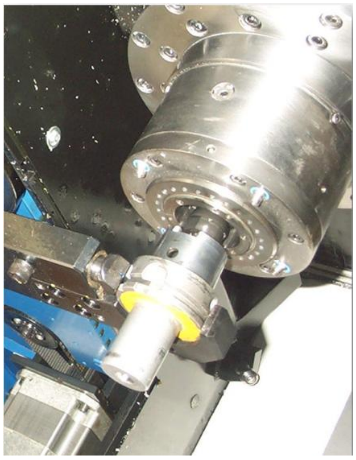


Hydrostatic Slideways

- Hydrostatic slideways use essentially the same principle of operation as a **Hovercraft**. **Oil** or **air is pumped into small cavities or pockets machined in the faces of the Carriage** which are in contact with the slideway of the machine.
- The pressure of the fluid gradually reduces to atmospheric as it seeps out from the pockets, through the gap between the contacting faces of the carriage and slideway.
- An almost **Frictionless condition exists** for the movement of the carriage.
- **One of the problems** with hydrostatic slideways is that surface area has to be a **relatively large** to provide adequate support.
- Machines may use pressure-balanced slideways where the pockets for the fluid are machined in all the faces of the carriage contacting the slideway.

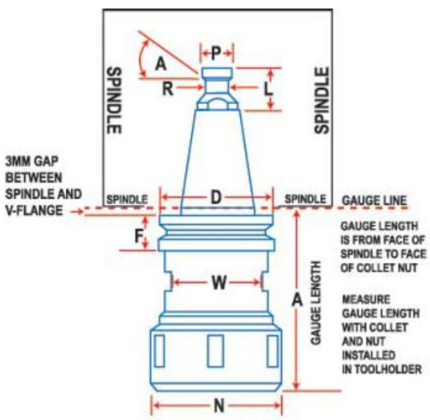
Main requirements of tools adapters for CNC machines are:

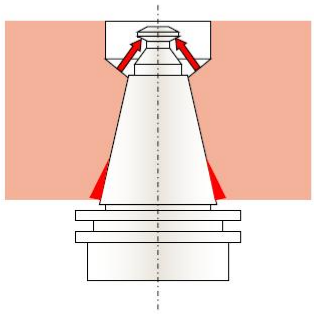
1. High speed of operation;
2. Running accuracy;
3. High static and dynamic stiffness;
4. Thermal stability;
5. Axial Load carrying capacity;
6. Axial Freedom for thermal expansion;



How the ISO (SK) Clamping System works

The ISO taper fits into the (electro) spindle and the clamping system grabs the *retention knol*. As the spindle gains the higher RPM, the taper of the electrospindle enlarges and the ISO tool holder gets pulled deeper into the spindle causing loss of Z-axis accuracy (with larger tooling).





- The Automatic Tool Changer (ATC) inserts the tool into the spindle (in some cases the spindle is descending over the tool). As the tool engages the spindle, a **Split Bushing** ("boccola") in the spindle will close on the tool **Retention Knob**. The split bushing holds the tool so that the tool changer can release its grip on the tool. The tool is then drawn completely up into the spindle and tightened.

accuracy and repeatability of the joint, both radially and axially, to 2.5 µm. At the end of the clamping cycle, the sleeve engages the coolant nozzle (6). The drive keys (7) and (8) transfer torque.

When the toolholder is clamped into the receiver, the drawbar force at first produces a firm metal-to-metal contact between the tapered shank and the inner diameter of the clamping unit. An additional application of drawbar force positively locks the two elements together into a joint with great radial and axial rigidity. During the clamping process, some of the clamping unit's energy will be spent compressing the shank taper to pull the shank deeper into the receiver. Depending on the amount of clearance, up to 20% of the axial clamping force may be needed to pull the toolholder in. The larger the clearance between the mating faces, the more energy will be needed to bring them together.

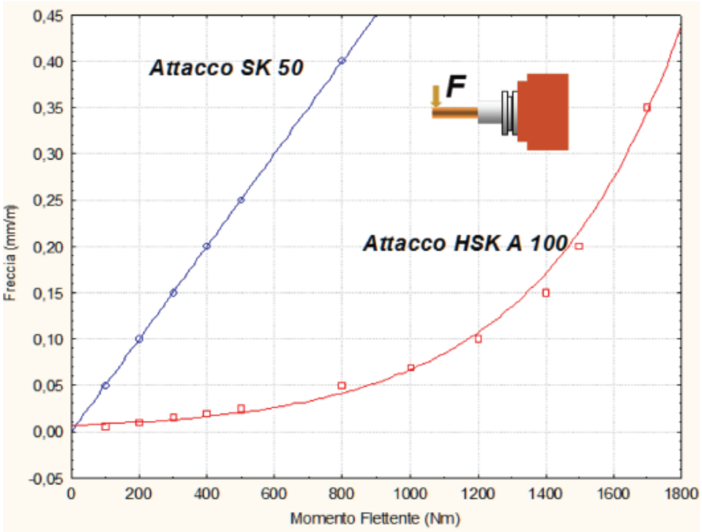
Centrifugal force also causes the relatively thin walls of the tapered shank to deflect radially at a faster rate than the wall of the spindle. This contributes to a secure connection by guaranteeing strong contact between the shank and the spindle. The changes that centrifugal force causes on the inside of the clamping mechanism won't affect the axial position of the cutting edge, because this is determined by the face-to-face contact between the flange and the receiver.

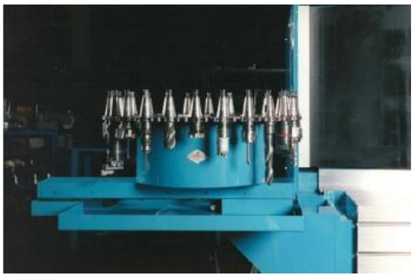
HSK vs. ISO (SK)

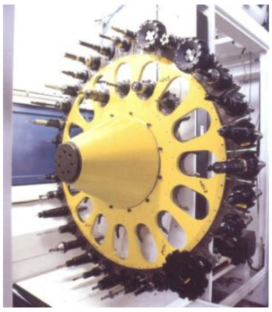
- The **HSK** electrospindle & tool holder arrangement offers the possibility of using **larger** (with greater diameters) and **heavier tools** and operating at **higher rotational speeds**.

- The **clamping quality**, which can be realized with the **HSK** system guarantees **maximum rigidity**. It is as if the HSK cone were an extension of the motor shaft. It eliminates any possibility of vibration caused by clamping irregularities. The **HSK** adapter is also **lighter** than the ISO holder causing less wear on the spindle over time.

- An HSK connection depends on a combination of axial clamping forces and taper-shank interference. All these forces are generated and controlled by the mating components' design parameters. Both the shank and the receiver must have precisely mating tapers and faces that are square to the taper's axis.

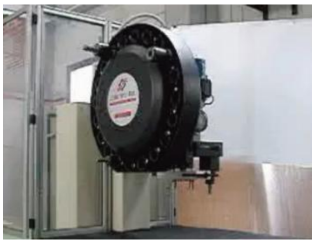






Drum type tool magazine

The drum rotates for indexing to bring the required tool. Tool change is carried out by a transfer arm and tool disengagement is performed by an axial movement of the tool adapter.
In the case of CNC lathes, the drum (cylindrical) type tool magazine will be more suitable for a very large storage requirement. In this case, the tool pockets are arranged on the surface of a cylinder along the length direction.



Chain type tool magazine

For storing a **large number of tools**, a chain type tool magazine provides the necessary flexibility. The tools are attached to the pockets which are in turn attached to the chain which is moving on appropriate sprockets. The chain allows for a very large variety of arrangements. The chain can be arranged to follow any path thereby increasing the capacity of the magazine. The capacity may be as small as 30 tools to and as high as 100.

Tool changing

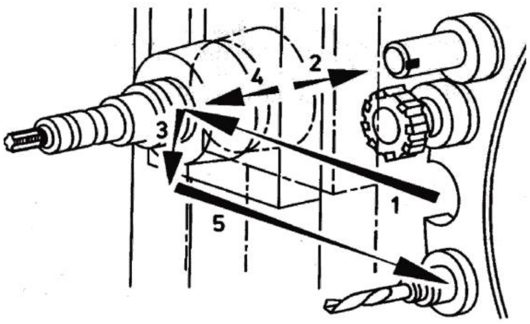
- *Tool changing*
  - *with tool change arm*
    - *Rotating around an axis*
      - *axis parallel to the spindle*
      - *axis tilted 45deg with respect to the spindle*
      - *tool parking position*
      - *transfer system*
      - *transfer system and tool parking position*
      - *special tool change arm*
    - *Rotating around two axes*
  - *without tool change arm (spindle direct)*
    - *tool axis normal to the spindle*
    - *tool axis parallel to the spindle*

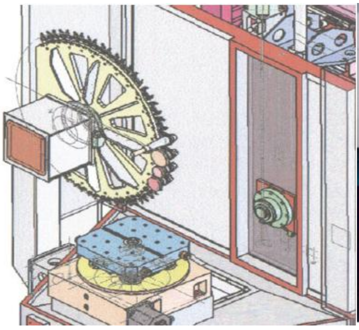
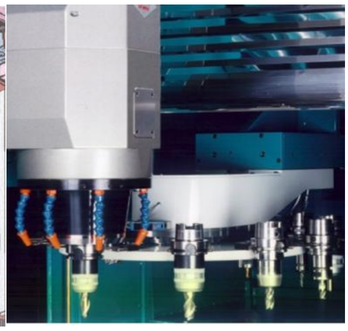
Spindle direct tool change

Without Tool Change Arm:

- Tool Axis **normal** to the spindle;
- Tool Axis **parallel** to the spindle.

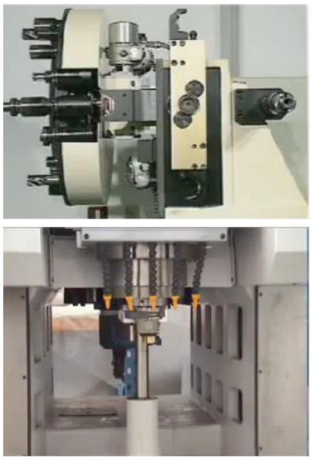
When a tool change is required, the spindle is directed to the tool change location. The tool carousel indexes to the required tool slot, moves out of its “parked” position to the tooling position, and engages the toolholder in the spindle. The drawbar is then removed from the toolholder, and the spindle moves upward, removing the tool. The carousel then indexes to align the required tool with the spindle, and the spindle moves downward, inserting the tool into it where the tool is secured. Finally, the carousel moves sideways away from the spindle, thus disengaging itself from the toolholder, and returns to its “parked” position. The tool change is now complete.



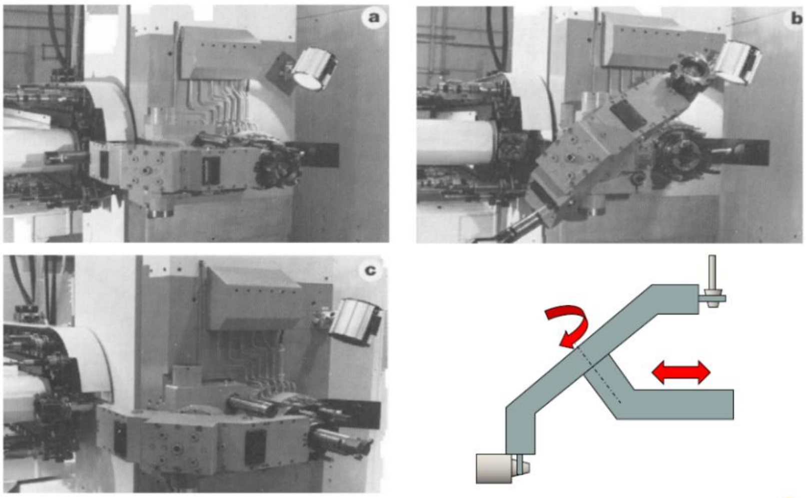
… Axis parallel to the spindle

Chain type tool magazine



Drum type tool magazine

… Axis tilted 45° with respect to the spindle



… Transfer system

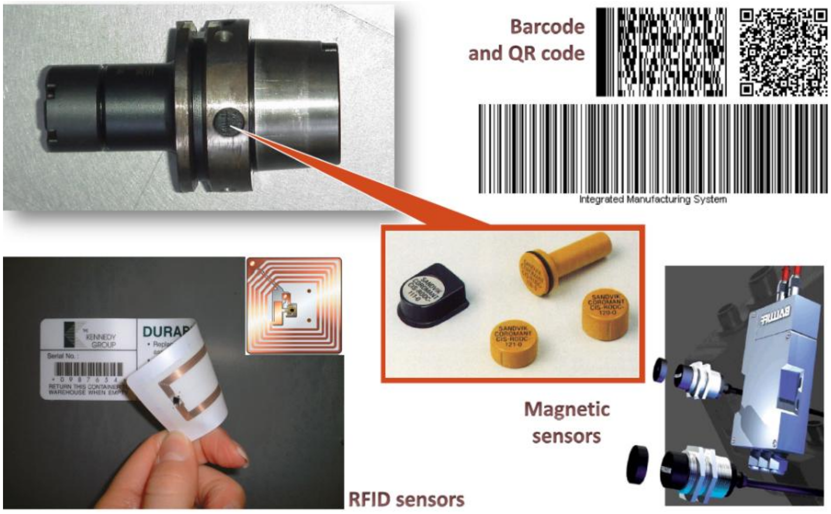
Random and fixed (sequential) tooling systems

Tool changers may be designed for either random or fixed tooling selection.

Random tool selection, the most common in CNC machining centers, is a system where there is no specific pattern of tool selection. Random tooling is generally widely used in industry because of the flexibility it offers compared to sequential tooling.
- Each tool is given a **specific tool identification** (**Magnetic sensors**) number and is **loaded into a specific pocket** in the tool magazine. As each tool is required for use in the CNC program, the previous tool is removed from the machine tool spindle by the tool changer arm and replaced in the correct tool-magazine pocket.
- The new tool, selected by the CNC program, is taken from the correct tool-magazine pocket and inserted into the machine spindle. Whenever a certain cutting tool, or one that has been used before, is needed for machining, the **MCU knows where to find it**.

Fixed (Sequential) tool selection is a system, used in older and less expensive CNC machining centers, where tools must be loaded in the sequence in which they will be used during the machining of a part. Therefore, it is important that the **correct sequence of tools** is programmed and loaded in the tool magazine as they are required to complete the machining operations on a part.
- If the cutting tools are not in the correct order, the next tool is automatically selected and the machine may try to tap a hole with an end mill. Therefore, when it is necessary to use a tool more than once, similar tools should be loaded in the tool magazine in the order that they are to be used.

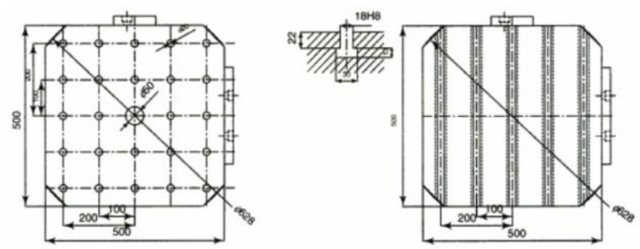
Tools identification (encoding)



Tools management: the tool Room

Automatic pallet changer (APC)

Manufacturers have developed a number of different pallet designs for machining centers. Each pallet can be loaded with the same part or with a different part, and machining on both pallets can perform the same operation or another operation, depending on the actual needs.



(a) Pallet with holes (b) Pallet with T-slots

Regardless of the specific design, the majority of pallets belong into one of **two general types**:

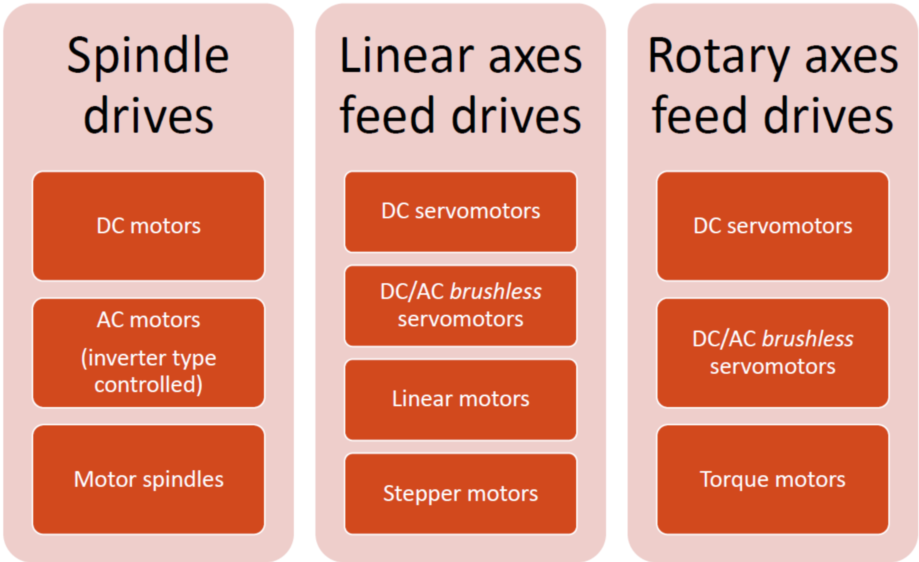
- Rotary type APC

- Shuttle type APC

The main differences between the two designs is the **method of transfer**: how the pallet table is loaded and unloaded.

A4 CNC – Drives, actuation systems and feedback devices

Driving Mechanism

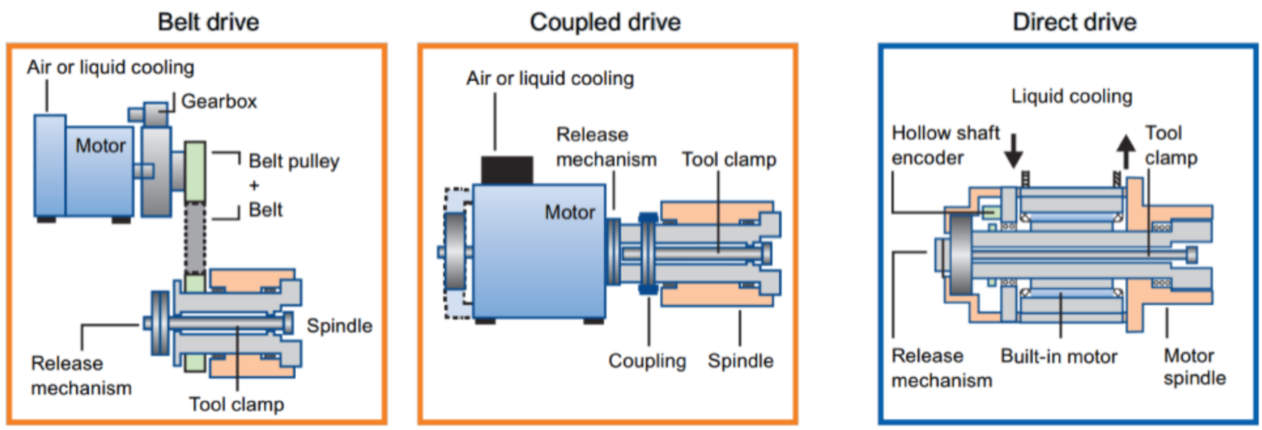


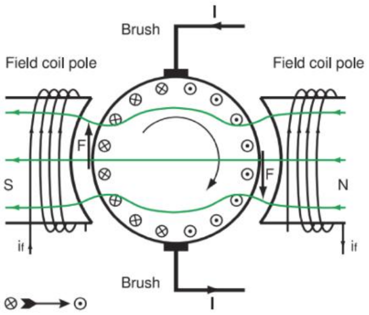
Driving Mechanism – Spindle

Conventional spindles are the most popular type of spindle in machine tools. They are modular in design, comprising the externally driven spindle unit with tool/workpiece holder and the motor for driving the spindle. There is a choice of two basic types. The motor and spindle are connected to one another either via a belt or via a coupling.

With the trend toward greater productivity and more compact machine design, the use of integrated motor spindle is becoming more and more commonplace. Their dynamic rigidity and low vibration tendency make a further leap in machining quality possible. Their ability to accelerate and operate at high speeds shortens the machining time, thereby increasing the productivity of the machine as a whole.

Conventional Spindles (most popular): - **Belt drive**;
- **Coupled drive**;
- **Direct drive** with integrated motor: Adv: Dynamic rigidity and low vibration tendency;

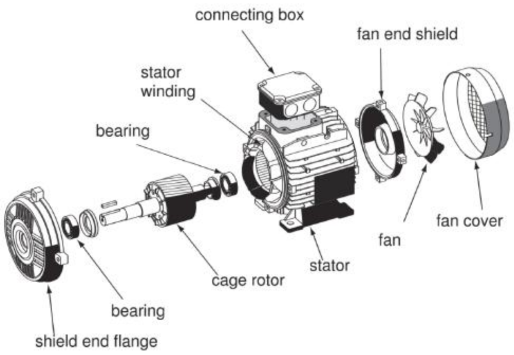




Spindle Drives – AC motors (inverter type)

3-phase asynchronous motor is the motor most usually used for spindle in CNC machine tools. These motors have a number of **advantages** that make them the obvious choice for many uses:

-The main advantage of the microprocessor-based frequency inverter is the possibility of using a spindle motor for C axis application **for speed control** in the range of 1:1,000,000 with positioning.
- AC motors are **more reliable** than DC motors under severe operating conditions including floating dust and coolant splash.
- Being **free of brushes** and other wearing part, AC motors do **not require frequent maintenance.**
- The unique stator cooling system in AC motors results in high speed and high output characteristics with a **compact size.**
- AC drive units provide stable and smooth operation with **reduced vibrations** and **noise** from low speed to high speed.



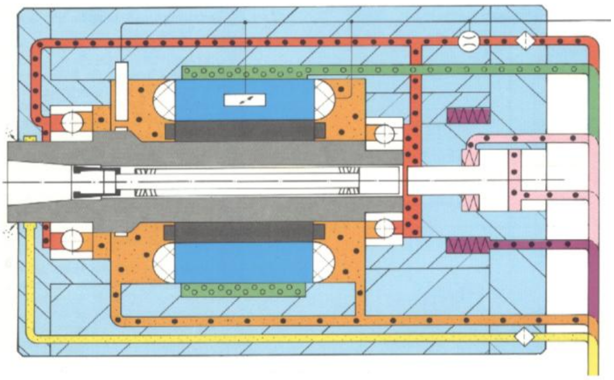
- With **speeds up to 20,000 rpm, power ratings from 2.8 to 300 kW** and different versions in terms of protection and cooling type as well as various bearing designs, AC motors are suitable for a wide range of spindle types.
- Integrated encoders maintain constant speed and allow the spindles to be positioned, for example on automatic tool changing.
- Benefits and characteristics:
    - Compact motors;
    - **High acceleration capability;**
    - Wide torque spectrum.

The figure shows typical speed – power/torque characteristics of an AC motor. It can be noted that the constant power region covers a range of 3 : 1

Motor spindles can be designed and made available with a **power range** of up to 130 kW and up to **1,250 Nm without gear, or up to 3,280 Nm with integrated gear.**

Benefits and characteristics:

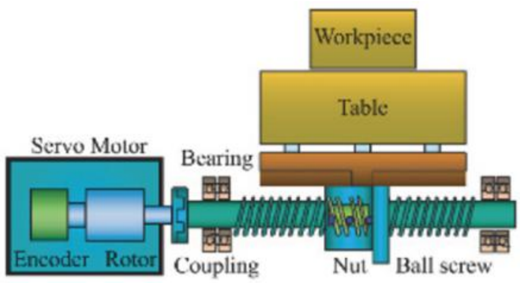
- Excellent quality of **surface finish**, maximum **concentricity** and **high dynamic rigidity**;
- **Short acceleration times** and high **maximum speeds**;
- **Compact design**;
- Flexible adaptation to user requirements thanks **to various tool and workpiece clamping systems**;
- **Easy installation** and commissioning due to self-contained system unit;
- Easy installation with defined interfaces for mechanics, cooling, electrics and hydraulics/pneumatics.



Driving Mechanism – Axis

- The **(Servo) Driving Mechanism** of machine tools is the **system that transforms the commands from NC to machine movements.**
- It consists in a **Servo Motor** and a **Power Transmission Device**.
- The command from NC makes the **Servo Motor** rotate;
- the rotation of the servo motor is transmitted to a **ballscrew** via a coupling,
- the rotation of the ballscrew is transformed into linear movement of a **Nut**, through which,
- finally the **table** with the workpiece moves linearly.

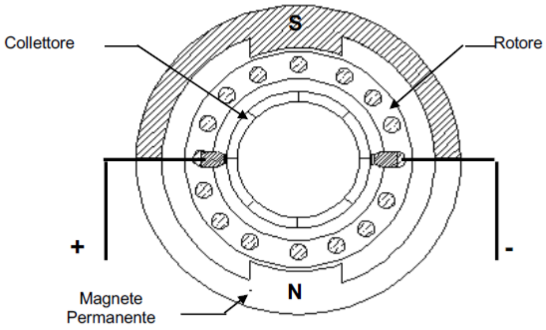
The servo driving mechanism controls the velocity and the torque of the table via the servo driving device of each axis based on the velocity commands from the machine control unit.

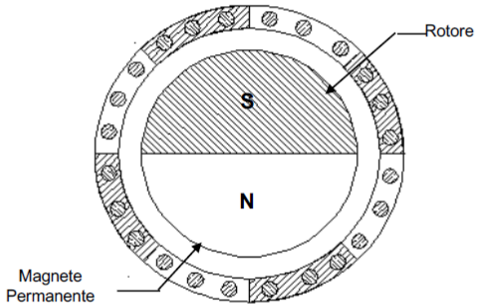


Feed drives requirements

- The **required constant torque** for overcoming frictional and working forces must be provided.
- The **drive speed** should be infinitely variable with **speed range of at least 1: 20,000** which means that both at a maximum speed, let's say of 2,000 rpm and at a minimum speed, let's say of 0.1 rpm. The feed motor must run smoothly without noiseable waviness.

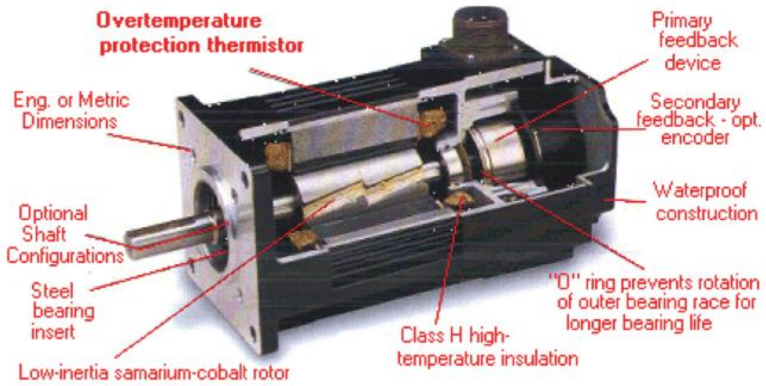
located on the rotor, require that the flux created by the current carrying conductors in the stator rotates around the inside of the stator in order to achieve motor action.





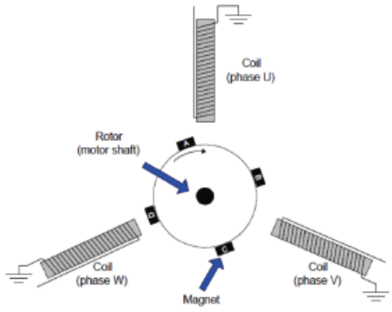
Feed drives – DC Brushless servomotors

- The stator windings are interconnected so that the introduction of a three phase excitation voltage to the three stator windings produces a rotating magnetic field. This construction speeds beat dissipation and reduces rotor inertia. The **permanent magnet poles** on the **rotor** are attracted to the **rotating poles of the opposite magnetic polarity in the stator creating torque**.
- **The magnetic field in the stator** rotates at a speed proportional to the frequency of the applied voltage and to the number of poles.
- In the brushless motor, the flux of the current carrying winding rotates with respect to the stator; but, like the DC motor, the current carrying flux stays in position with respect to the field flux that rotates with the rotor.

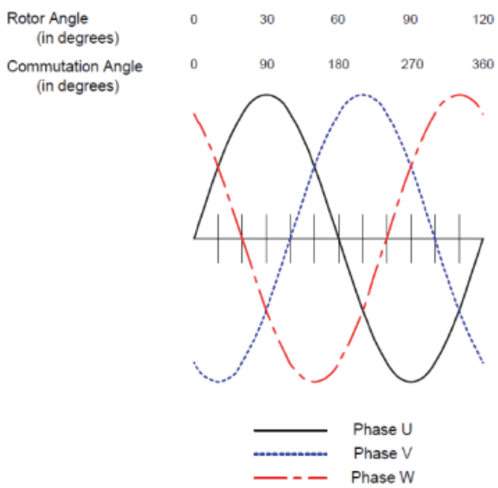


- The major difference is that **the brushless motor maintains its position** by **electrical commutation**, rather than by mechanical commutation.
- The commutation function may be performed by various shaft position sensors: optical encoder, magnetic encoder (resolver, synchro, etc), or Hall effect magnetic sensors.

- Three coils are mounted 120 degrees apart. When current is applied to a coil it will attract the nearest rotor magnet. If current is applied to the phase U coil, the rotor will turn clockwise until magnet A is aligned with the coil (at a detent). This simple brushless motor is similar to how a stepper motor operates, turning on one coil will cause the shaft to rotate by one magnet pole.



- When using sinusoidal commutation to drive a three-phase brushless AC motor, **different current levels** are applied to each of the three coils. **The current levels are phase shifted by 120 degrees** (as are the motor coils).



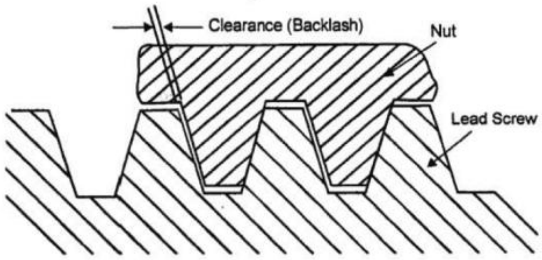
- The **velocity** of a brushless AC motor **is controlled by the amplitude** (peak to peak voltage level) **of the sine output**. The greater the amplitude of the sine waves, the more current flows through the coils, the greater the torque (velocity) of the motor. The phase relationship of the sine signals does not change with velocity.

Feed drives – Stepper motors

- A stepper motor rotates (steps) in **fixed angular increments**. Step size or **step angle** is determined by the **construction of the motor** and the **type of drive scheme** used to control it.
- A **typical step revolution is 1.8 degrees (200 steps per rev)**. However, micro step motors are capable of 0.0144-degrees (25,000 steps per rev).
- Stepper motors are usually used in open loop control systems even though an encoder may be used to confirm positional accuracy.
- There are many types of step-motor construction. However, **permanent magnet (PM**) are the most common type.
- The permanent magnet step motor **moves in steps** when its **windings** are sequentially energized. Two rotor sections (N and S) are offset by one half tooth pitch to each other. As energy is switched from Phase 2 to Phase 1, a set of rotor magnets will align with Phase 1 and the rotor will turn one step. If both phases are energized simultaneously, the rotor will establish its equilibrium midway between steps. Thus, the motor is said to be half-stepping.

Ballscrews

- The rotary motion from the **Drive Motor** needs to be converted to the **linear motion** to move the various **axes** of the machine tool.
- In conventional machine tools the **square (ACME) thread** is normally used for this purpose.
- However, in view of the metal to metal and **sliding contact between the nut and the screw**, the **friction** is very high. This results in **greater power** being utilized for the movement of the axes.



Type	Efficiency (%)		
	High	Medium	Low
Recirculating Ball screw - nut	95	90	85
Acme with metal nut *	55	40	35

-In the case of a **lead screw** with **ACME nut** ("dado"), if any attempt is made to reduce the backlash, the friction increases. Hence most of the CNC machine tools use a **lead screw** with a **re-circulating ball nut**.
Ballscrew:
- In the case of re-circulating ballscrews, the **nut is replaced by a series of balls** which circulate in the **channel in the forms of threads**.
- This results in a **highly efficient rolling motion of balls** in the space between the screw shafts and the nut.
- The balls at the end of the **thread portion** in the nut will be **repositioned back** into the beginning of the thread form by a **deflector**.

When compared with conventional trapezoidal screws, the ball screws provide many **advantages**:

- **low coefficient of friction**: it is of the order of **0.004** as compared to 0.1 to 0.5 which is typical of sliding friction power screws. **Wear is therefore less** and there is **very little need for frequent adjustment**;
- in a ball screw, the load between the threads of the screw and the nut is not transmitted by direct method contact but through intermediate rolling members (spherical balls). The balls rotate between the helical grooves of the screw and the nut in a manner akin to their function in ball bearings. An essential feature of almost all ball screws is the provision of recirculation of balls;
- **by preloading the assembly**, clearance and consequent **backlash** can be eliminated and the **axial stiffness** of the ball screw can be increased. It should be noted that the axial stiffness of an ordinary power screw and the accuracy of ball screws also high;
- friction force is virtually independent of the travel velocity and the friction at rest is very small consequently. The **stick slip phenomenon is absent** ensuring uniformity of motion.
- high transmission efficiency (2-9 times) which is particularly marked at low values of helix angle of screw (2° - 5°) that are typical for power screws. This high efficiency allows larger thrust loads to be carried with less torque.

- fixing plate

The steel balls make **only one revolution** around the screw shaft. The circuit is closed by **a ball return cap** in the nut allowing the balls to cross over adjacent ball tracks.
Since the **ball return caps are located inside the nut body**, this is called the internal recirculation type ballscrew.
The size of the nut, being as internal return of the balls, is **small** as compared to the external return type using an external return tube.

Advantages of Ballscrews

Advantages of recirculating ball screws in comparison to the conventional types of screws:

- the **stick slip phenomenon is absent** ensuring uniformity of motion;
- **low coefficient of friction** (order of **0.004**);
- **low wear**:
-> they have **longer life**;
-> they maintain their **accuracy** during entire life;
-> smaller required **power**: higher permitted velocity for carrying heavier loads;
- **by preloading the assembly**, **backlash** can be eliminated and the **axial stiffness** can be increased.

Preload of Ballscrews

Preload does:

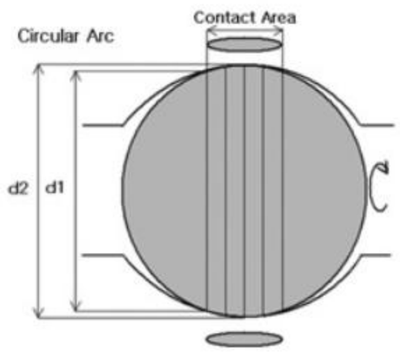
- eliminate **backlash**,
- adds **stiffness**,
- keeps the **nut centered on the screw**.

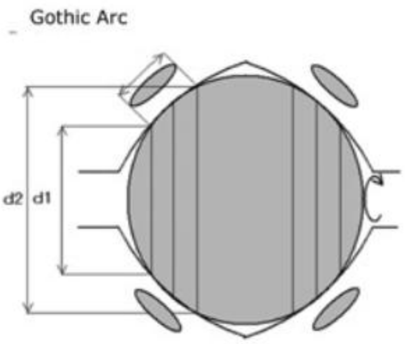
There are two ways to achieve preload:

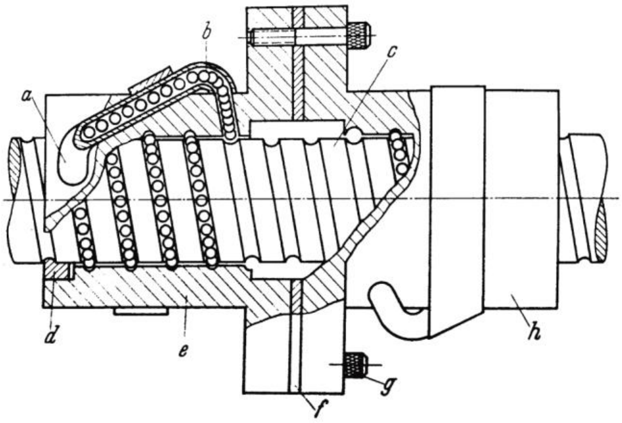
- the **nut** can be **permanently forced** in one direction;
- preload can also come from using **oversized balls**.

Regardless of what generates the preload force, the **number of contact points** of each ball determines how the balls **move** and transmit **loads** from nut to screw, and vice versa. Therefore, all nuts:

- with a four-point contact are "**single nuts**,"
- with a two-point contact are "**double nuts**".

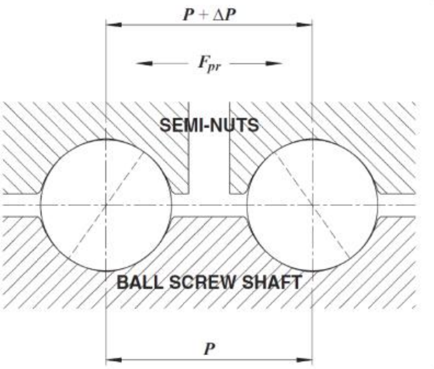


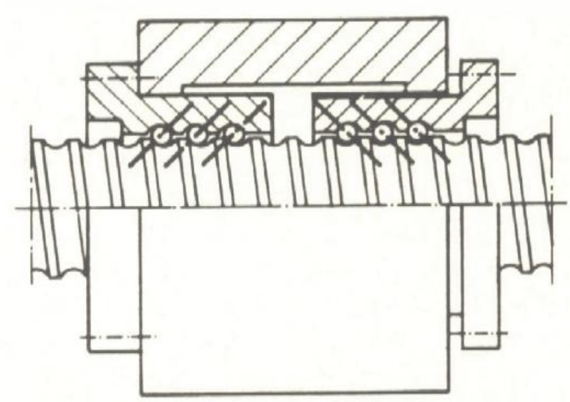




In case of ball screws with **double preloaded nut - traction preload**, the contact points have "**O configuration**". The preload force tries to make **two semi-nuts more distant** and pulls the part of threaded shaft between them.

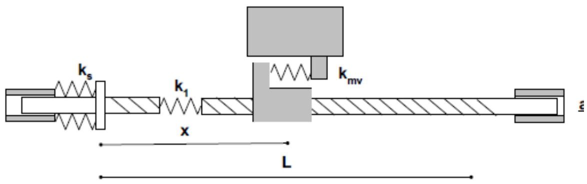
This solution is applied to preloaded nuts with flange or cylindrical, where the preloading force is obtained by **interposing a** spacer ring with calibrated thickness between the two semi-nuts. The actual preload force depends on the **distance Δ**" so this distance **must be determined very carefully**, in order to avoid **overloading or overheating** of ball screw, with consequent reduction of its performances and **life**.





Overall system stiffness considers not only **nut stiffness** but also that of the **ballscrew shaft** and **support bearing** is:

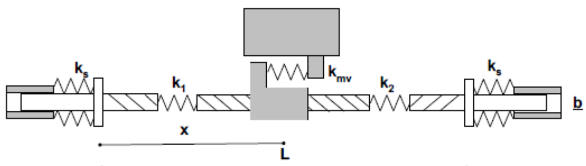
$$\frac{1}{K_{tot}} = \frac{1}{K_S} + \frac{1}{K_1} + \frac{1}{K_{mv}}$$



When the shaft is simply supported:

$$\frac{1}{K_{tot}} = \frac{1}{2 \cdot K_S} + \frac{1}{K_1 + K_2} + \frac{1}{K_{mv}}$$

with bearings on both shaft ends.



Shaft stiffness ($K_{1,2}$) keys to Young's modulus of the material, shaft cross section and length, and of course to the support arrangement. **Nut stiffness (K_{mv})** is a function of preloaded condition, number of balls and diameter, thread-profile geometry, and nut type.

The greatest difference between the two motors is that in a rotary motor the output is a turning motion of a shaft, as opposed to a sliding (forward and back) linear movement in a linear motor.

To convert the rotary output of a rotary motor to the linear motion necessary for machining operations, a ballscrew and nut mechanism is used. However, the magnetic field of the linear motor produces a linear motion directly **without mechanical linkages**.

Machine tool builders have been using linear motor technology for more **than 15 years**. Machines equipped with linear motors may **not be suitable for every job**, but where they are used, no other machine can match its **acceleration and deceleration speed**. Linear motor advantages become most apparent where there is a **need for rapid and precise positioning of parts for machining**, making them highly suitable for drive systems in high-speed CNC machine tools.

The linear motor drives are **much simpler**: there is no need for lead screws, and couplings to convert rotary motion to linear motion as this is done directly by the motor drive.

As a result, the motor can provide accurately **controlled speeds** (within 0.01 %) **from 1 μm/s to 6 m/s**. Rapid acceleration and deceleration of up to **10 G**, may also be achieved by settling times of less than 20 milliseconds (jerk - the rate of change of acceleration), which, when combined with the linear motor's accurate, repeatable positioning capability, permits much higher positioning and machining speeds than is possible with rotary motors.

The simplicity of the linear motor, which consists in two rigid, **non-contacting parts** (slider and permanent magnet) supported by a linear bearing, results in the **elimination of most of the checks and adjustment** required for the rotary motor. The electronic control system may be designed to automatically adjust for the small amount of wear that will occur.

Types of Linear Motor:

- Linear type;
- Tubular type.

Linear motors – Flat-bed type

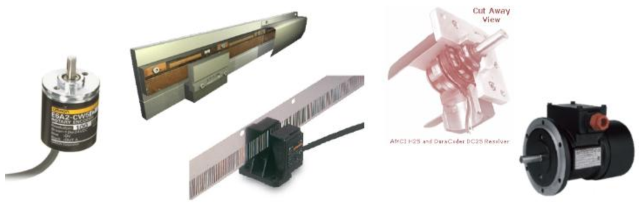
kg of loading wear. In order to compensate for this phenomenon, the structural design features of the machine will add to the overall cost of the machine.
The linear motor **positions** the workpiece so that it can be machined by the cutting tools mounted in the spindles:
- To take full advantage of the increased workpiece positioning speed offered by the linear motor, the cutting tools will be required to rotate more rapidly.
- Spindle rotation speeds will have to increase from the present maximum of approximately 20,000 rpm to 40,000 to 50,000 rpm.

In general, as the design features required to utilize linear motors in machine tools become commonplace, the cost factor will reduce and linear motors will replace rotary motors in most machining applications.
The application actually determines whether or not a linear motor is right for the job. These machines really excel when it comes to **high-speed cutting of aluminum.**
- When ferrous metals are being machined, linear motors really may not be as advantageous as for nonferrous materials. The density of steel does not allow for the high-speed penetration rates that linear motors can produce. So the motor's maximum speed does not give advantages.
- Rough milling of iron and steel (ferrous metals) may not be the best application for machine tools equipped with linear motors. When machining ferrous materials, light cuts may be necessary.
- Linear motor machine **tools cost 10% to 30% more** than a ballscrew machine and **power consumption is higher**, **but** linear motor machines can provide **double the productivity** than ballscrew machines. Machines with linear motors are about **five times more cost effective** than machines with ballscrews.
- Costs should be reduced as more machine tool manufacturers build and use linear motors. However it would be quite expensive to install a linear motor on an existing machine tool and expect it to work. Design changes to the machine structure, spindles, etc. are necessary.
- High performance machine tools require structures specifically designed to optimize the use of linear motors (elements that move, such as columns and slides, must be as light as possible, yet stiff at the same time. Machine bases must be designed for minimum deflection under static and dynamic loading.)

Advantages/Disadvantages of linear motors (Summary)

Advantages:

- The linear motor drives are **much simpler;**
- (**Increased accuracies)**
- Controlled speeds (within 0.01 %) **from 1 µm/s to 6 m/s**.
- Rapid acceleration and deceleration of up to **10 G.**
- Linear motors provide **regular movement** because **no sliding parts contact** each other, **eliminating friction, wear, and backlash + elimination of most of the checks and adjustment.**
- **Long axis travel is not a problem** since linear **motor magnets** can be **joined together** to make any length of motor.
- Linear motors can run approximately **50,000 hours compared to 8,000 hours** for a rotary motor with a ballscrew.
- Increased motor life **reduces the amount of required maintenance.**
Disadvantages:



Analog/Digital – Absolute/Incremental

- Analog. The output is continuous and proportional to the physical quantity being measured. An example of an analog sensor is a **tachometer**.
- **Digital**. The signal is a **complex waveform** and can be defined as a discrete waveform having a finite set of levels. An example of a digital sensor is an **encoder**.

- **Absolute**. The output is always relative to a fixed reference, regardless of the initial conditions (e.g. where the sensing element was when the power was first turned on). An example is a **common ruler with numbers on the markings** representing the distance of each marking from the endpoint.
- **Incremental**. The output is a series of binary pulses, where each pulse represents a change in the physical quantity by one **resolution unit** of the sensor. The measured quantity is only known by counting pulses with respect to an initial state that must be defined when the measurement first begins (e.g. when the power is turned on). An example would be a **ruler without numbers on the markings.**

Direct/Indirect Measurement

- **Direct measurement** involves the measurement of the position of the slide directly by fitting **a linear transducer** to the slide. Direct measurement is preferred for a more accurate positioning.
- **Indirect measurement** involves the measurement of the position of the slide by fitting a **rotary transducer** to the ballscrew of the slide or mounting the transducer on the servomotor shaft.

Apart from these solutions, nowadays, CNC machines are designed with the feedback device mounted on the rear side of the servomotor. Any backlash, in the ball screw and the nut, and the pitch error in the lead screw can be compensated in the software.

The indirect feedback is more economical and adequate for most of the CNC machine tools particularly when the used ballscrew is of a high class of accuracy.

Classification of feedback devices

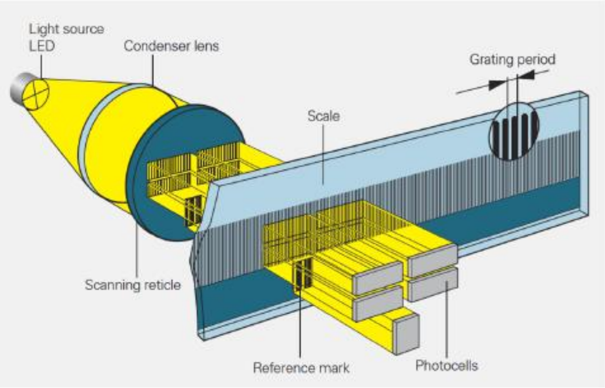
The most widespread **position feedback devices** can be classified into **two major groups**. They are:

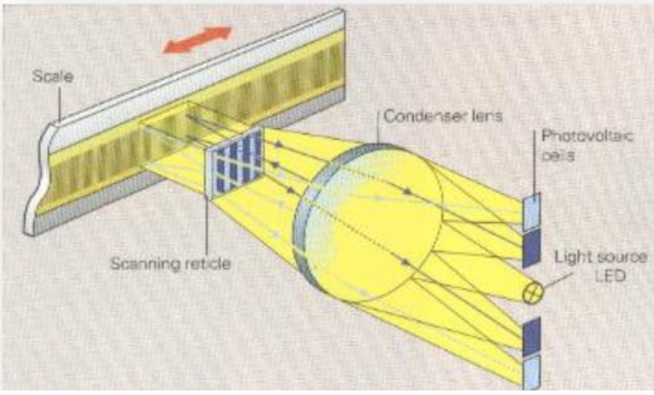
- Digital incremental/absolute type measuring systems.
    - **Optical encoder** (linear or rotary)
- Analog type measuring devices.
    - **Inductosyn** (linear or rotary)
    - **Resolver** (rotary)

While the most used **velocity feedback device** is the **tachometer**.

Optical encoders

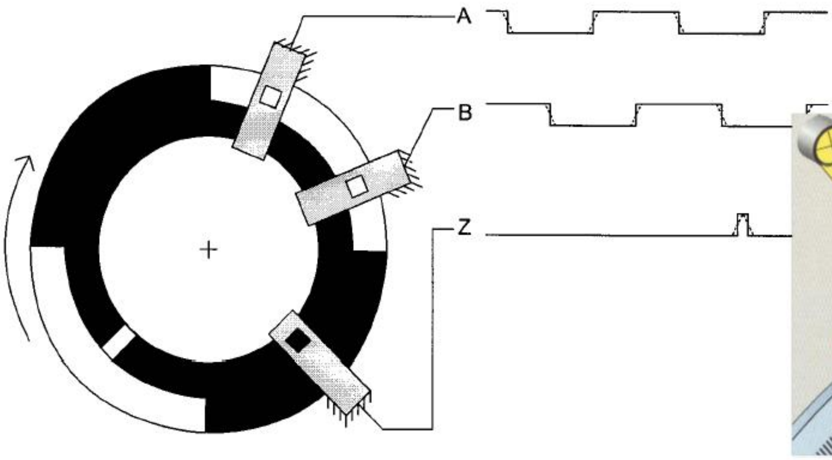
Optical encoders are used to measure either **angular or linear positions**. Those used for angular detection are commonly named rotary or shaft encoders, since they usually detect the rotation of a shaft. Optical incorporate any masking element.

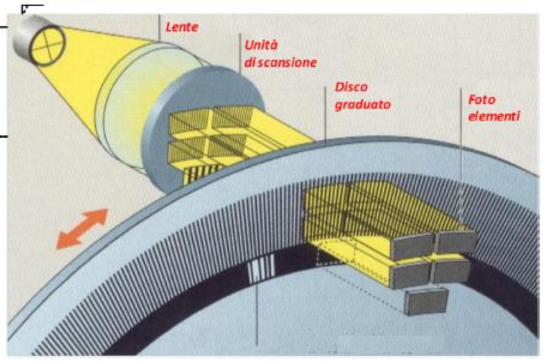




Incremental Encoders

The figures illustrate the concept of an **incremental rotary optical encoder**. The shaft-mounted disk has a series of alternating dark and light sectors of equal length and in equal number. The dark and light code is detected by a stationary mask with two apertures, A and B, *displaced one quarter of a cycle from each other*. When a light sector covers a window, a 1 signal is produced, and a 0 results from a dark sector. At a transition, a rising or falling signal occurs.





These signals require some pre-treatment to square them and avoid problems associated with slow movement at the transition positions, resulting in slow rise time and fall time, in the presence of low noise.

The resulting cleaned A and B signals are two square waves 90° out of phase and are called quadrature signals. Since the A and B signals have only four possible states, they clearly do not provide a means of distinguishing more than four different locations. As a result, absolute position discrimination is only possible within one quadrature cycle.

Instead, the quadrature signals are used to increment or decrement a counter that gives the actual position. The counter is initialized (usually reset) on a *z*phase signal produced on a separate track: the innermost track.

corresponding to the reading head position in figure is

$1 \times 2^0 + 1 \times 2^1 + 1 \times 2^2 + 0 \times 2^3 = 7$

The code configuration just described is not suitable for practical use because some transitions require that two or more bit values change simultaneously. For example, from position 7 to position 8, all bits change values. Unless the change is simultaneous, an incorrect position readout results at some position.

This would require that the scale is geometrically perfect, that the read head is perfectly aligned with the scale, and that the electronics are perfectly adjusted and stable over time. This problem is solved by either the use of a *vee-scan detection* method or the use of a unit-distance code such as the *Gray code*.

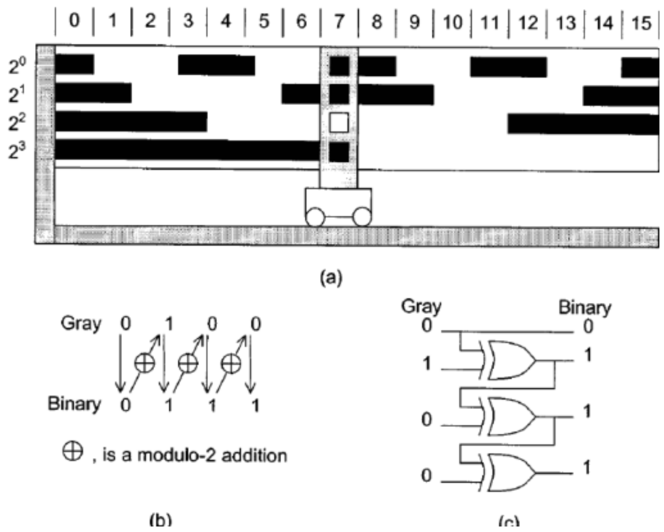
Absolute Encoders – Gray Code

The Gray code is a unit-distance code and so only one bit of data changes between representations of two consecutive numbers or successive positions. This removes the possibility of ambiguous readout. It has the following advantages: (1) it is easily converted to direct binary code, and (2) the finest tracks are twice the width of equivalent direct binary code tracks.

Figure (b) shows a scheme for the conversion from Gray code to binary code and proceeds as follows:

1. the most significant bit (msb) of the binary code equals the msb of the Gray-coded number;
2. add (modulo-2) the msb of the binary number to the next significant bit of the Gray-coded number to obtain the next binary bit;
3. repeat step 2 until all bits of the Gray-coded number have been added modulo-2.

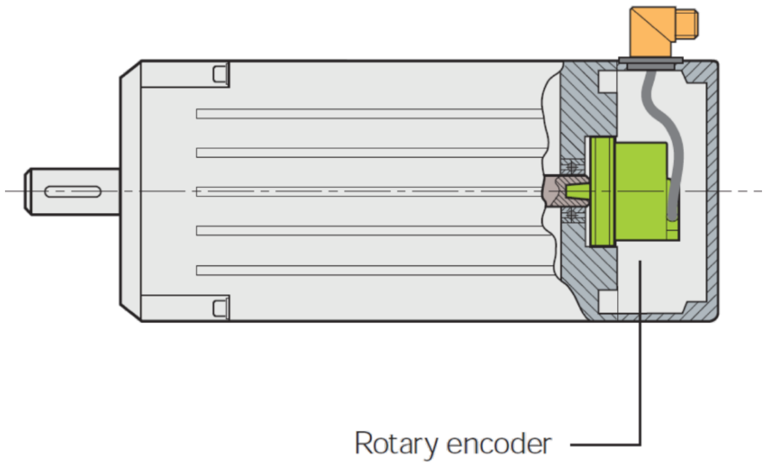
The resultant number is the binary equivalent of the Gray-coded number.
The modulo-2 addition is equivalent to the action of an exclusive-OR. The figure shows a simple circuit using combinational logic to perform Gray to binary conversion.



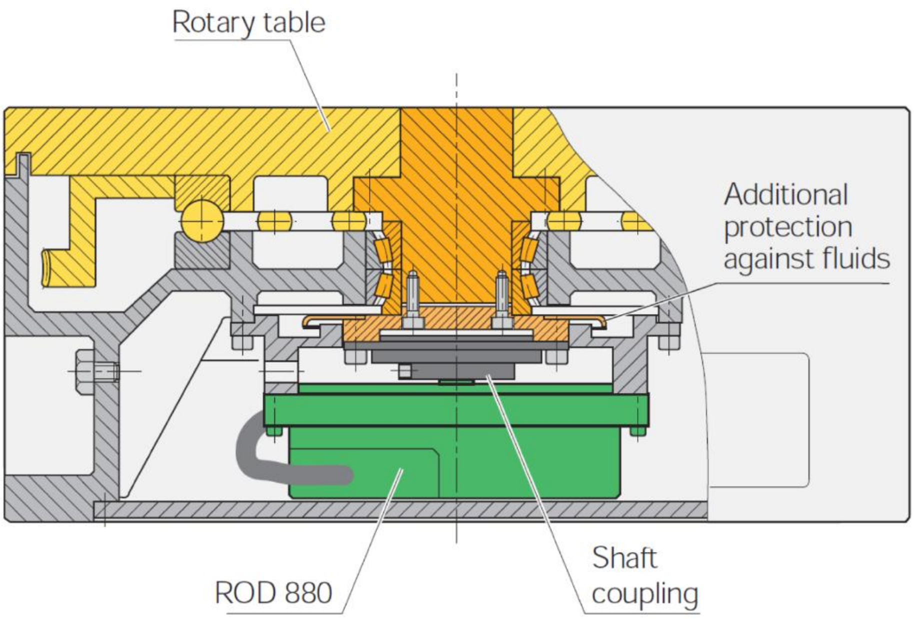
Optical Encoders – Considerations

The choice of an encoder demands careful consideration of a number of factors, such as:

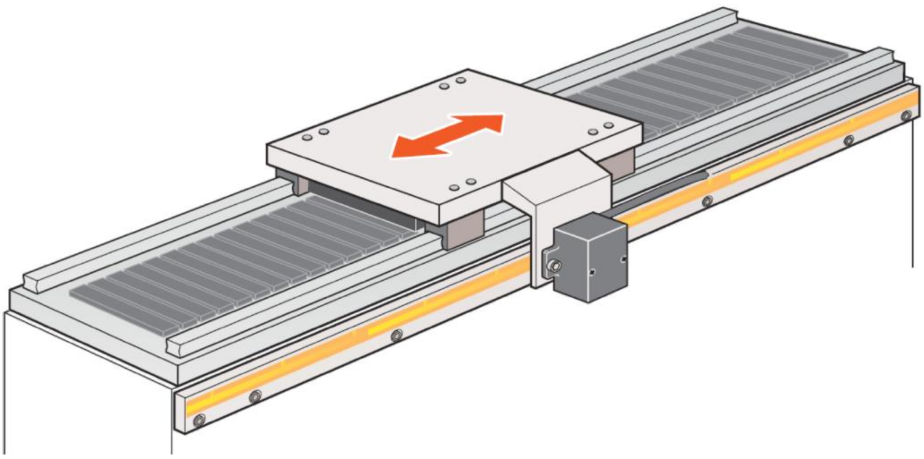
- the required resolution, repeatability, and accuracy (linearity);
- the maximum and minimum operating speeds;
- the environmental conditions: temperature range, relative humidity (condensing or not condensing), contaminants such as dust, water, oil, etc.;
- minimum friction torque (or force) acceptable;
- maximum inertia acceptable;
- available space;



- Angle encoder mounted on the rotary table:



- Linear encoder mounted for linear motors drive system:



A5 CNC – Machine control unit

Classification of (C)NC systems

The numerical control systems can be classified according to:

- the **structure of the controller**: NC or CNC;
- the **type of control loop**: open-loop or closed-loop; (methods to activate the servo drives)
- the **mode of the control**: point-to-point versus continuous path.

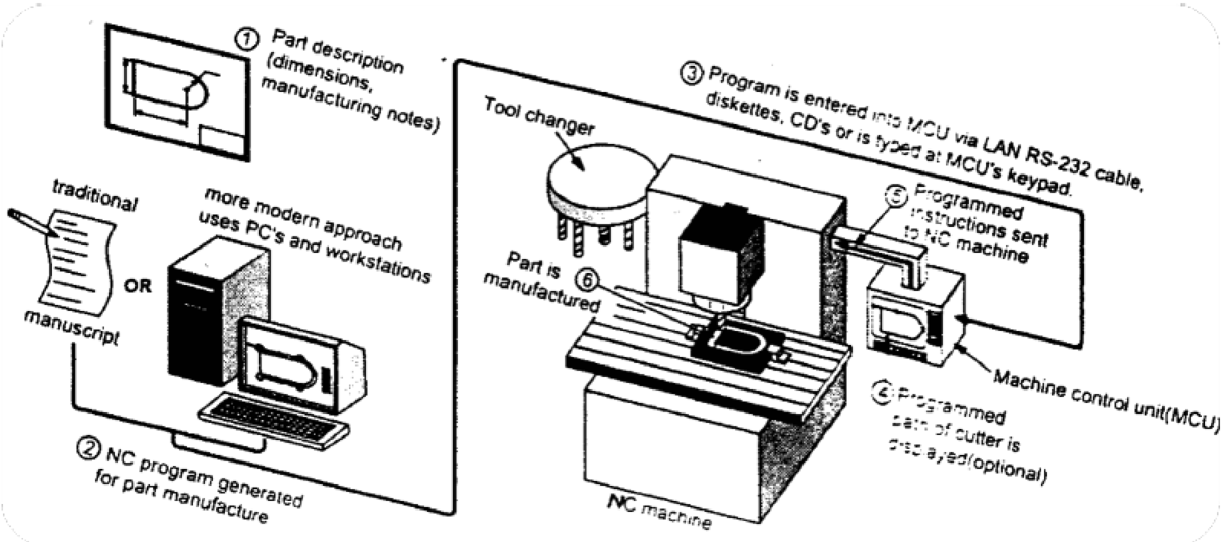
CNC systems require motor drives to control both the position and the velocity of the machine axes. Each axis must be driven separately and follows the command signal generated by the control unit. There are two ways to activate the servo drives: the **open-loop system** and the **closed-loop system**

Two modes of the control of CNC systems are commonly recognized. The first one is named **point-to-point**, where a cutting tool and workpiece are positioned with respect to each other before a cut is taken, (i.e. drilling operation). The second class is **continuous-path**, or continuous tool path control, which does contouring or profiling of lines, curves, and surfaces of all shapes.

NC (hard-wired) to CNC (soft-wired)

Numerical Control (NC) is often referred to as the older generation of numerical control technology. NC systems are ***hard-wired* controls** in which most *functions* are *implemented by electronic hardware* based upon digital circuit technology.

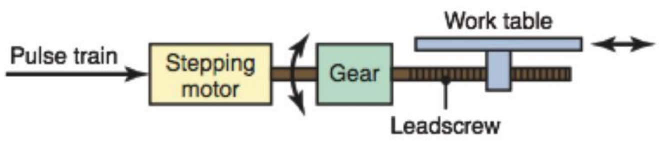
Computer numerical control (CNC) is a numerical control system in which a dedicated, stored program computer is built into the control to perform basic and advanced NC functions. CNC controls are also referred to as ***soft-wired* NC systems** because most of their control *functions* are *implemented by control software programs*. All numerical control machines manufactured since the Seventies are of CNC type.



Loop Systems for Controlling Axis Movement

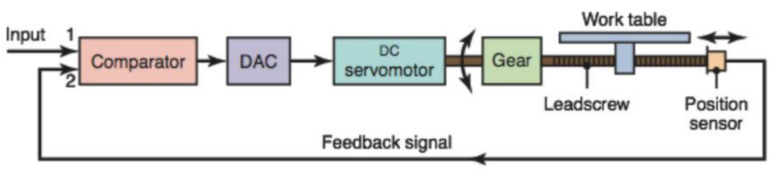
Open Loop System

Uses **stepping motor** to create movement. Motors rotate a fixed amount for each *pulse* received from the MCU. The motor sends a signal back indicating that the **movement is completed.** No feedback to check how close the actual machine movement comes to the exact programmed movement.



Closed Loop System

AC and DC servo-motors are used. The speed of these motors is variable and controlled by **the amount of current or fluid**. The motors are connected to the spindle and the table. A **position sensor** continuously monitors the movement and sends back a signal to the **comparator** to make adjustments.

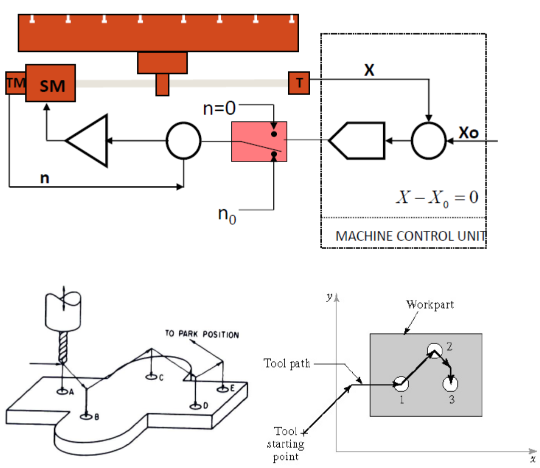


Point-to-Point Tool Movements (1)

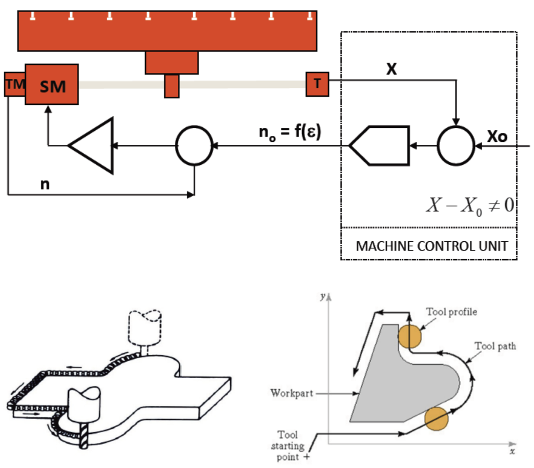
- The cutting tool and workpiece are positioned with respect to each other before a cut is taken.
- Point-to-point control systems cause the tool to move to a point on the part and execute an operation at that point only.
- The tool is not in continuous contact with the part while it is moving.
- Boring, Drilling, Punching and Tapping are examples of point-to-point operations.

Continuous-Path Tool Movements (2)

- Continuous-path controllers cause the tool to maintain **continuous contact** with the part as the tool cuts a contour shape.
- These operations include milling along any lines at any angle, milling arcs and lathe turning.

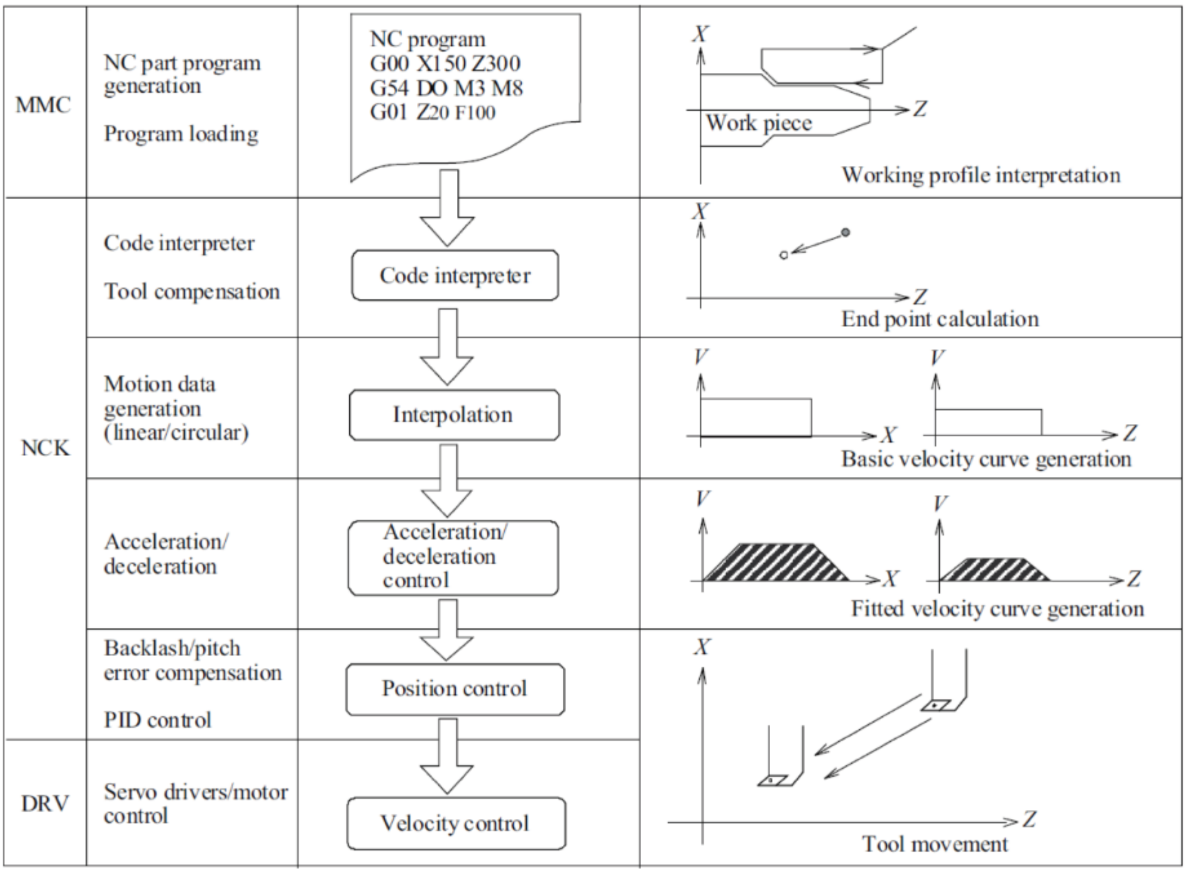


(1)



(2)

Internal behaviour of the CNC system



The part program that a programmer generates based on the shape of the part, the cutting conditions, and the tools is entered into CNC via the MMC and the NCK subsequently generates the control commands for the drivers from the part program through various stages:

- calculating the movement path by interpreting the part program;
- generating velocity profile and displacement for each axis by interpolation;
- smoothing the movement by acceleration/deceleration (acc/dec) control;
- generating position control command.

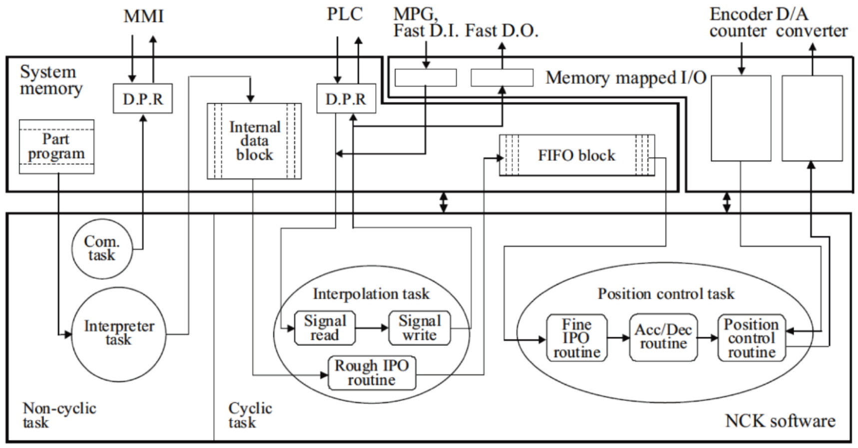
Numerical Control Kernel (NCK) functions

This unit (the core of the CNC system):
1. consists of two sub-units: The Data Processing Unit (DPU) and the Control Loop Unit (CLU),
2. **interprets** the Part Program,
3. **executes** Interpolation, Position Control, and Error Compensation based on it.
4. Therefore, NCK unit controls the **Servo System** and causes the **workpiece to be machined.**

In general, the NC system interprets the input data, keeps them in memory, sends commands to the driving system, and detects feedback signals from the drive system.

The NC system also performs logical decision making such as when coolant is provided and when the spindle starts rotating and mathematical calculations for acceleration control and interpolation of lines, circles and parabola. Therefore, the NCK unit is in charge of the servo and driving control and the PLC unit has the task of being in charge of logic control, so the burden that occurs during control is adequately balanced.

the **main characters** of the NCK unit are:
The **Interpreter, Interpolator, acceleration/deceleration Controller**, and **position Controller**.



NCK functions – Interpreter

An interpreter plays the role of **reading** a part program**, interpreting** the **ASCII blocks** in the part program, and **storing** interpreted data in an internal memory for the interpolator.

It translates the part program into internal commands;

In general, NC issues the orders related to the interpreted data and the interpreter reads and interprets the next block while the command is being performed.

However, if the time to interpret the block is longer than the time to finish the command, the machine should wait for the completion of interpretation of the next block so that a machine stop can be avoided. Therefore, in order to prevent machine tools from stopping, a buffer that temporarily stores the interpreted data is used. The buffer, named the **internal data buffer**, always keeps a sufficient number of interpreted data and all interpreted data are stored in the buffer.

Interpreter:

The code interpreter is a software module, which translates the part program into internal commands for moving tools and executing auxiliary functions in a CNC system.

Summary on the characters of NCK

Interpreter:

- It **reads** the **part program**, **interprets** the **Ascii blocks** in the part program;
- It **storages** the interpreted data in its **internal memory**;
- It reads and interprets the **next block** while the previous command is being performed.
- **If the time** to interpret the block is longer than the time to finish the command, the machine should wait the completion of the interpretation of the next block.
- To avoid machine stops, an **Internal Data Buffer** is used. This always keep a sufficient number of interpreted data.

Interpolator:

- It **reads** the data from the **Internal Data Buffer**, calculating the position and velocity of **each axis**.
- It **storages** the results in a **FIFO Buffer**.
- **Typologies of Interpolator: Linear, Circular** (most common), **Parabola** and **Spline** Interpolator.
- It generates a **pulse** and sends to the FIFO buffer.
- The **number of pulses** is decided on the base of the **length of the path**, while the **frequency** is based on the **velocity.**
- In an NC system, the **displacement per pulse** determines the accuracy; for example, if an axis can move 0.002 mm per pulse, the accuracy of the NC system is 0.002 mm.

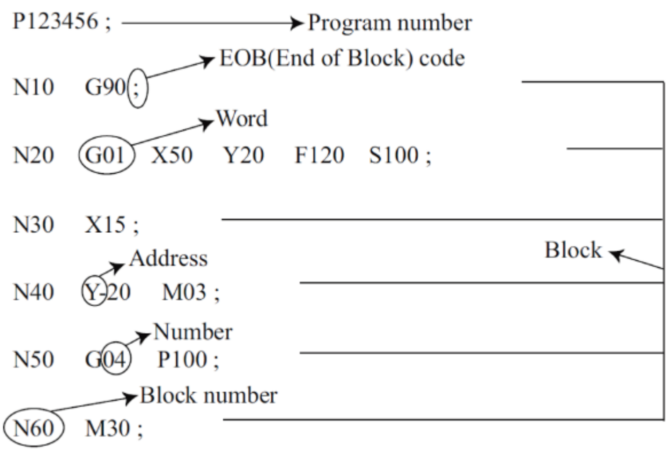
Acceleration and Deceleration Controller and Position Controller:

- In order to avoid **mechanical vibration** and **shock**, the **interpolated data** are first send to an **Acceleration and Deceleration Controller** before to the Position Controller.
- This method is named the "**acceleration/deceleration after-interpolation" method.** An **"acceleration/deceleration-before-interpolation"** method exists too, where acceleration/deceleration control is executed before interpolation.
- The data from the acceleration/deceleration controller is sent to a **Position Controller.**
- The **Position Controller** send **velocity commands** to the **motor driving system.**
- Through the use of the **encoder** is possible to control the **error**, which is the **difference between the programmed position and the commanded position**.

Part Program Structure

A part program contains the commands, named **blocks**, for machining a part and each block can be defined using the following commands:

- NC commands such as G, M, S, T, H, D, F code and related address;
- call of sub program and displaying message;
- setting variable and conditional program calls.



Part program: consists of a sequence of NC **blocks**, each block consists of several **words**, and a word of these is composed of an **address** and a **number.**
(Program number: is a number for **identifying** the particular part program on CNC, where more than one part program is executed, and is written using a particular address. It is at the head of the part program.)
Block: consists of a **block number**, **other words** (at least one) and the **EOB (End Of Block).**
Word**:** is a **set of characters** in a specific order: first an **address** and then a **number**. It is the minimum unit for command the machine tools to perform a particular behavior.
Address**:** is constructed from one of the alphabetic characters (A – Z) or a combination of alphabetic characters. The subsequent number provides the data that is required to execute the behaviour related with the address.

Example of Part Program

```
                                              (BLANK LINE MAY BE NECESSARY - OR % SYMBOL)
O0701 (ID MAX 15 CHARS)                       (PROGRAM NUMBER AND ID)
(SAMPLE PROGRAM STRUCTURE FOR FIXED CYCLES)   (BRIEF PROGRAM DESCRIPTION)
(PETER SMID - 07-DEC-2008)                    (PROGRAMMER AND DATE OF LAST REVISION)
                                              (BLANK LINE)
N1 G21                                        (UNITS SETTING IN A SEPARATE BLOCK)
N2 G17 G40 G80 G49                            (INITIAL SETTINGS AND CANCELLATIONS)
N3 T01                                        (TOOL T01 INTO WAITING POSITION)
N4 M06                                        (T01 INTO SPINDLE)
N5 G90 G54 G00 X.. Y.. S.. M03 T02            (T01 RESTART BLOCK - T02 INTO WAITING POSITION)
N6 G43 Z25.0 H01 M08                          (TOOL LG OFFSET - CLEAR ABOVE WORK - COOLANT ON)
N7 G99 G82 X.. Y.. R.. Z.. P.. F..            (FIXED CYCLE - G82 USED AS AN EXAMPLE)
(---- CUTTING MOTIONS WITH TOOL T01 ----)
...
N33 G80 Z25.0 M09                             (CYCLE CANCEL - CLEAR ABOVE PART - COOLANT OFF)
N34 G28 Z25.0 M05                             (HOME IN Z ONLY-SPINDLE OFF)
N35 M01                                       (OPTIONAL STOP)
                                              (— BLANK LINE —)
N36 T02                                       (TOOL T02 INTO WAITING POSITION - CHECK ONLY)
N37 M06                                       (T02 INTO SPINDLE)
N38 G90 G54 G00 X.. Y.. S.. M03 T03           (T02 RESTART BLOCK - T03 INTO WAITING POSITION)
N39 G43 Z25.0 H02 M08                         (TOOL LG OFFSET - CLEAR ABOVE WORK - COOLANT ON)
N40 G99 G81 X.. Y.. R.. Z.. F..               (FIXED CYCLE - G81 USED AS AN EXAMPLE)
(---- CUTTING MOTIONS WITH TOOL T02 ----)
...
N62 G80 Z25.0 M09                             (CYCLE CANCEL - CLEAR ABOVE PART - COOLANT OFF)
N63 G28 Z25.0 M05                             (HOME IN Z ONLY - SPINDLE OFF)
N64 M01                                       (OPTIONAL STOP)
                                              (— BLANK LINE —)
```

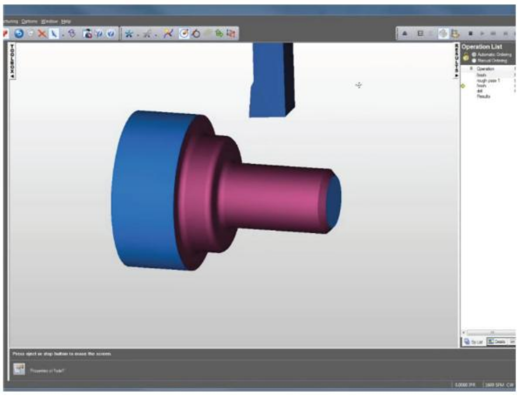
Spindle Functions (S)

- The spindle function (S-code) is for specifying the **spindle speed** and the spindle speed is restricted by the maximum spindle speed specified by the user. The S-code is a modal code and, therefore, the spindle speed specified by the S-code is effective until another spindle speed is specified.
- The spindle speed specified by an S-code **is cancelled after power on**, or when the system is **reset** or when **M30 is commanded.**
- During the execution of a part program, the change of spindle speed is limited to being less than or equal to the specified **maximum spindle speed** specified by the user.
- The constant surface speed control function is used for rotating the spindle with a constant surface speed regardless of the position of the tool. This function is applied for turning and the surface speed for this function is specified by the S-address.

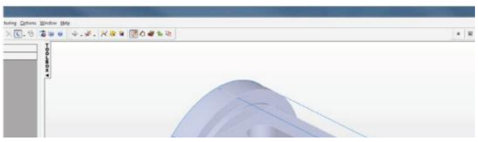
GØØ (Rapid Positioning/Traverse) ....
GØ1 (Linear Interpolation) ....
GØ2 & GØ3 (Circular Interpolation) ....
GØ4 (Dwell) ....
G2Ø & G21 (Imperial /Metric Data Input) ....
G28 (Reference Point Return) ....
G4Ø, G41 & G42 (Cutter Compensation) ....
G73-G89 (Canned Cycles) ....
G73 (High SpeedPeck Drilling) ....
G74 (Counter Tapping) ....
G76 (Fine Boring) ....
G8Ø (Canned Cycle, Cancel) ....
G81 (Drilling - Spot Boring) ....
G82 (Drilling - Counter Boring) ....
G83 (Deep Hole Peck Drilling) ....
G84 (Tapping) ....
G85 (Boring) ....
G86 (Boring) ....
G87 (Back Boring) ....
G89 (Boring) ....
G Codes - Program Example Using Canned Cycles ...
G9Ø (Absolute Zero Command) ....
G91 (Incremental Command) ....
G94 (Feed per Minute) ....
G95 (Feed per Revolution) ....
G98 (Return to Initial Level) ....
G99 (Return to R Point Level) ....
G17Ø-G173 (Circular/Rectangular Pocket) ....
G17Ø & G171 (Circular Pocket Example A) ....

MØØ (Program Stop)
MØ1 (Optional Stop) .
MØ2 (Program Reset)
MØ3 (Spindle Forwar
MØ4 (Spindle Reverse
MØ5 (Spindle Stop) ..
MØ6 (Automatic Tool
MØ8 (Coolant On) ....
MØ9 (Coolant Off) ....
M1Ø (Vice Open) .....
M11 (Vice Close) ......
M13 (Spindle Forwarc
M14 (Spindle Reverse
M2Ø (ATC Arm In) ....
M19 (Spindle Orienta
M21 (ATC Arm Out) ..
M22 (ATC Arm Down
M23 (ATC Arm Up) ..
M24 (ATC Drawbar U
M27 (Reset Carousel
M25 (ATC Drawbar C
M3Ø (Program Reset
M32 (Carousel CW) ..
M33 (Carousel CCW)
M38 (Door Open) .....
M39 (Door Close) .....
M62, M63, M64, M6
M76 & M77 (Auxiliar

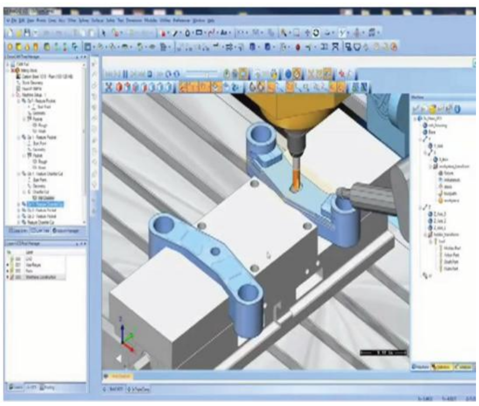
CAM – Turning



CAM – Turn/Mill



CAM – CNC Machining Simulation



The interpolator can be classified as either a hardware interpolator or a software interpolator by considering the implementation method.

Hardware Interpolator

- The hardware interpolator generates pulses by using an **electric circuit**.
- In the hardware interpolator, **highspeed execution** is possible, but it is difficult to adapt **new algorithms** or **modify algorithms.**
- The hardware interpolator was widely used until CNC was developed.
- The typical method for hardware interpolation uses a **DDA (Digital Differential Analyzer) integrator**.
- This method, using the DDA integrator, was transformed into a **software version** to be applied to modern CNC. (The hardware interpolator was limited to **control simple systems)**

Hardware Interpolation – DDA integrator

The hardware interpolator uses a DDA based on the principle of a **numerical integration**. Understanding of the concept of integration should be preceded by knowledge of the principle of interpolation.

- Given the **velocity function V(t),** the **displacement S(t)** can be approximated by summing up the areas of the thin rectangles under the velocity curve.

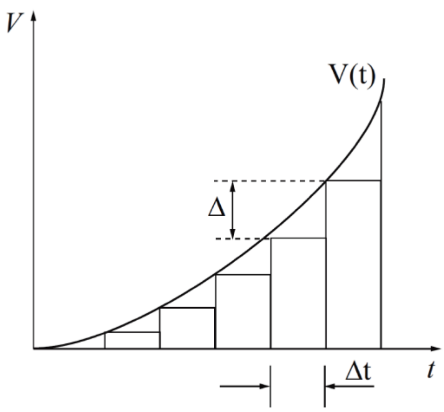
$$S(t) = \int_0^t V \cdot dt \cong \sum_{i=1}^{k} V_i \cdot \Delta t$$

Where Δt stands for an **iteration time interval**.

If displacement at time $t = k \cdot \Delta t$ is defined as S_k, the equation can be rewritten:

$$S_k = \sum_{i=1}^{k-1} V_i \cdot \Delta t + V_k \cdot \Delta t \quad or \quad S_k = S_{k-1} + \Delta S_k$$

$$where\ \Delta S_k = V_k \cdot \Delta t$$



The following three phases are necessary for integration:

- calculating the current velocity by summing up the velocity at the previous time unit and the velocity increment at the current time unit:

$$V_k = V_{k-1} + \Delta V_k$$

- calculating the distance increment at the current time unit:

$$\Delta S_k = V_k \cdot \Delta t$$

- calculating the total displacement by summing up the displacement at the previous time unit and the distance increment at the current time unit:

$$S_k = S_{k-1} + \Delta S_k$$

The above integration process is repeated for every constant time interval and the iteration frequency is given by:

- $D_k < 0$: this case means that the position %", '" is located on the inside of a circle and, in this case, the step moves in the positive direction of X-axis;
- $D_k > 0$: this case means that the position %", '" is located on the outside of a circle and, in this case, the step is moved in the negative direction of Y-axis;
- $D_k = 0$: one of the above rules can be arbitrarily selected and applied.

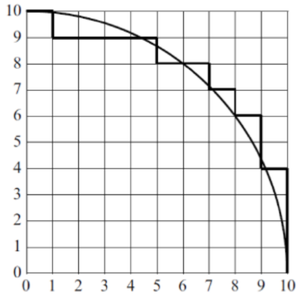
After one step has been completed by applying the above rules, the position (X_{k+1}, Y_{k+1}) is updated and the procedure repeated until the tool reaches the commanded position (X_f, Y_f).

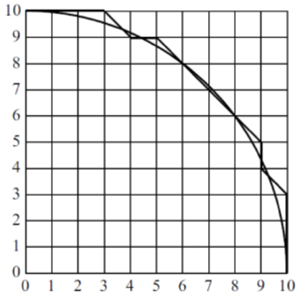
Direct Search Algorithm

One of the weaknesses of the Stairs Approximation algorithm is that a lot of iterations are required because simultaneous movement of axes is not considered in the algorithm.

- As an alternative, the Direct Search algorithm carries out optimal interpolation because the algorithm *searches through all possible directions and finds a direction with the minimum path error*.

- Basically, the Direct Search algorithm is very similar to the Stairs Approximation algorithm. However, the Direct Search algorithm *considers the simultaneous movement of axes based on path error*, in contrast to the Stairs Approximation algorithm.





Servo Control for Positioning

Position Control:

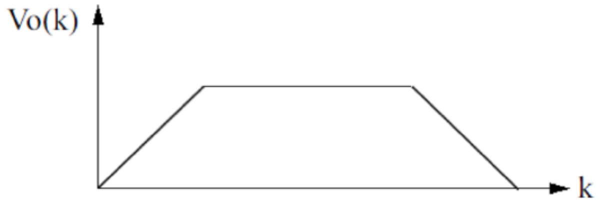
The position controller has the displacement at each interpolation interval from the interpolator as input and performs feedback control to minimize the position error.
The **Servo Control System** of the positioning machines is the **core** and most important part for the machine **performance and quality.**
The **control strategy** of each axis results in various **positioning errors**. Generally, the axis control strategy of a CNC system can be classified into point-to-point control and contour control.
To maintain high quality of performance for a machine, errors affecting a multi-axis machine have to be detected and eliminated.
The **Machine tool control systems** maintain two control objectives:

- to follow a **pre-specified trajectory** as closely as possible;

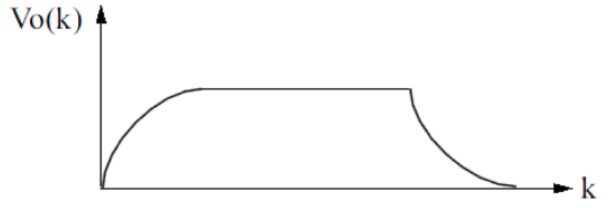
Acc/Dec Control after interpolation (ADCAI)

- It is applied in an **identical manner** for all the interpolation methods. Therefore, the implementation is simple but machining errors occur because each axis movement is determined separately. Since Acc/Dec control in ADCAI is individually applied for each axis, acceleration and deceleration for movements of each axis are carried out regardless of the interpolated position. Accordingly, the interpolated points deviate from the desired path. A typical example of this deviation occurs during the corner machining process and the longer the Acc/Dec time, the larger the machining error.

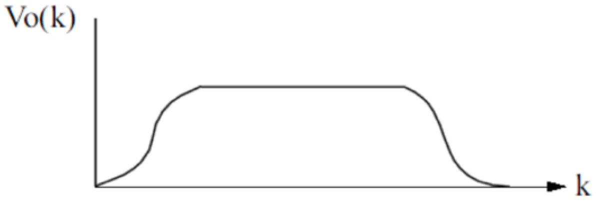
Speed-profile Generation



Linear



Exponetial



S-shape

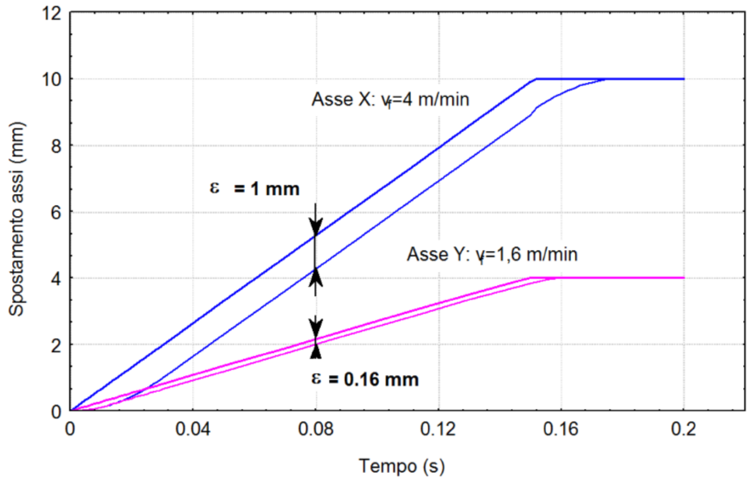
The Servo Controller

The servo controller, which enables the movement control of each axis based on position commands from the interpolator, is the last one in the NCK system.

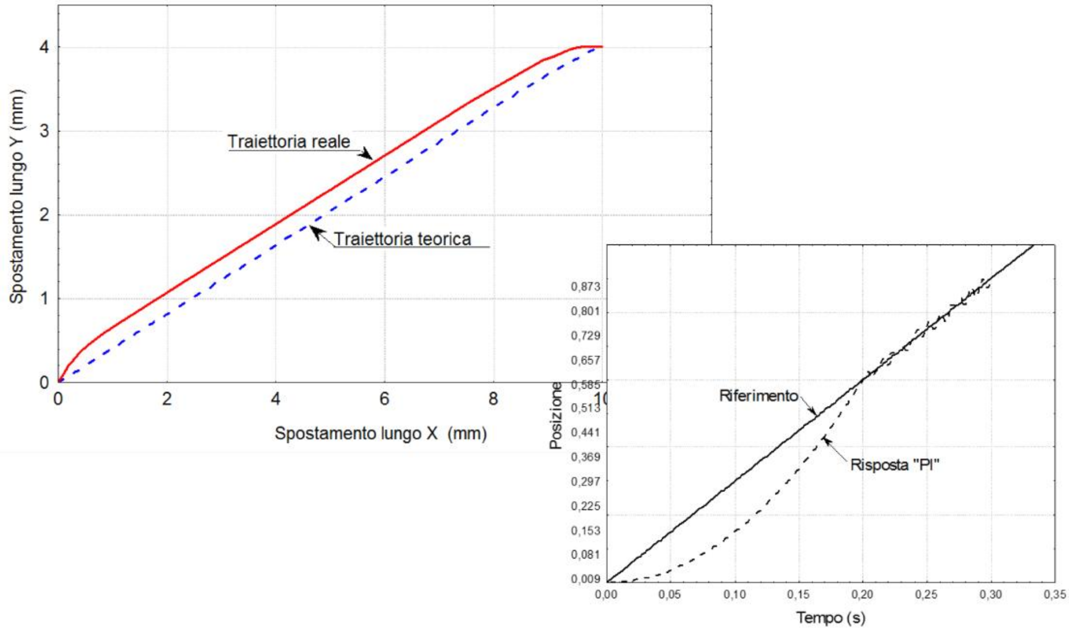
The servo controller should be able to control speed over a wide range, from fast speed for high speed machining (m/min) to slow speed for high-accuracy machining (mm/min). Furthermore, it should also guarantee practically reasonable accuracy and have robustness against external disturbances.

To fulfil the above-mentioned requirement, a closed-loop control, where the actual speed and position data are monitored and fed back to the servo controller, is commonly considered.

In most systems actuated by servo motors, because the position and speed instructed to the servo motors are practically different from the actual values, the servo controller includes a feedback control loop where the actual position and speed data from the servo motors are fed back to the controller, and the controller generates commands to compensate for errors between commanded values and the feedback data.



$$K_v = \frac{\dot{x}_0}{\varepsilon} = 2 \cdot \frac{\ddot{x}}{\dot{x}_0} = = k \cdot \frac{C_{\max}}{I_{eq}} \cdot \frac{1}{v_f}$$



Position Control – P, PI, PID Controller

In the **point-to-point** control, the most important factor is the **elapsed time** for moving from one point to another, **ignoring the contour error** during the axis movement. In general, the point-to-point control is used for controlling the movement to the commanded position within a short settling time, **regardless of the intermediate path**, by utilizing a **P controller** or **PI controller**.
Compared with the point-to-point control, however, the contour/tracking control has many problems to be considered. Because of inherent system specific errors, including disturbance, friction force, backlash, distortion of table, and the characteristics of the servo system as well as dynamic errors due to high speed operation of the servo system, acceleration or deceleration operation, and the change of movement direction, some differences between the desired path and the actual controlled path cannot be avoided during contour machining by multi-axis machine tools.
Therefore, in the position controller of a CNC system there is a variety of control algorithms, including the **P controller**, **PID controller**, fuzzy controller, **feed-forward controller**, predictive controller, and cross-coupling controller that have been introduced to support point-to-point control, tracking control, and contour control. Compared with the P controller, feedback controllers such as the PID controller and the Fuzzy controller decrease the position errors of each axis. The feed forward controller is useful for reducing

Second, **I control**, meaning integral control, is used in the case of not going to the reference point after transition to the steady state. In I control, the error is integrated over a period of time, multiplied by a constant I, named the integral gain, to reduce the integrated errors from the past. A larger integral gain results in a faster response during transition states. Accordingly, it is necessary to use an integral gain within an adequate range because a large integral gain results in excessive overshoot or undershoot.

Third, in **D control**, meaning derivative control, the first derivative over time (the slope of the error) is calculated, and this derivative is multiplied by a constant D, named the derivative gain, for damping the system and removing the vibration of a system during a steady state. A larger derivative gain results in a faster response. However, a large derivative gain causes vibration of a system. Therefore, the amount of the derivative gain should be restricted because the first derivative of position over time is sensitive to noise.

Therefore, in practice, a variety of combinations of P control, I control, and D control has been selectively used according to the purpose for which the control is used. Typically, the PI controller, which has a relatively fast response, has been widely used because D control has difficulty in gain tuning and easily results in vibration.

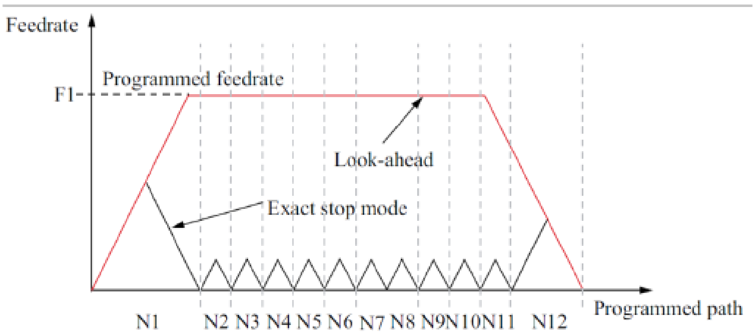
If an adequate gain for the PID controller is not set, the system response may become slow, vibration may occur, or the desired accuracy may not be achieved.
Therefore, setting adequate gains is an important design factor.

As the gain tuning method for a PID controller, there are the Ziegler–Nichols method, and the Relay method. For these methods, a user with a lot of experience should tune P, I, D gain by trial and error and, therefore, it takes a long time to complete gain tuning. As gain tuning methods based on a target process model, there are the Frequency response method, the Pole placement method, and the Pole-zero cancelation method. However, because of the complication of the mathematical model for the target process, it is difficult to derive the model of a target process in practice.

Recently a controller with an auto tuning function has been developed that tunes the gains automatically to help users. The auto-tuning function in this controller performs internally advanced gain tuning methods including those mentioned above.

Feedforward Control

The feedback controller, which is widely used as a servo controller, works based on the difference between input and output. The PID controller, being one type of feedback controller, mentioned previously, is very stable and robust even when there is disturbance. However, tracking error cannot be avoided when only a PID controller is used.
As an alternative, a feedforward controller is used together with a feedback controller in order to make up for the feedback controller disadvantage and enable a system to track the desired reference path. The feed-forward controller does not work based on the difference between the commanded point and the actual point, as does the feedback controller, but works based on a pre-specified system model.
As the feedforward controller is an open-loop type, it generates the output with calculations based on the pre-specified system model in order to increase the response characteristics of the complete system.
Because of the error in the system model, perfect control of the complete system cannot be achieved.
Therefore, it is typical to use the feedback control and the feedforward control together.
The purpose of the feedforward control method is to overcome the response limitations of a position control loop and feedforward control belongs to tracking control that enables the system to track the desired path by minimizing the tracking error.



Machining speed and machining accuracy are the key factors for the performance of CNC machine tools. Machining accuracy depends on the ability to follow the trajectory of the controller.

The accuracy of the machining trajectory is inversely proportional to the feedrate and sudden changes of feedrate result in reduction of accuracy of the CNC equipment. In the ADCBI type of NCK, the accuracy of machining is very high (theoretically the error is zero) and sudden change of feedrate is a major factor of machining error.

Therefore, in the ADCBI-type NCK, in order to minimize the machining error, it is necessary to smooth down change of feedrate and limit the axis speed to an allowable value. To smooth down the change of feedrate, axes should always be accelerated by an adequate acceleration value. Consequently, to maximize the performance of CNC systems it is necessary to maximize the acceleration ability of the CNC system.

In the case when two short blocks are connected, the length of two blocks is too short to reach the commanded feedrate and the resulting speed profile shows a special shape similar to a saw tooth. The reduction of feedrate results in an increase of the machining time. To overcome this problem a method of minimizing the reduction of feedrate was introduced by considering the commanded feedrate and the length of the successive blocks.

To minimize the reduction of feedrate and decrease in machining time for short blocks, a Look Ahead algorithm has been widely used. The Look Ahead algorithm enables minimization of the decrease of feedrate by calculating the maximum allowable feedrate and the end feedrate for a current block investigating not only the current block but also successive blocks.

The latest FANUC controller is able to calculate the end speed of a current block by pre-interpreting about 1000 blocks. Therefore, it is not necessary to make the end speed of the current block zero and it is possible to control the speed of successive blocks depending on the commanded feedrate and the length.

A Look Ahead algorithm calculates the start speed and the end speed of each block based on the remaining length of the successive blocks and the maximum allowable acceleration.

- Look Ahead with Respect to Length;
- Speed at a Corner;

Adaptive Control Systems

In general, the axis control module for CNC systems of machine tools can be classified into a three-tier architecture.

The perception of a robot as given in science fiction literature in the mid-twentieth century is different from the present form of industrial robot which cannot move on its own but their physical pattern resembles the human arm. Hence the i**ndustrial robots** are known as **anthropomorphic *robotic manipulators* or *robot arms*.**

The industrial applications and atmospheres are diverse in nature, frequent, complex, non-reachable or harmful to human being. In all these cases the robot can be **an alternative to human hands.** In this advanced technological world the skill, the perfection, the productivity and the speed with which the work has to be done influence the people making decision regarding introducing a robot for efficient manufacturing and manipulation.

History of robots

Year	*Type, name*	*Application Feature*	*Firm Developed.*
1959	Commercial	Controlled by limit switches and cams.	Planet corporation.
1960	'Unimate' Hydraulic drive robot.	'Programmed article Transfer' with manipulator control.	Devol's U.S. firm.
1966	Spray painting Type of Robot.	Controlled spray of paint.	Trallfa, a Norwegian firm.
1968	'Shakey'	Mobile robot with sensors and camera.	Stanford research Institute.
1971	Stanford Arm.	Electrically powered robot.	Stanford University.
1974	IRB6 robot	All electric drive.	ASEA
1974	T³ Robot (The Tomorrow Tool)	Computer controlled robot.	Cincinnati Malicron.
1975	Sigma	Assembly operation	Olivetti "Sigma"
1978	PUMA (Programmable Universal Machine for Assembly)	Assembly operation.	Unimation by GM.
1979	SCARA (Selective compliance arm for Robotic Assembly)	Assembly operation.	Yamanashi University of Japan.
1982	RS-1 robot with robot language AML	Assembly operation.	IBM
1983	APAS-adoptable programmable assembly system	Flexible automated Assembly line.	Westinghouse Corporation.

-> Industrial robots are known as **anthropomorphic robotic manipulators** or **robot arms** and represent an **alternative to human hands**.

Definition

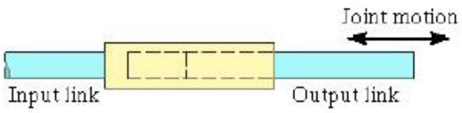
"A robot is a mechanical device with links and joints, guided by sensors, driven by actuators and controlled through a programmed software, to handle and manipulate parts, materials, tools and devices for performing various tasks in variety of work environments".

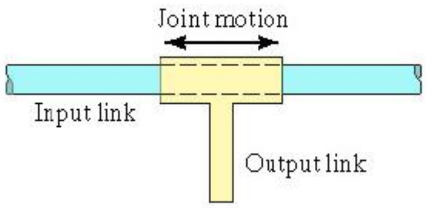
- **Linear joint (type L joint).** The relative movement between the input link and the output link is a translational sliding motion, with the axes of the two links being parallel.
- **Orthogonal joint (type O joint)**. This is also a translational sliding motion, but the input and output links are perpendicular to each other during the move.

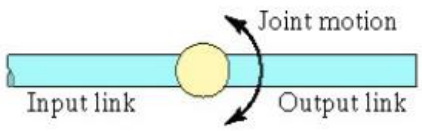
Revolute Joints - Rotary motion

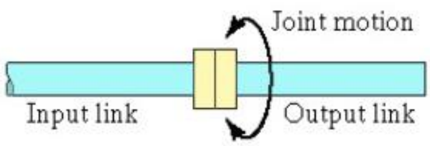
- **Rotational joint (type R joint).** This type provides rotational relative motion, with the axis of rotation perpendicular to the axes of the input and output links.
- **Twisting joint (type T joint).** This joint also involves rotary motion, but the axis of rotation is parallel to the axes of the two links.
- **Revolving joint (type V joint)**. In this joint type, the axis of the input link is parallel to the axis of rotation of the joint, and the axis of the output link is perpendicular to the axis of rotation.

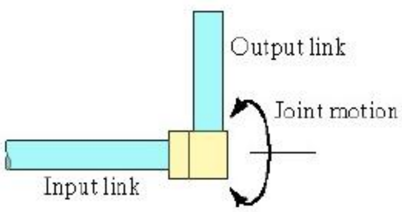
Each of these joint types has a range over which it can be moved. The range for a translational joint is usually less than a meter. The three types of rotary joints may have a range as small as a few degrees or as large as several complete turns.











Common Robot Configurations

A **robot manipulator** can be divided into **two sections**:
- **Body-and-Arm Assembly**;

2) Cylindrical Body-and-Arm Assembly (TLO) – Cylindrical Coordinate Robot

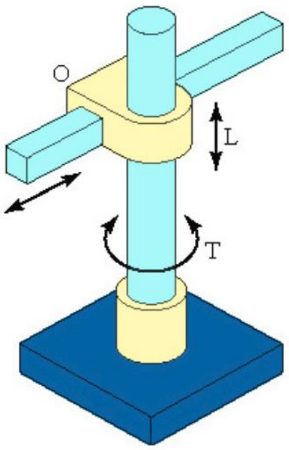
If the end effector of the robot arm forms a **cylindrical work envelope**, the robot is called a **cylindrical robot**. A cylindrical coordinate robot has two **prismatic joints** and one **revolute joint** for the positioning of the part. The main frame of the **cylindrical coordinate robots** consists of a **horizontal arm** mounted on a **rotary base**. The horizontal arm moves in and out. The **carriage** moves up and down in the column. These two units rotate on a unit on the base. Thus the **work volume** is **annular space** of the cylinder.

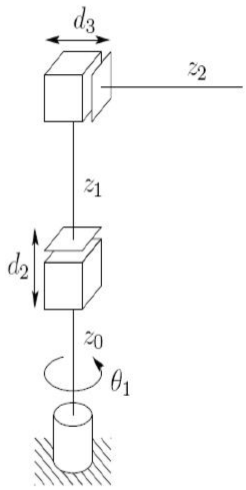
The **advantages** of the cylindrical robot are:

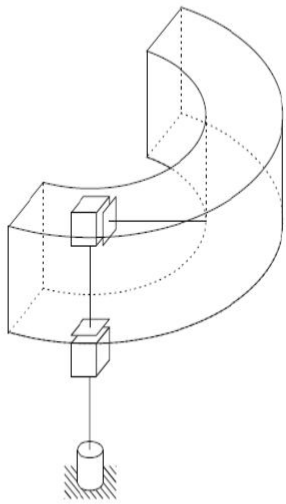
- almost independent of gravity, collision free movement;
- two linear axes make the mechanical design easier.

The main **disadvantages** of the cylindrical robot are:

- large size of structures,
- limited compatibility with other robots;
- less accurate on the end resolution compared to Cartesian robot.







4) Jointed-Arm (TRR) - Articulated Robot

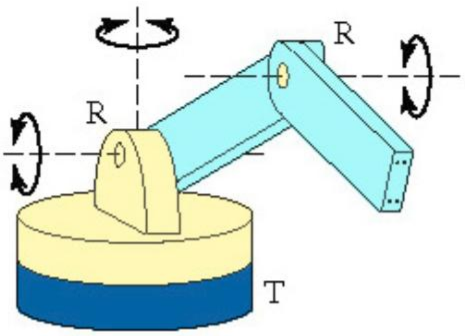
Articulated robot is also known as **revolute robot**. The articulate robot arm consists of **three rigid members** connected by **two rotary bases**. The joints of an articulate robot are all revolute and they closely resemble the **human arm**.

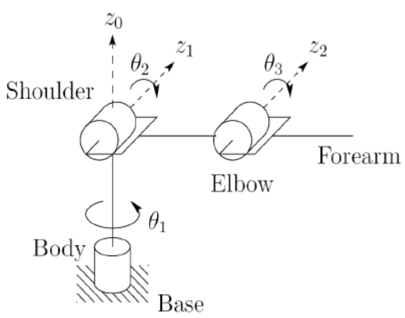
The **advantages** of revolute joint robot arm are:

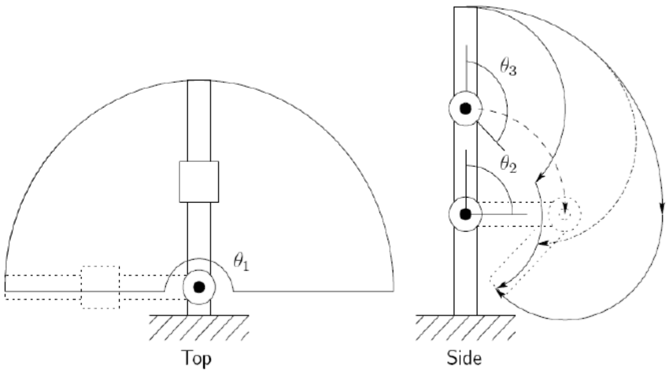
- excellent mechanical flexibility,
- compatibility with other robots working in the same common workspace,
- the robot can rotate at higher speed.

The main **disadvantages** of the articulate arm are:

- poor accuracy and resolution due to revolute joint, hence more positional errors;
- large and variable torque on the joints creating counter balancing problems;
- limited ability to avoid obstacles;
- higher moment of inertia and gravity and hence **dynamic instability**.



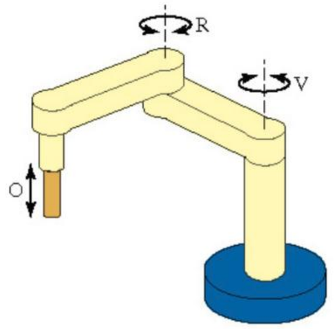


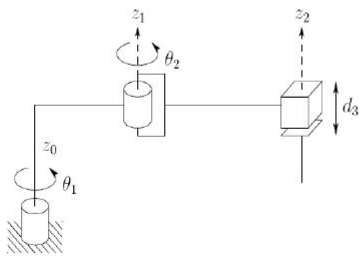


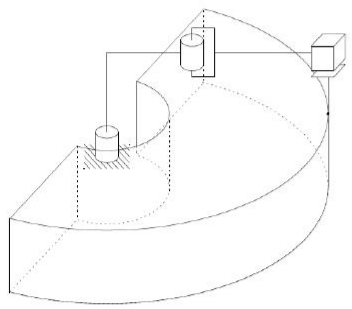
5) SCARA robot (VRO)

Selective Compliance Assembly Robot Arm (SCARA) has **two revolute joints** that are **parallel** and allow the robot to move in the **horizontal plane**, plus an additional **prismatic joint** that moves **vertically**. SCARA is very common in **assembly operations**.

This configuration is **similar** to the jointed arm robot except that the **shoulder** and **elbow** rotational **axes** are v**ertica**l, which means that the arm is very rigid in the vertical direction but compliant in the horizontal direction. This permits the robot to perform insertion tasks (for assembly) in a vertical direction, where some side-to-side alignment may be needed to mate the two parts properly.



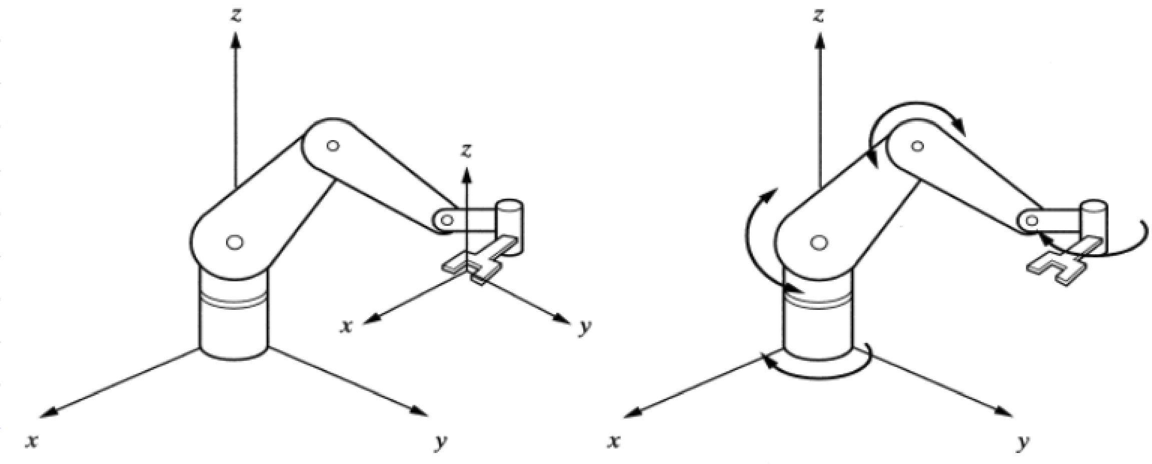




The Reference Frames

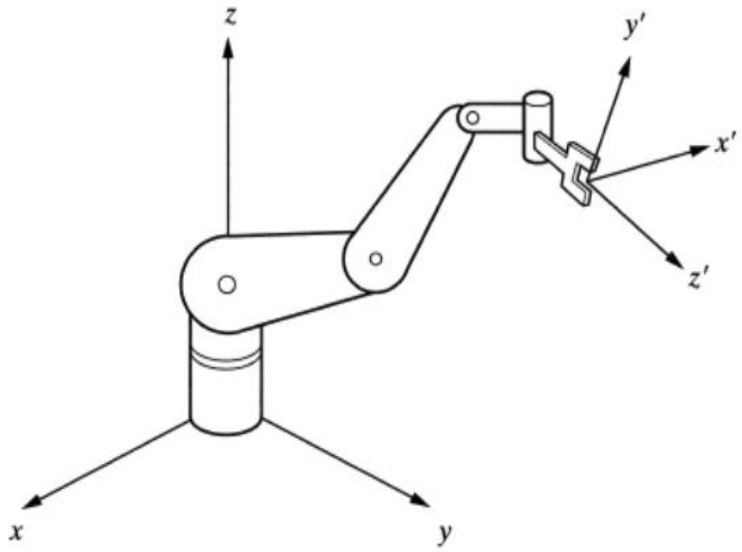
World (Base) Reference Frame. The basic x, y and z axes are the three axes of the **base.** The base may be **fixed** or **rotate around the z-axis** according to the need of the **application**. The base reference frame is the universal reference frame for a robot. **The frame is fixed.**

Joint Reference Frame. The reference axes defined at the joints of the robot are named the joint reference frame. The joint can have both **translatory and rotational movements** about its defined axes. In this case **the frame is not fixed**.



World reference frame   Joint reference frame

Tool Reference Frame. This is the local frame of reference defined by the axes at the arm tip or the robot hand. The **tip or the tool reference frame** is related to the **base reference frame** by the **transformation of the coordinates.**



Tool reference frame

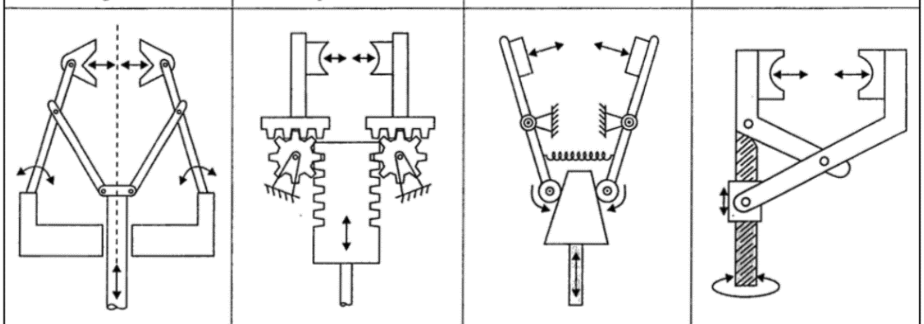
Grippers

Grippers are end effectors used to grasp and manipulate objects during the work cycle. The **objects** are usually **workparts** that are moved from one location to another in the cell**. Machine loading** and **unloading applications** fall into this category. Owing to the variety of part shapes, sizes, and weights, grippers must usually be **custom designed**.

Types of grippers used in **industrial robot applications** include the following:

- **Mechanical grippers**, consisting of **two or more fingers** that can be actuated by the robot controller to open and close to grasp the workpart;
- **Vacuum grippers**, in which **suction cups** are used to hold **flat objects**;
- **Magnetized devices**, for holding **ferrous parts**;
- **Adhesive devices**, where an adhesive substance is used to hold a **flexible material** such as a fabric.
- **Simple Mechanical devices** such as **hooks** and **scoops**.

Mechanical grippers



1. Linkage Actuation	2. Rack-pinion Actuation	3. Cam Actuation	4. Screw Actuation
(a)	(b)	(c)	(d)
• Many design possibility using linkages. • Higher gripping force at less actuating force due to leverage. • Opening width and the speed of gripping depends on the linkage configuration.	• A rack actuated by a hydraulic/pneumatic cylinder operates two pivoted pinions. • Pinions oscillate to move the racks (two) • The fingers attached to the racks (two) open and close to grab and release the object.	• A cam attached to a cylinder moves to and fro. • Spring-loaded followers moves on the cam profile. • The finger pads attached to the pivoted liver connected to the followers open and close to release and grab the object.	• A threaded block engages with a screw moves forward and backward, the fingers attached to levers connected to the threaded block by a hinged joint, open and close providing releasing and gripping action. • The screw is rotated by a motor through reduction box.

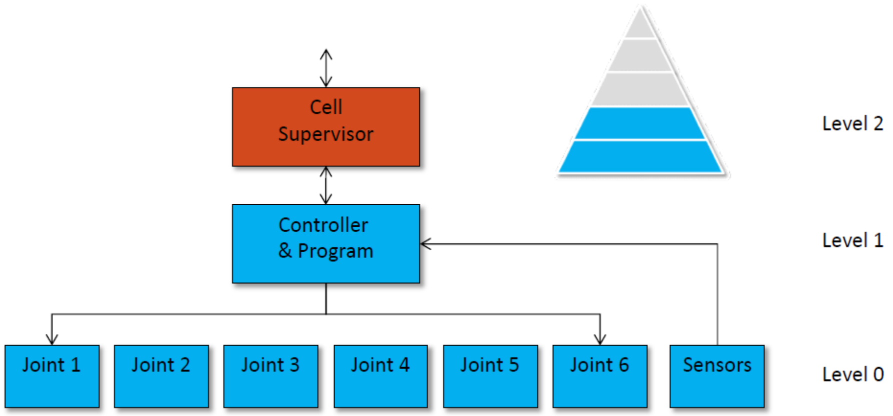
Mechanical grippers are the **most common** gripper type. Some of the **innovations** and **advances** in mechanical gripper technology **include**:

- **Dual grippers**, consisting of **two gripper devices** in one end effector, which are useful for **machine loading and unloading**. With a single gripper, the robot must reach into the production machine **twice**, once to unload the finished part from the machine, and the second time to load the next part into the machine. With a dual gripper, the robot picks up the next workpart while the machine is still processing the preceding part: when the machine finishes, the robot reaches into the machine once to remove the finished part and load the next part. This reduces the **cycle time per part**;
- **Interchangeable fingers** that can be used on one gripper mechanism. **To accommodate different parts**, different fingers are attached to the gripper;
- **Sensory feedback** in the fingers that provide the gripper with capabilities such as: sensing the presence of the workpart or applying a **specified limited force** to the workpart during gripping (for **fragile workparts**);
- **Multiple fingered grippers** that possess the general **anatomy of a human hand**;
- **Standard gripper products** that are **commercially available**, thus reducing the need to custom-design a gripper for each separate robot application.

Robot Control System

The actuations of the individual joints must be controlled in a coordinated fashion for the manipulator to perform a desired motion cycle. Microprocessor-based controllers are commonly used today in robotics as the control system hardware. The **controller** is organized in a **hierarchical structure** so that **each joint** has its own feedback control system, and a supervisory controller coordinates the combined actuations of the joints according to the sequence of the robot program.

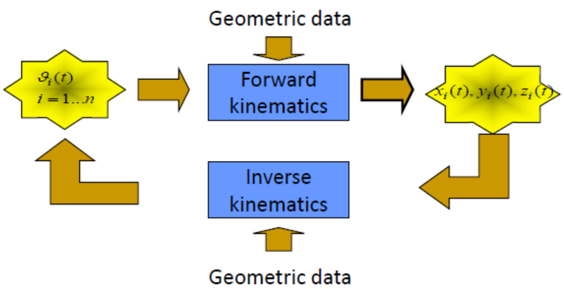
The actuation of joints must be coordinated by a **supervisory controller** that is organized in a hierarchical structure.



Forward and inverse kinematics

- The **forward kinematics problem** is stated as follows: "Given the angles for each robot joint, where is the robot hand?"
- The **inverse kinematics problem** is much more interesting and its solution is more useful. At the position level, the problem is stated as, "Given the desired position of the robot hand, which must be the angles at all of the robot joints?"

  - The existence of multiple solutions adds to the challenge of the inverse kinematics problem. Typically we will need to know which of the solutions is correct.



Different types of control are required for different applications. **Robot controllers** can be classified into four categories:

- Limited Sequence Control;
- Playback with Point-To-Point Control;
- Playback with continuous path Control;
- Intelligent Control.

Sensors

Sensors used in industrial robotics can be classified into two categories:
- Internal
- External

Internal sensors are those used for controlling **position** and **velocity** of the **various joints** of the robot. These **sensors form** a **feedback control loop** with the **robot controller**. Typical sensors used to control the position of the robot arm include **potentiometers** and **optical encoders**. To control the speed of the robot arm, **tachometers** of various types are used.
External sensors are used to coordinate the **operation of the robot** with other **equipment in the cell.** In many cases, these external sensors are relatively **simple devices**, such as limit switches that determine whether a part has been **positioned properly in a fixture** or that indicate that a **part is ready to be picked** up at a conveyor. Other situations require **more-advanced sensor technologies**, including the following: **tactile sensors, proximity sensors, optical sensors** and **machine vision.**

External Sensors

-**Tactile sensors**. Used to determine whether contact is made between the sensor and another object. In robot applications, tactile sensors can be divided into two types: (1) **touch sensors** and (2) **force sensors**. Touch sensors are those that indicate simply that contact has been made with the object. Force sensors are used to indicate the **magnitude of the force** with the object. This might be useful in a gripper to measure and control the force being applied to grasp an object.
- **Proximity sensors**. Indicate when an **object is close** to the sensor. When this type of sensor is used to indicate the **actual distance** of the object, it is named a **range sensor**.
- Optical sensors. Photocells and other photometric devices can be utilized to detect the **presence or absence of objects** and are often used for proximity detection.
- **Machine vision**. Used in robotics for **inspection, parts identification, guidance**, and other uses.
- **Other sensors**. This miscellaneous category includes other types of sensors that might be used in robotics, such as devices for measuring **temperature, fluid pressure, fluid flow, electrical voltage, current, and various other physical properties.**

Robot Programming

To do useful work, **a robot must be programmed to perform its motion cycle**. A robot program can be defined as a **path in space** to be followed by the **manipulator**, combined with **peripheral actions** that support the work cycle, examples of the peripheral **actions include opening and closing the gripper**, performing logical decision making, and **communicating with other pieces of equipment** in the robot cell.

In the case of **limited sequence robots**, programming is accomplished by **setting limit** switches and **mechanical stops** to control the **endpoints** of its motions. The sequence in which the motions occur is regulated by a sequencing device. This device determines the order in which each joint is actuated to form the complete motion cycle. Setting the stops and switches and wiring the sequencer is more a manual setup than programming.

Today nearly all industrial robots have digital computers as their controllers, together with compatible storage devices and their memory units. For this robots, **three programming methods** can be distinguished:

- Leadthrough Programming;
- Computer-like robot Programming language;
- Off-line Programming.

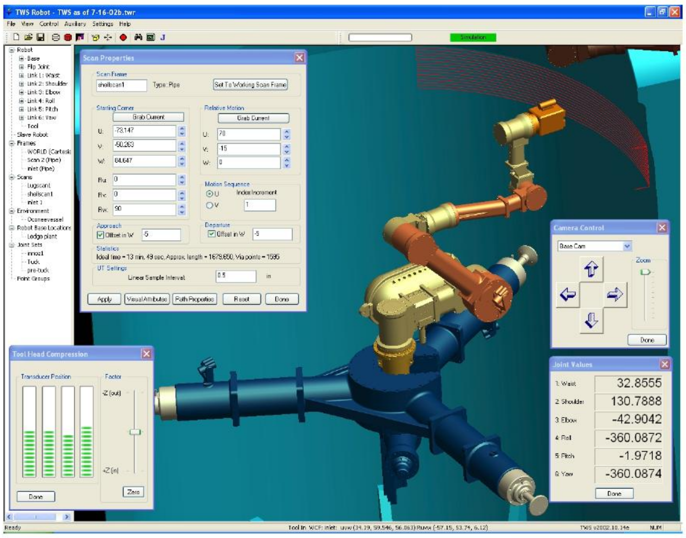
Simulation and Off-line Programming

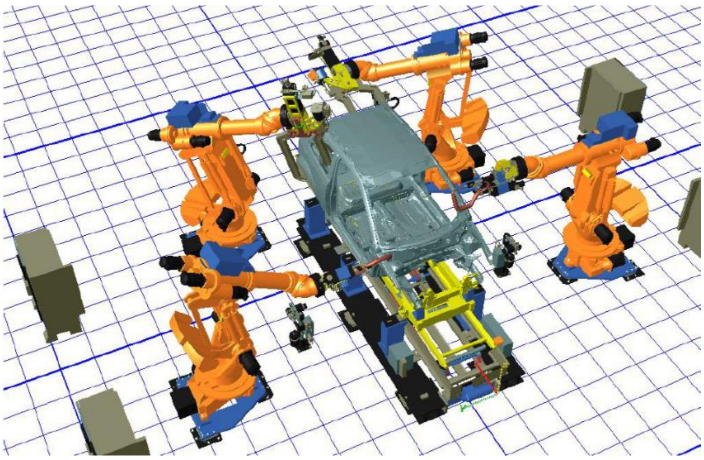
The trouble with leadthrough methods and textual programming techniques is that **the robot** must be **taken out of production** for a certain length of time to **accomplish the programming.**

Off-line programming permits the robot program to be **prepared** at a **remote computer terminal** and **downloaded** to the robot controller for **execution.** In true off-line programming there is no need to physically locate the positions in the workspace for the robot as required with present textual programming languages. Some form of graphical computer simulation is required to validate the programs developed off-line, similar to offline procedures used in NC part programming. The advantage of true off-line programming is that new programs can be prepared and downloaded to the robot **without interrupting production.**

The off-line programming procedures being developed and commercially offered use **graphical simulation** to construct a **three-dimensional model** of a robot cell for evaluation and off-line programming. The cell might consist of the robot, machine tools, conveyors, and other hardware. The simulator permits these cell components to be displayed on the graphic, monitor and for the robot to perform its work cycle in **animated computer graphics.**

After the program has been developed using the simulation procedure, it is then **converted** into **the textual language** corresponding to the particular robot employed in the cell. This is a step in the off-line programming procedure that is equivalent to postprocessing in NC part programming.





Robot Specifications

The classification of the robots is conveniently based on **drive system types**, **work space geometries** and **movement control techniques**. Apart from these, there are **specific characteristics** provided to the customer, useful in the selection of the robotic manipulators, precisely to the required application.

Specifications	*Dimensions*
1. Number of Axes	—
2. Capacity	kgf
3. Speed	mm/sec
4. Reach and stroke	mm
5. Operating environment	—
6. Tool orientation	deg. or radians
7. Performance parameters	mm.

Number of Axes

- The translatory movements of the links along a particular direction and/or rotational motions about a specific axis decide on the number of axes attached to a given robotic manipulator. To achieve arbitrary position for the wrist and any specific position for the tool or the gripper the general axes for the robotic manipulator are given in the table below:

Type of axis	*Axes*	*Arbitration*
Major	1 to 3	Positioning the wrist
Minor	4 to 6	Orienting the gripper
Redundant	7 to *i*	Preventing obstacles

- The movements assigned to links, aiding in positioning the wrist, are the major types of axis which vary from 1 to 3, which can be regarded as the independent axes of motion.
- Activating the tool and griper fingers is the function of the mechanisms, the movement of which are not considered to be about/along independent axis which are called minor types and they vary from 4 to six axes.
- The obstacles within the work envelop are to be tackled by one or more redundant axes assigned to the redundant manipulator links. The incorporation of the redundant axes adds extra complexity to the design of robot mechanism.

Capacity

- "It is nothing but load carrying ability of the robot with the allowed deflection of the manipulator end". Capacity is dependent upon the synthesis of the manipulator dimension based on statics and dynamics of the forces coming on the manipulator. The selection of a particular robot for a given application should be just enough to the required capacity rather than to go in for additional specification.

Speed

- "It is the distance moved by the tool tip in unit time". The time required to execute periodic motion while performing work can be one of the meaningful measure of speed. Sometimes the accuracy with which a task is to be performed may override the speed. The higher speed may be a requisite in high volume production. Higher speeds put a limit on the capacity of the robot.

Reach and Stroke

- The work volume (the term work envelope is also used) of the manipulator is defined as the envelope or space within which the robot can manipulate the end of its wrist. Work volume is determined by the number and types of joints in the manipulator (body-and-arm and wrist), the ranges of the various joints, and the physical sizes of the links. The shape of the work volume depends largely on the robot's configuration.

Material Handling Applications

Material handling applications are those in which the robot **moves materials or parts from one place to another.** To accomplish the transfer, the robot is equipped with a **gripper type end effector**. The gripper must be designed to handle the specific part or parts that are to be moved in the application.
Included within this application category are the following cases:

- material transfer;
- pick-and-place (the robot picks up a part and deposits it at a new location);
- palletizing and depalletizing;
- stacking (placing flat parts on top of each other, such that the vertical location of the drop-off position is continuously changing with each cycle);
- insertion (the robot inserts parts into the compartments of a divided carton).
- machine loading and/or unloading.

In nearly all material handling applications, the parts must be presented to the robot in a known position and orientation. This requires some form of material handling device to deliver the parts into the work cell in this defined position and orientation.

Industrial robot applications of machine **loading and/or unloading** include the following **processes:**

- **Die casting**. The robot unloads parts from the die casting machine. Peripheral operations sometimes performed by the robot include dipping the parts into a water bath for cooling.
- **Plastic molding**. Plastic molding is a robot application similar to die casting. The robot is used to unload moulded parts from the injection molding machine.
- **Metal machining operation**. The robot is used to load raw blanks into the machine tool and unload finished parts from the machine. The change in shape and size of the part before and after machining often presents a problem in end effector design, and dual grippers are often used to deal with this issue.
- **Forging**. The robot is typically used to load the raw hot billet into the die, hold it during the forging blows, and remove it from the forge hammer. The hammering action and the risk of damage to the die or end effector are significant technical problems. Forging and related processes are difficult as robot applications because of the severe conditions under which the robot must operate.
- **Pressworking**. Human operators work at considerable risk in sheet metal press working operations because of the action of the press. Robots are used as substitutes for the human workers to reduce the danger. In these applications, the robot loads the blank into the press, the stamping operation is performed, and the part fails out the back of the machine into a container. In high-production runs, press working operations can be mechanized by using sheet metal coils instead of individual blanks. These operations require neither humans nor robots to participate directly in the process.
- **Heat treating**. These are often relatively simple operations in which the robot loads and/or unloads parts from a furnace.

A7 Coordinate Measuring Machines CMM

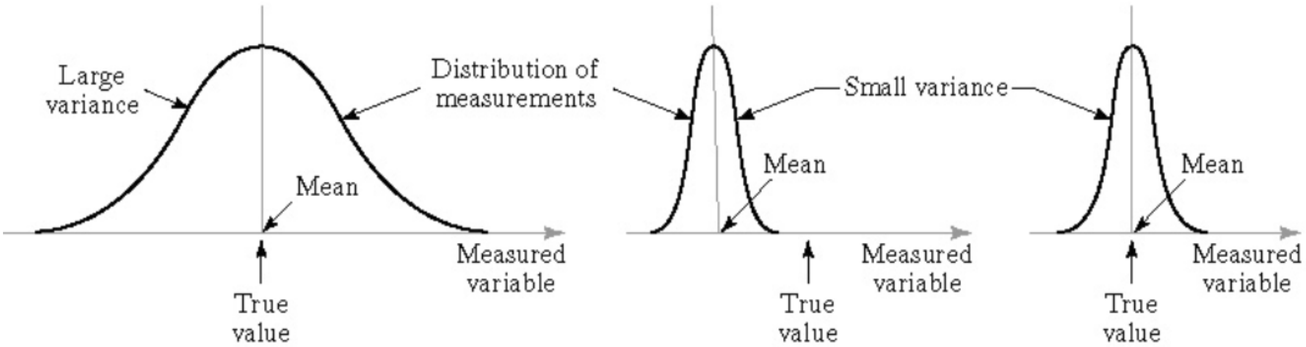
Inspection Metrology

- **Measurement** is a procedure in which an unknown quantity is compared to a known standard, using an accepted and consistent system of units. The measurement may involve a simple linear rule to scale the length of a part, or it may require measurement of force versus deflection during a tension test. Measurement provides a numerical value of the quantity of interest, within certain limits of accuracy and precision. It is the means by which inspection for variables is accomplished.

- **Metrology** is the science of measurement. The science is concerned with seven basic quantities: length, mass, time, electric current, temperature, luminous intensity, and matter. From these basic quantities, other physical quantities are derived, such as area, volume, velocity, acceleration, force, electric voltage, energy, and so forth. *In manufacturing metrology, our main concern is usually with measuring the length quantity in the many ways in which it manifests itself in a part or product.* These include length, width, depth, diameter, straightness, flatness, and roundness. Even surface roughness is defined in terms of length quantities.

Characteristics of Measuring Instruments

All measuring instruments possess certain characteristics that make them useful in the particular applications they serve. Primary among these are accuracy and precision, but other features include speed of response, operating range, and cost. They can be used as criteria in selecting a measuring device. No measuring instrument scores perfect marks in all of the criteria. Compromises are required in choosing a device for a given application, emphasizing those criteria that are most important.



a) High accuracy but low precision, (b) low accuracy but high precision, and (c) high accuracy and high precision.

Two Basic Types of inspection Techniques

Inspection techniques can be divided into two broad categories:

- contact inspection
- noncontact inspection.

In contact inspection, physical contact is made between the object and the measuring or gaging instrument, whereas in noncontact inspection no physical contact is made.

Reasons why these contact inspection methods are technologically and commercially important include the following:

- They are the most widely used inspection technologies today.
- They are accurate and reliable.
- In many cases, they represent the only methods available to accomplish the inspection.

Noncontact Inspection Technologies

Noncontact inspection methods utilize a sensor located at a certain distance from the object to measure or gage the desired features. The noncontact inspection technologies can be classified into two categories:

- optical
- non-optical

Optical inspection technologies make use of light to accomplish the measurement or gaging cycle. The most important optical technology is machine vision; however, other optical techniques are important in certain industries.

Non-optical inspection technologies utilize energy forms other than light to perform the inspection; these other energies include various electrical fields, radiation (other than light), and ultrasonics.

Noncontact inspection offers certain advantages over contact inspection techniques. **The advantages** include:

- Avoidance of damage to the surface that might result from contact inspection.
- Inherently faster inspection cycle times. The reason is that contact inspection procedures require the contacting probe to be positioned against the part, which takes time. Most of the noncontact methods use a stationary probe that does not need repositioning for each part.
- Noncontact methods can often be accomplished on the production line without the need for any additional handling of the parts, whereas special handling and positioning of the parts is usually required in contact inspection.
- Increased opportunity for 100% automated inspection. Faster inspection cycle times and reduced need for special handling means that 100% inspection is more feasible with noncontact methods.

Contact vs. Noncontact Inspection Technologies

Inspection Technology	*Typical Resolution*	*Relative Speed of Application*
Conventional instruments:		
Steel rule	0.25 mm (0.01 in)	Medium speed (medium cycle time)
Vernier caliper	0.025 mm (0.001 in)	Slow speed (high cycle time)
Micrometer	0.0025 mm (0.0001 in)	Slow speed (high cycle time)
Coordinate measuring machine	0.0005 mm (0.00002 in)*	Slow cycle time for single measurement. High speed for multiple measurements on same object.
Machine vision	0.25 mm (0.01 in)**	High speed (very low cycle time per piece)

*Also see Table 23.5 for other parameters on coordinate measuring machines.

** Precision in machine vision is highly dependent on the camera lens system and magnification used in the applications.

Coordinate Metrology

A coordinate measuring machine (CMM) consists of a contact probe and a means of positioning the probe in 3D space relative to the surfaces and features of a work part. The probe is not merely positioned relative to the part but its location can be accurately and precisely recorded to obtain dimensional data concerning the part geometry.

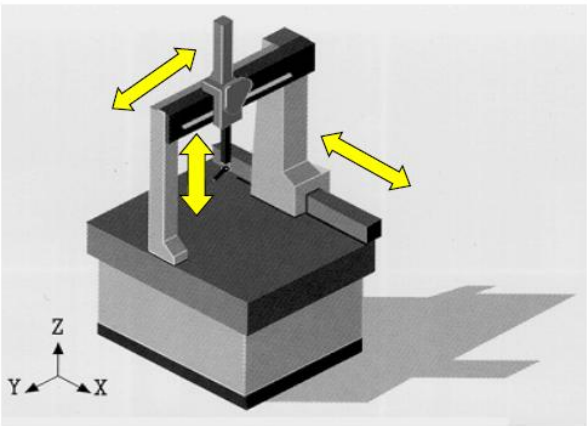
CMMs are controlled by computers or numerical control systems; when a component is to be inspected for its profile and other features, the program or coordinate data is downloaded from the central computer. The systems are capable of transmitting data from the measuring machine back to the computer.

CMM Configurations

In the construction of a coordinate measuring machine, the probe is fastened to some type of structure that allows movement of the probe relative to the part. The part is located on a worktable that is usually connected to the structure. There are several different physical configurations for achieving the motion of the probe, including the following common types:

Bridge construction:

The bridge configuration is the most common type used in industry. To achieve the y-axis movement of the probe, the arm is supported on both ends like a bridge. This construction provides greater inherent rigidity and this makes the bridge construction more accurate than the cantilevered CMM.



Cantilever construction:

In the cantilever configuration, the probe is attached to a vertical quill that moves in a z-axis direction relative to a horizontal arm that overhangs the worktable. The quill can also be moved along the length of

The bridge can move in y-direction while the probe arm can move on the bridge in xdirection and the probe itself can be moved in z-direction. The weight of the moving elements is borne by the air bearings and thereby the bridge, the arm and the probe can be **moved with a very light force** in their respective directions of movement. The measuring machine can be made work in force axes by mounting a rotatory table on the bed. These movements can be done either manually or by switch or program control.

These machines have electromechanical probes of the touch trigger type. **Multistyle probes for CMM** are also available which are found quite useful while inspecting complex components. Standard blocks and spheres are supplied as accessories with the machines and are to be used for calibration and setting references.

- Stationary granite measuring table

Granite table provides a stable reference plane for locating parts to be measured. It is provided with a grid of threaded boles defining clamping locations and facilitating part mounting. As the table has a high load carrying capacity and is accessible from three sides, it can be easily integrated into the material flow system of CIM.

- **Length measuring system**

A three-axis CMM is provided with a digital incremental length measuring system for each axis.

- **Air bearings**

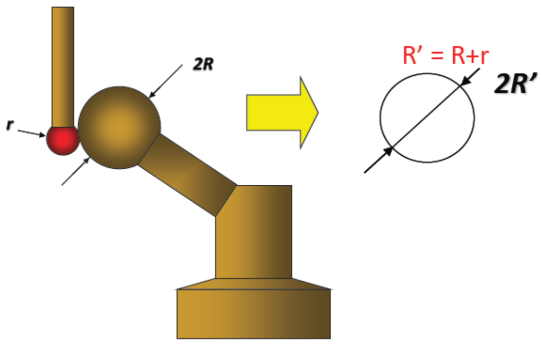
The bridge, cross beam and spindle of the CMM are supported by air bearings with high rigidity. They are designed to be insensitive to vibrations.

- **Control unit**

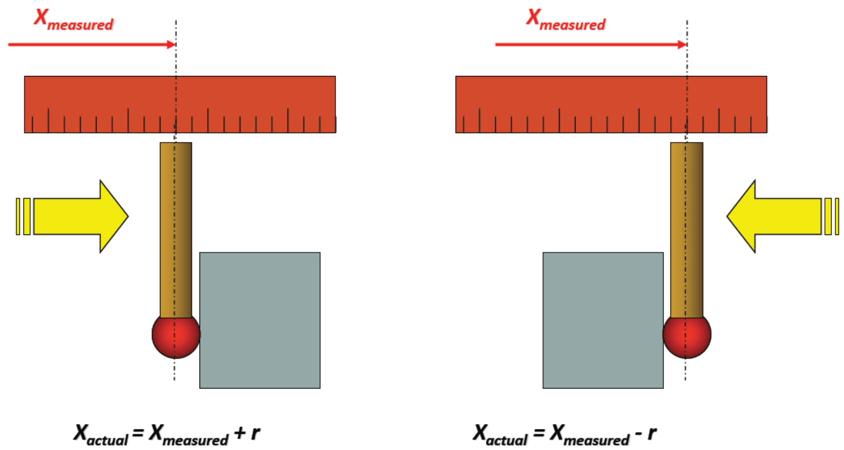
The control unit allows manual measurement and self-teach programming in addition to CNC operation. The control unit is microprocessor controlled. Usually a joystick is provided to activate the drive for manual measurement.

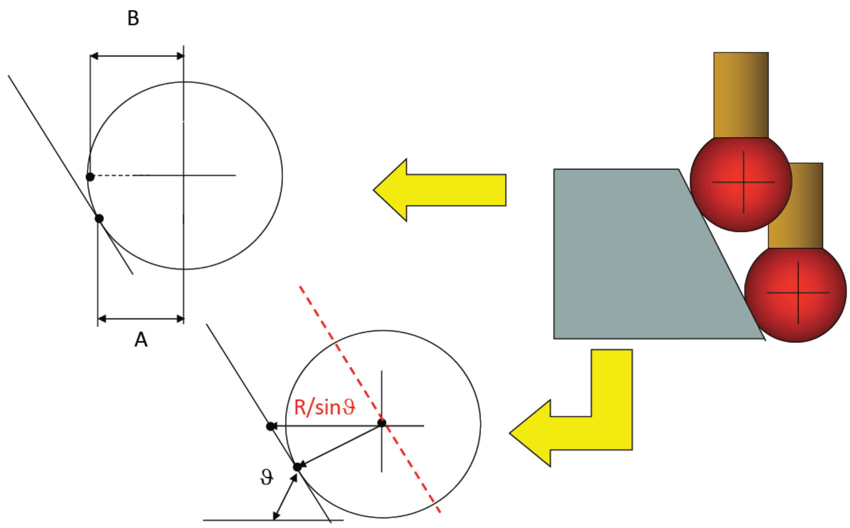
CNC measuring centers are provided with dynamic probe heads and a probe changing system which can be operated manually or automatically.

The probes are generally of the ball ended type. However, conical probes, which are more rigid, are convenient to be used for determining the position of the center of a hole. The touch trigger type has a number of different probes mounted on it enabling measurement in difficult positions under servomotor control. The probe is carried on a light and flexible mechanism which communicates an electric signal when touched and the information is not affected by over-travel. The coordinates at that instant with respect to a reference are displayed on the indicating unit of the instrument.



Radius compensation:





CMM Programming

There are two principle methods of programming measuring machine:

(1) manual leadthrough
(2) off-line programming.

In the **manual leadthrough** method, the operator leads the CMM probe through the various motions required in the inspection sequence, indicating the points and surfaces that are to be measured and recording these into the control memory. This is similar to the robot programming technique of the same name. During regular operation, the CMM controller plays back the program to execute the inspection procedure.

Off-line programming is accomplished in the manner of computer-assisted NC part programming. The program is prepared off-line based on the part drawing and then downloaded to the CMM controller for execution. The programming statements for a computer-controlled CMM include motion commands, measurement commands, and report formatting commands. The motion commands are used to direct the probe to a desired inspection location, in the same way that a cutting tool is directed in a machining operation.

The measurement statements are used to control the measuring and inspection function of the machine, calling the various data processing and calculation routines into play. Finally, the formatting statements permit the specification of the output reports to document the inspection.

An enhancement of off-line programming is CAD programming, in which the measurement cycle is generated from CAD geometric data representing the part rather than from a hard copy part drawing. Off-line programming on a CAD system is facilitated by the Dimensional Measuring Interface Standard (DMlS). DMlS is a protocol that permits two-way communication between CAD systems and CMMs. Use of the DMIS protocol has the following advantages:

(1) It allows any CAD system to communicate with any CMM;
(2) it reduces software development costs for CMM and CAD companies because only one translator is required to communicate with the DMlS;
(3) users have greater choice in selecting among CMM suppliers, and
(4) user training requirements are reduced.

CMM Software

The CMM, the computer and the software together represent one system whose efficiency and cost effectiveness depend to a large extent on the software.

The features of a CMM software will include

a) Measurement of diameter, center distances, lengths, geometrical and form errors in prismatic components, etc.
b) Online statistics for statistical information in a batch;
c) Parameter programming to minimize CNC programming time of similar parts;
d) Measurement of plane and spatial curves;
e) Data communications;
f) Digital input and output commands for process integration;
g) Programs for the measurement of spur, helical, bevel and hypoid gears;
h) Interface to CAD software.

Core CMM Software – Geometric Feature Construction

Dimensions. A dimension of a part can be determined by taking the difference between the two surfaces defining the dimension. The two surfaces can be defined by a point location on each surface. In two axes (x-y), the distance L between two point locations (x_1, y_1) and (x_2, y_2) is given by

$$L = \pm\sqrt{(x_2 - x_1)^2 + (y_2 - y_1)^2} \tag{23.3}$$

In three axes (x-y-z), the distance L between two point locations (x_1, y_1, z_1) and (x_2, y_2, z_2) is given by

$$L = \pm\sqrt{(x_2 - x_1)^2 + (y_2 - y_1)^2 + (z_2 - z_1)^2} \tag{23.4}$$

See Example 23.1.

Hole location and diameter. By measuring three points around the surface of a circular hole, the "best–fit" center coordinates (a, b) of the hole and its radius R can be computed. The diameter = twice the radius. In the x-y plane, the coordinate values of the three point locations are used in the following equation for a circle to set up three equations with three unknowns:

$$(x - a)^2 + (y - b)^2 = R^2 \tag{23.5}$$

where a = x-coordinate of the hole center, b = y-coordinate of the hole circle, and R = radius of the hole circle. Solving the three equations yields the values of a, b, and R. $D = 2R$. See Example 23.2.

Cylinder axis and diameter. This is similar to the preceding problem except that the calculation deals with an outside surface rather than an internal (hole) surface.

Sphere center and diameter. By measuring four points on the surface of a sphere, the best–fit center coordinates (a, b, c) and the radius R (diameter $D = 2R$) can be calculated. The coordinate values of the four point locations are used in the following equation for a sphere to set up four equations with four unknowns:

$$(x - a)^2 + (y - b)^2 + (z - c)^2 = R^2 \tag{23.6}$$

where a = x-coordinate of the sphere, b = y-coordinate of the sphere, c = z-coordinate of the sphere, and R = radius of the sphere. Solving the four equations yields the values of a, b, c, and R.

Definition of a line in x-y plane. Based on a minimum of two contact points on the line, the best-fit line is determined. For example, the line might be the edge of a straight surface. The coordinate values of the two point locations are used in the following equation for a line to set up two equations with two unknowns:

$$x + Ay + B = 0 \tag{23.7}$$

where A is a parameter indicating the slope of the line in the y-axis direction and B is a constant indicating the x-axis intercept. Solving the two equations yields the values of A and B, which defines the line. This form of equation can be converted into the more familiar conventional equation of a straight line, which is

$$y = mx + b \tag{23.8}$$

where slope $m = -1/A$ and y-intercept $b = -B/A$.

Angle between two lines. Based on the conventional form equations of the two lines, that is, Eq. (23.8), the angle between the two lines relative to the positive x-axis is given by:

$$\text{Angle between line 1 and line 2} = \alpha - \beta \tag{23.9}$$

where $\alpha = \tan^{-1}(m_1)$, where m_1 = slope of line 1; and $\beta = \tan^{-1}(m_2)$, where m_2 = slope of line 2.

Definition of a plane. Based on a minimum of three contact points on a plane surface, the best–fit plane is determined. The coordinate values of the three point locations are used in the following equation for a plane to set up three equations with three unknowns:

$$x + Ay + Bz + C = 0 \tag{23.10}$$

where A and B are parameters indicating the slopes of the plane in the y- and z-axis directions, and C is a constant indicating the x-axis intercept. Solving the three equations yields the values of A, B, and C, which defines the plane.

Flatness. By measuring more than three contact points on a supposedly plane surface, the deviation of the surface from a perfect plane can be determined.

Angle between two planes. The angle between two planes can be found by defining each of two planes using the plane definition method above and calculating the angle between them.

Parallelism between two planes. This is an extension of the previous function. If the angle between two planes is zero, then the planes are parallel. The degree to which the planes deviate from parallelism can be determined.

Angle and point of intersection between two lines. Given two lines known to intersect (e.g., two edges of a part that meet in a corner), the point of intersection and the angle between the lines can be determined based on two points measured for each line (a total of four points).

- **Measurement of geometric features requiring multiple contact points**. Available CMM software facilitates evaluation of these features.
- **Multiple inspection setups are required if parts are manually inspected**. Manual inspections are generally performed on surface plates using gage blocks, height gages, and similar devices, and a different setup is often required for each measurement. The same group of measurements on the part can usually be accomplished in one setup on a CMM.
- **Complex part geometry**. If many measurements are to be made on a complex part, and many contact locations arc required, then the cycle time of a DCC CMM will be significantly less than the corresponding time for a manual procedure.
- **High variety of parts to be inspected**. A DCC CMM is a programmable machine, capable of dealing with high parts variety.
- **Repeat orders**. Using a DCC CMM, once the part program has been prepared for the first part, subsequent parts from repeat orders can be inspected using the same program.

When applied in the appropriate parts quantity-parts variety range, the advantages of using CMMs over manual inspection methods are:

- **Reduced inspection cycle time**. Because of the automated techniques included in the operation of a CMM, inspection procedures are speeded and labor productivity is improved. A DCC CMM is capable of accomplishing many of the measurement tasks in one-tenth the time or less, compared with manual techniques. Reduced inspection cycle time translates into higher throughput.
- **Flexibility**. A CMM is a general-purpose machine that can be used to inspect a variety of different part configurations with minimal changeover time. In the case of the DCC machine, where programming is performed off-line, changeover time on the CMM involves only the physical setup.
- **Reduced operator errors**. Automating the inspection procedure has the obvious effect of reducing human errors in measurements and setups.
- **Great inherent accuracy and precision**. A CMM is inherently more accurate and precise than the manual surface plate methods that are traditionally used for inspection.
- **Avoidance of multiple setups**. Traditional inspection techniques often require multiple setups to measure multiple part features and dimensions. In general, all measurements can be made in a single setup on a CMM, thereby increasing throughput and measurement accuracy.

Classification of prototypes

Prototyping is the process of developing solutions in a piecewise fashion that allows clients to test ideas and provide feedback during the development process.

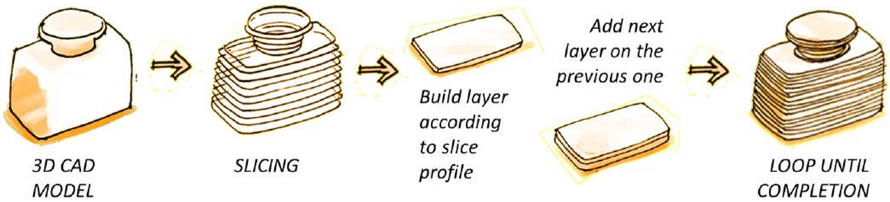
	Conceptual prototype	Functional prototype	Technical prototype	Pre-series prototype
AIM	• Geometry evaluation • Assembly Test • Analysis of technical issues	• Evaluation of performances by functional tests • Optimization of the product for its function	• Evaluation of product performances and process • Optimization of fabrication techniques	Final evaluation of the product (only small changes are admitted)
MATERIAL	Any	Similar	Very Similar	Final
FABRICATION TECHNIQUE	Any	Any	Similar	Final

Rapid Prototyping

Rapid Prototyping is used widely to describe technologies which create physical prototypes directly from digital data.

The basic principle of this technology is that a model, initially generated using a three-dimensional Computer Aided Design (3D CAD) system, can be fabricated directly without the need for process planning.

The model is built in a few hours, without the need for tools. It is possible to build virtually any shape.

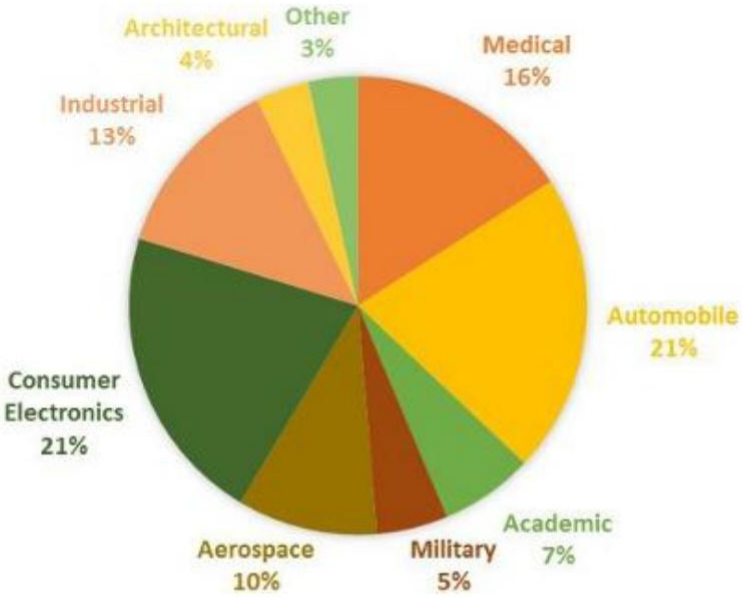


Rapid Prototyping vs. Additive Manufacturing

The term Rapid Prototyping does not effectively describe more recent applications of the technology. Many parts are in fact now directly manufactured in these machines; so it is not possible to label them as "prototypes."

Recently adopted term is **Additive Manufacturing.**


Industrial sectors



AM Facts & Forecasts

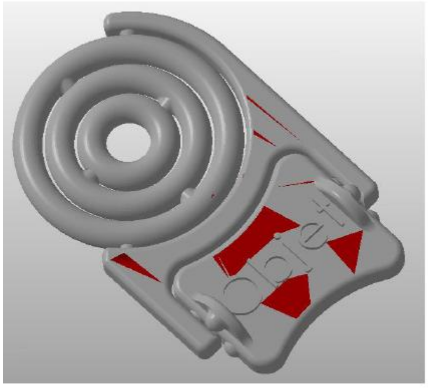
- Although additive manufacturing will not replace conventional production methods, it is expected to revolutionize many niche areas. Exponential growth is on the horizon.

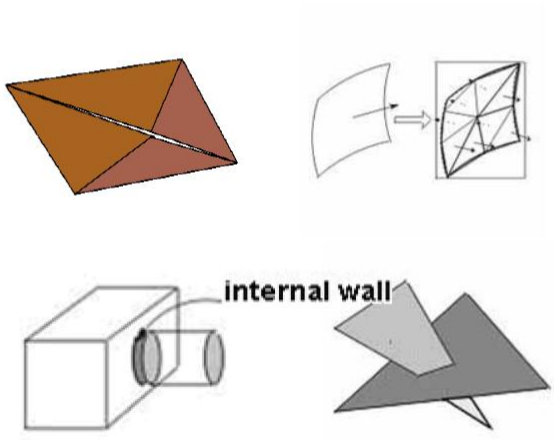
- "Moneywill be made with manufacturing, not with prototypes" forecasts Tim Caffrey, a consultant at Wohlers.

- AM allows to design products in such a way that the products can do things that conventional ones can't.

Errors in an STL File

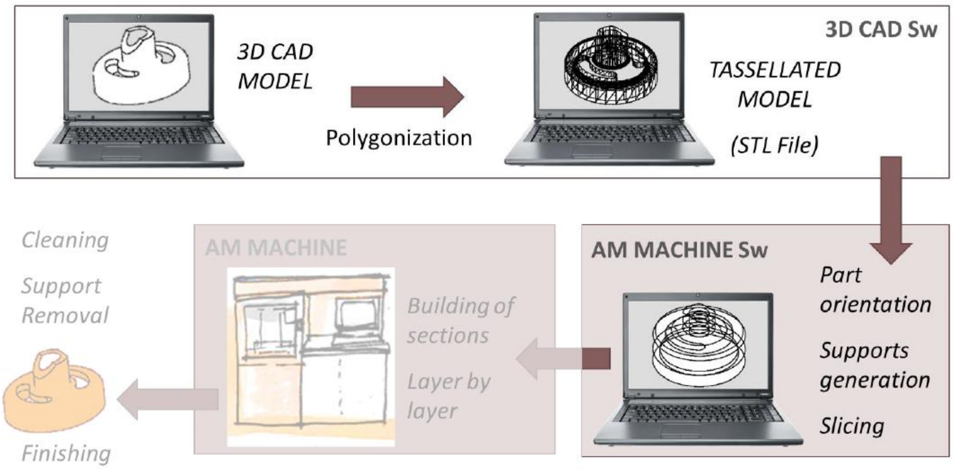
Gaps between cells, Inverted normals, Intersection of triangles, Internal walls.





Steps of Digital Fabrication

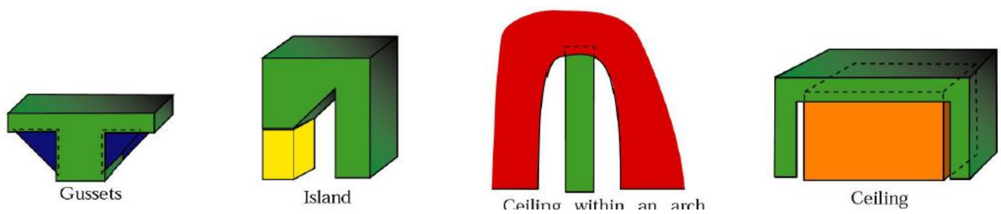
The STL file describing the part must be transferred to the AM machine. Here, there may be some general manipulation of the file so that it is the correct size, position, and orientation for building.



Supports

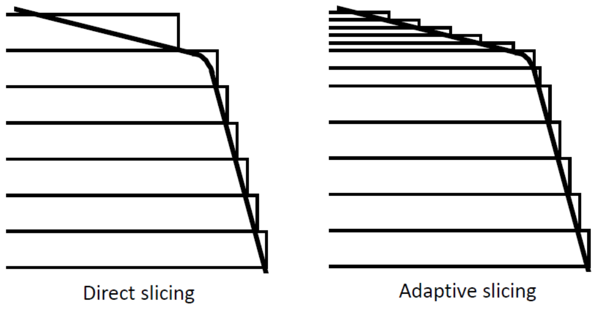
Many additive manufacturing machines need a means to hold in place unsupported geometries during fabrication, such as the top of a part in the shape of the letter "T."

These supports are usually calculated and added to the part by the system's software and may be formed of the same material as the part, or from a different material. Support structures are either mechanically removed or dissolved away in secondary operations before the part can be used.



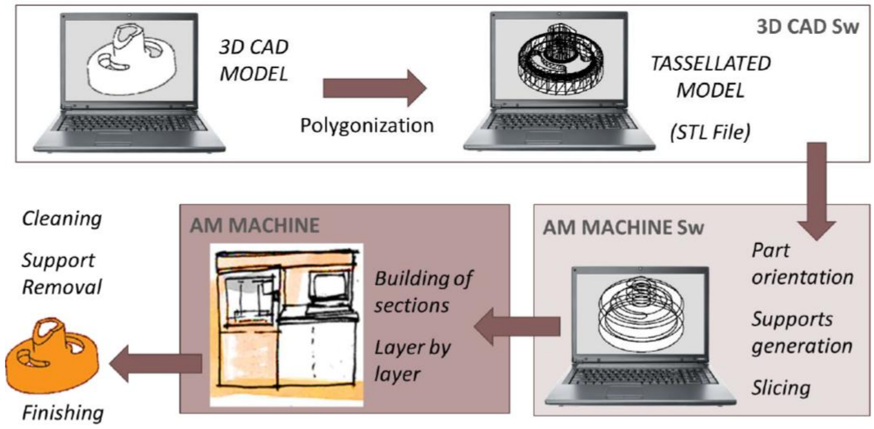
Adaptive Slicing

Adaptive slicing methods by automatically adjust the build layer thickness to accommodate surface geometry (curvature).



Steps of Digital Fabrication

Additive Manufacturing processes are automated systems that take 2-dimensional layers of computer data and rebuild them into 3D solid objects.



AM Steps

- The AM machine must be properly set up prior to the build process. Such settings would relate to the build parameters like the material constraints, energy source, layer thickness, timings, etc.
- Building the part is mainly an automated process and the machine can largely carry on without supervision. Only superficial monitoring of the machine needs to take place at this time to ensure no errors have taken place like running out of material, power or software glitches, etc.
- Once the AM machine has completed the build, the parts must be removed. This may require interaction with the machine, which may have safety interlocks to ensure for example that the operating temperatures are sufficiently low or that there are no actively moving parts.
- Once removed from the machine, parts may require an amount of additional cleaning up before they are ready for use. Parts may be weak at this stage or they may have supporting features that must be removed. This therefore often requires time and careful, experienced manual manipulation.
- Parts may now be ready to be used. However, they may also require additional treatment before they are acceptable for use. For example, they may require priming and painting to give an acceptable surface texture and finish. Treatments may be laborious and lengthy if the finishing requirements are very demanding. They may also be required to be assembled together with other mechanical or electronic components to form a final model or product.

AM vs. CNC

Both AM and CNC are computer-based technologies that are used to manufacture products. CNC differs mainly in that it is primarily a subtractive rather than additive process.

Material

AM technology was originally developed around polymeric materials, waxes and paper laminates. Subsequently, there has been introduction of composites, metals, and ceramics. When using CNC machining to make final products, it works particularly well for hard, relatively brittle materials like steels and other metal alloys to produce high accuracy parts with well-defined properties.

Speed

High speed CNC machining can generally remove material much faster than AM machines can add a similar volume of material. CNC machines require considerable setup and process planning, particularly as parts become more complex in their geometry. Speed must therefore be considered in terms of the whole process rather than just the physical interaction of the part material.

Complexity

the higher the geometric complexity, the greater the advantage AM has over CNC. AM processes are not limited by tool accessibility constraints and undercuts and internal features can be easily built without specific process planning.

Accuracy

AM machines generally operate with a resolution of a few tens of microns (variable resolution along different orthogonal axes). The accuracy of CNC machines is mainly determined by the positioning resolution along all three orthogonal axes and by the diameter of the rotary cutting tools

Geometry

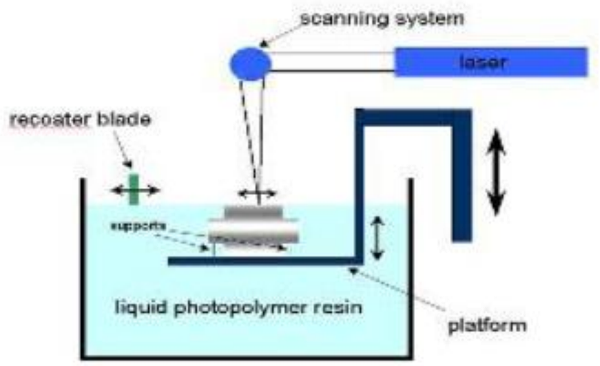
AM machines essentially break up a complex, 3D problem into a series of simple 2D cross-sections with a nominal thickness. In CNC, machining of surfaces must normally be generated in 3D space. Freeform surfaces can become extremely difficult to produce with CNC, even with 5-axis control or greater.

Programming

Determining the program sequence for a CNC machine can be very involved, including tool selection, machine speed settings, approach position, and angle, etc. Many AM machines also have options that must be selected, but the range, complexity and implications surrounding their choice are minimal in comparison.

Vat Photopolymerization

Descritpion	Material	Processs Name	Company (Country)
Liquid photopolymer in a vat is selectively cured by light-activated polymerization	Photopolymer	Stereolithography Digital Light processing Digital Light processing SLA / DLP	3D Systems (USA) Envisiontec (Germany) Asiga (USA) DWS (Italy)
	Photopolymer (ceramic)	CeraFab CeramPilot	Lithoz (Austria) 3DCeram (France)



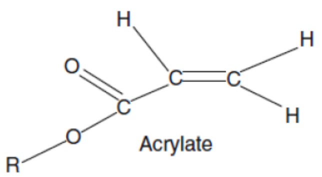
- The first commercial system was the 3D Systems Stereolithography process based on liquid photopolymers.
- Photopolymerization processes make use of liquid, radiation curable resins, or photopolymers as their primary materials.
- Photopolymers react to radiation in the ultraviolet (UV) range of wavelengths. Upon irradiation, these materials undergo a chemical reaction to become solid. This reaction is called photopolymerization, and is typically complex, involving many chemical participants.

Photopolymers

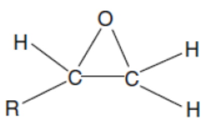
The first US patents describing SL resins were published in 1989 and 1990. These resins were prepared from *acrylates*, which had high reactivity but typically produced weak parts due to the inaccuracy caused by shrinkage and curling.

The *epoxy resins* produce more accurate, harder, and stronger parts than the acrylate resins. The epoxy resins have disadvantages of slow photo speed and brittleness of the cured parts. Another disadvantage is their sensitivity to humidity, which can inhibit polymerization.

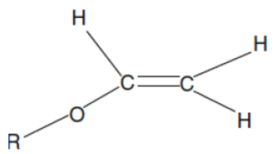
As a result, most SL resins commercially available today are epoxides with some acrylate content.



Acrylate

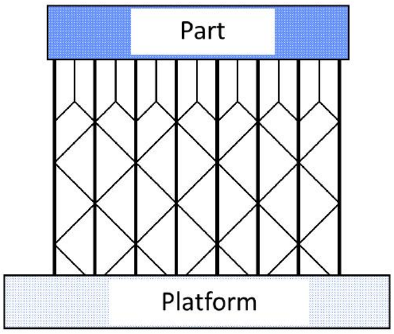


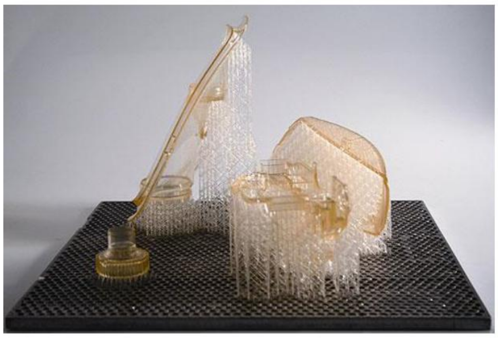
Epoxy



Vinylether

Stereolithography – Support Structure





Stereolithography – Characteristics

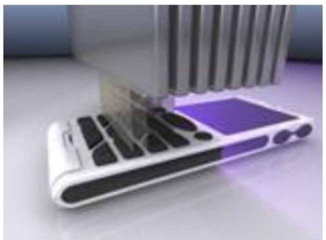
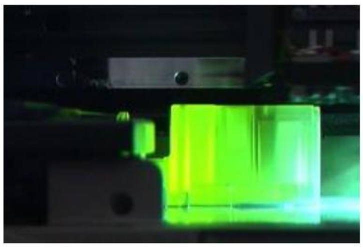
Two of the main advantages of SL technology over other AM technologies are part accuracy and surface finish, in combination with moderate mechanical properties.

- Layerthickness0.05 –0.025 mm
- Accuracy< 0.1mm
- Translucent
- Surface finish ranges from submicron Ra for up facing surfaces to over 100 micrometres Ra for surfaces at slanted angles.

Stereolithography – Variables Affecting Product Quality


Material Jetting

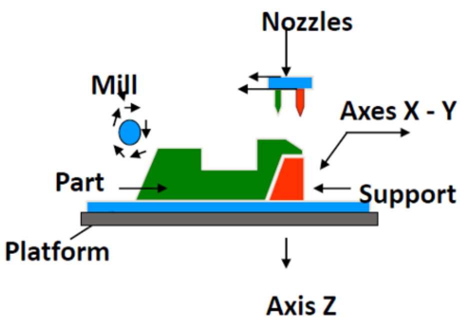
Description	Material	Processs Name	Company (Country)
Droplets of build material are selectively deposited 	Photopolymer	Polyjet Projet Ink-jetting	Objet (Israel) 3D Systems (USA) LUXeXcel (Netherlands)
	Wax	Thermojet / Projet T-Benchtop	3D Systems (USA) Solidscape-Stratasys (USA)

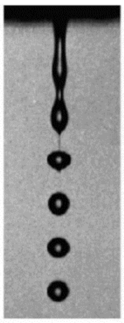



Material Jetting - DoD

Drop on Demand (DoD) machines employs two single jets –one to deposit a thermoplastic part material and one to deposit a waxy support material –to form layers 1.3·10-2 mm thick.

It should be noted that these machines also fly-cut layers after deposition to ensure that the layer is flat for the subsequent layer. Because of the slow and accurate build style as well as the waxy materials, these machines are often used to fabricate investment castings for the jewellery.

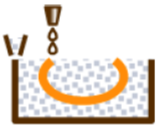


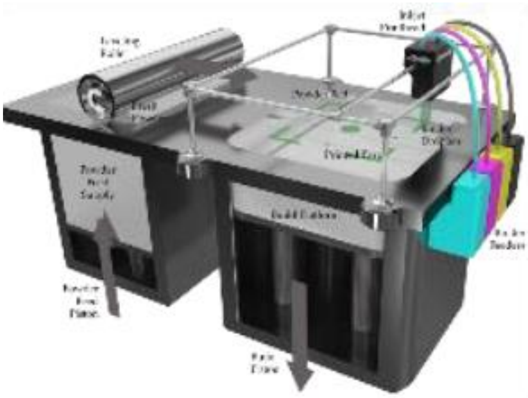


Material:

non-toxic thermoplastic materials featuring lost wax casting qualities.

Binder Jetting

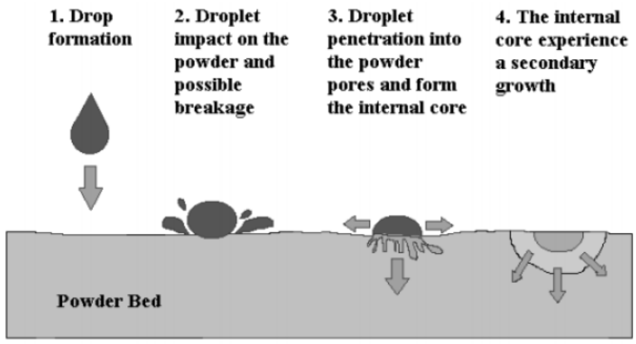
Description	Material	Processs Name	Company (Country)
Liquid bonding agent is selectively deposited to join powder material	Metal	M-Print / M-Lab	ExOne (USA)
	Polymer	3DP	Voxel Jet (Germany)
	Ceramic	3DP (models & parts) 3DP (medical implant) S-Print (sand cores)	3D Systems (Z-Corp) Therics (USA) ExOne (USA)



Three-Dimensional Printing (3DP) was invented at MIT and has been licensed to more than five companies for commercialization. In contrast to the printing processes described earlier, 3DP prints a binder into a powder bed to fabricate a part. Hence, in 3DP, only a small portion of the part material is delivered through the print-head; most of the part material is comprised of powder in the powder bed.



Droplet – Powder Interaction



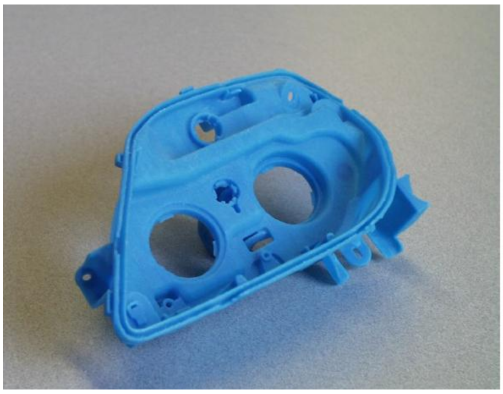
Droplet Interaction with Powder

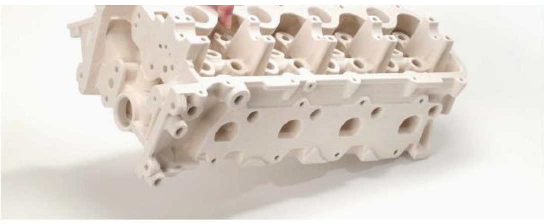
Analogous to inkjet paper printer:

(Binder ≡ Ink Powder Layer ≡ Paper)

Exception: Binder must penetrate to bond with previous layer

3DP – Examples:



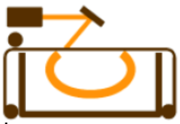


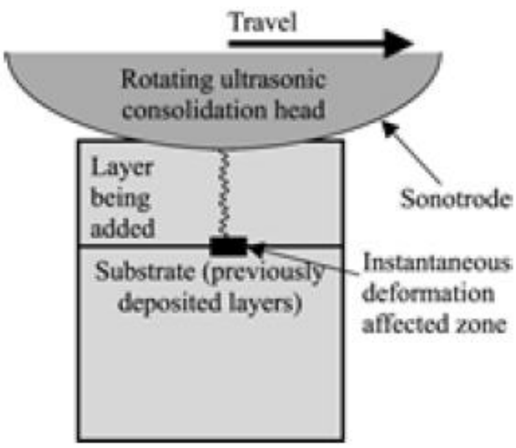
-In general, printing machines can be assembled from standard components (drives, stages, print heads), while other machines have many more machine-specific components.
- High speed and scalability are related: by using print heads with hundreds or thousands of nozzles, it is possible to deposit a lot of material quickly and over a considerable area. Scalability in this context means that printing speed can be increased by adding another print head to a machine, a relatively easy task, much easier than adding another laser to a SLA or SLS machine.

Drawbacks of Printing

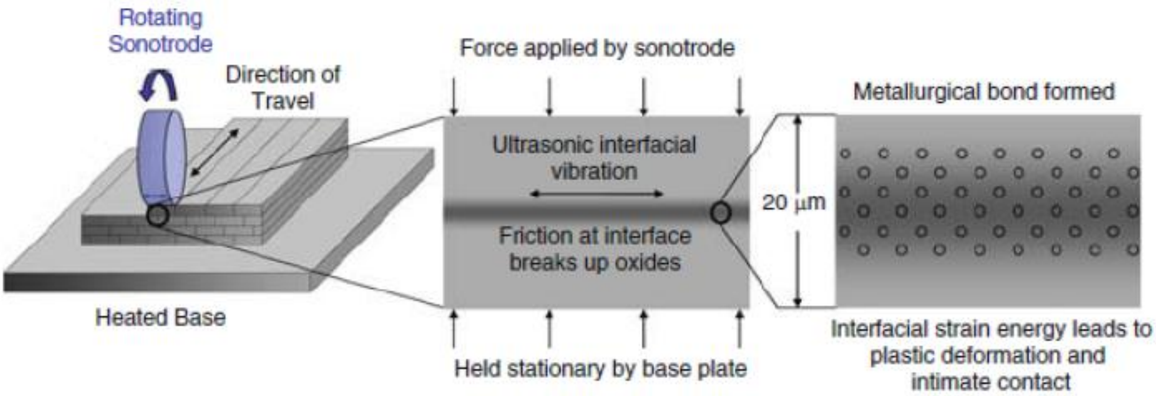
The choice of materials to date is limited.
For direct printing, only waxes and photopolymers are commercially available.
For binder printing, some polymer-ceramic composites and metals are available, but they come with many limitations.
Part accuracy, particularly for large parts, is generally not as good as with some other processes, notably SLA and Fused Deposition Modelling.
However, accuracies have been improving across the industry and are expected to improve among all processes.

Sheet Lamination

Description	Material	Processs Name	Company (Country)
Sheets of material are bonded to form an object	Metal	Ultrasonic Consolidation	Fabrisonic / Solidica (USA)
	Ceramic	Laminated Objet Manufacture	CAMLEM (USA)



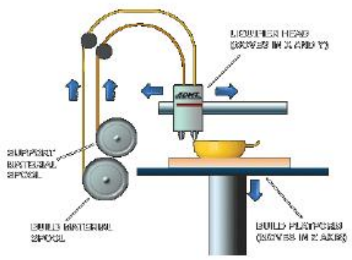
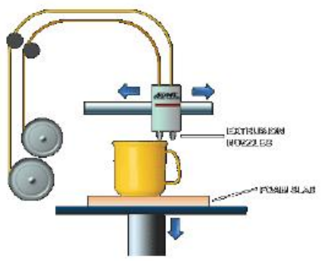
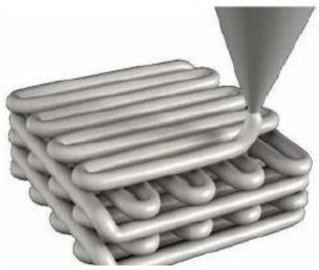
One of the first commercialized (1991) additive manufacturing techniques was Laminated Object Manufacturing (LOM). LOM involved layer-by-layer lamination of paper material sheets, cut using a CO2 laser, each sheet representing one cross sectional layer of the CAD model of the part. In LOM, the portion



The object is built up on a base plate bolted onto a heated platen (up to 200°C). A rotating sonotrode travels along the length of a thin metal foil (100–150 mm). The foil is held in contact with the base plate or previous layer by applying a normal force via the rotating sonotrode. The sonotrode oscillates transversely to the direction of motion, at a constant 20 kHz frequency and user-set oscillation amplitude. After depositing a foil, another foil is deposited adjacent to it. This procedure is repeated until a complete layer is placed. The next layer is bonded to the previously deposited layer using the same procedure. After deposition of four layers, the CNC milling head shapes the deposited foils/layers to their slice contour. This additive-subtractive process continues until the final geometry of the part is achieved.

Material Extrusion

Description	Material	Processs Name	Company (Country)
Material are selectively dispensed through a nozzle or orifice 	Polymer	FDM (Dimension & Fortus) FDM (Replicator) FDM (UP) FDM (Cube & BFB)	Stratasys (USA) MakerBot (USA) Delta Microfactory (China) 3D Systems (USA)

Fused Deposition Modelling

FDM uses a heating chamber to liquefy polymer that is fed into the system as a filament. The filament is pushed into the chamber by a tractor wheel arrangement and it is this pushing that generates the extrusion pressure.

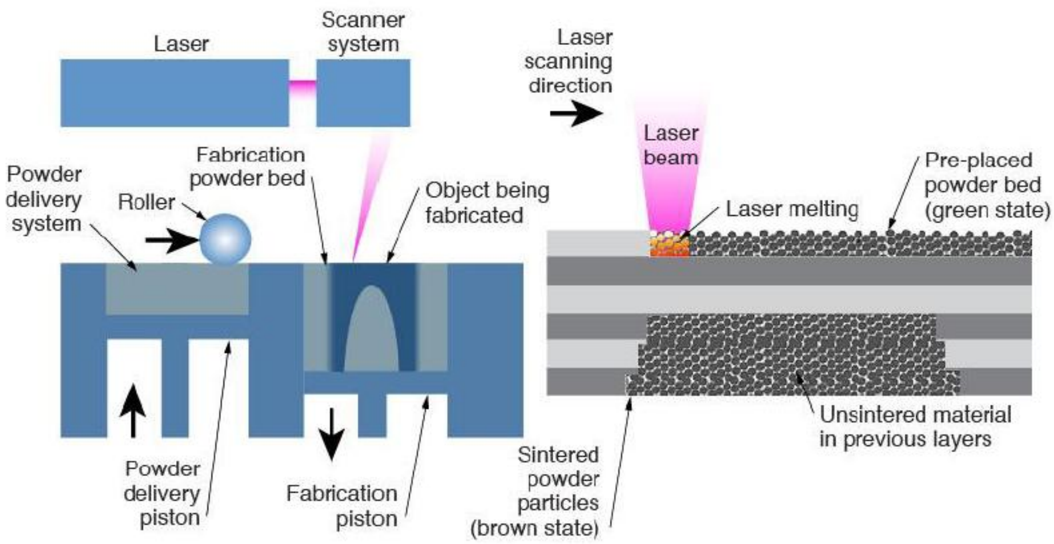
Material: Thermoplastic (ABS)

Powder Bed Fusion

Description	Material	Processs Name	Company (Country)
Thermal energy selectively fuses regions of a powder bed 	Metal	Direct metal laser sintering Selective laser melting Selective laser melting Selective laser melting Selective laser melting Selective laser melting Selective laser melting Electron beam melting	EOS (Germany) Concept Laser (Germany) Renishaw (UK) Realizer (Germany) Phenix (France) SLM Solutions (Germany) Matsuura (Japan) ARCAM (Sweden)
	Polymer	Selective Laser Sintering	EOS (Germany) 3D Systems (USA)
	Ceramic	Selective Laser Sintering	Phenix (France) EOS (Germany)

Powder bed fusion (PBF) processes were among the first commercialized AM processes.

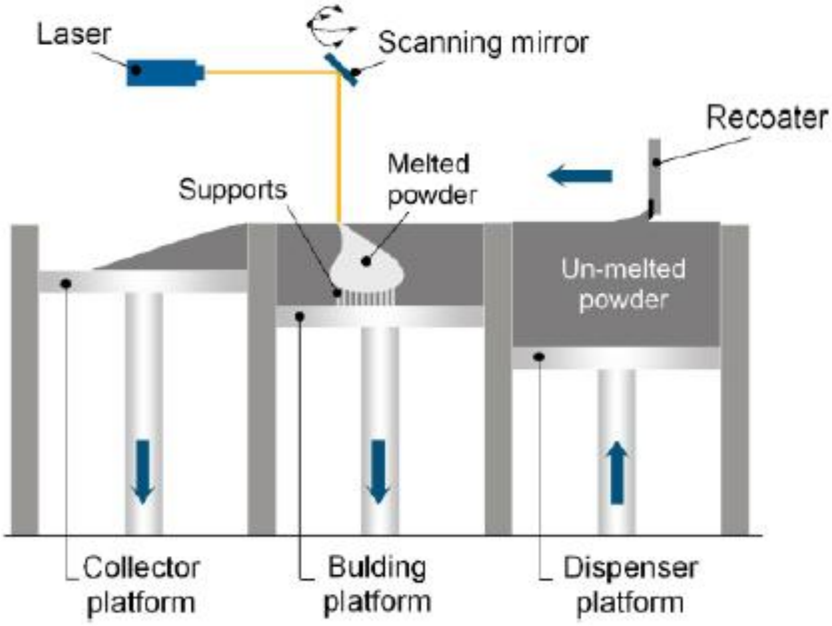
All PBF processes share a basic set of characteristics. These include one or more thermal sources for inducing fusion between powder particles, a method for controlling powder fusion to a prescribed region of each layer, and mechanisms for adding and smoothing powder layers.



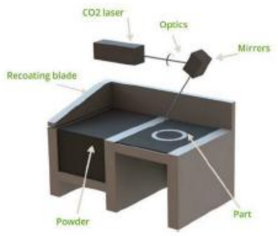
Selective Laser Sintering (SLS)

- SLS fuses thin layers of powder (typically ~0.1 mm thick) which have been spread across the build area using a counter-rotating powder levelling roller.

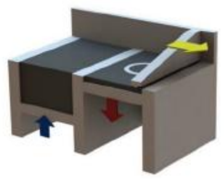
At the end of the building process, the platform with the part is subjected to a thermal treatment for stress relieving and, thereafter, the partis removed from the platform.



The DMLS process

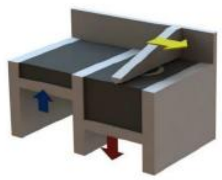


A layer of powder (from 0.02 mm to 0.08 mm thick) is deposited on the build platform by a recoating blade. The bottom layer of the part is then created by the laser, which locally melts the powder



The roller then deposits another layer of powder as the build platform lowers one layer and the powder reservoir is raised by the same amount

The laser then fuses the second layer to the first and so on...



As the layers build, the level in the build chamber goes down and the powder reservoir base rises

When the final layer of the part has been built, the powder is removed...

...revealing the part attached to the build platform

EOS M 290	
Building volume	250 mm x 250 mm x 325 mm (9.85 x 9.85 x 12.8 in)
Laser type	Yb-fibre laser; 400 W
Precision optics	F-theta-lens; high-speed scanner
Scan speed	up to 7.0 m/s (23 ft./sec)
Focus diameter	100 µm (0.004 in)
Power supply	32 A
Power consumption	max. 8.5 kW / typical 3.2 kW
Nitrogen generator	integrated
Compressed air supply	7,000 hPa; 20 m^3/h (102 psi; 706 ft^3/h)
Dimensions (B x D x H)	
System	2,500 mm x 1,300 mm x 2,190 mm (98.4 x 51.2 x 86.2 in)
Recommended installation space	min. 4,800 mm x 3,600 mm x 2,900 mm (189 x 142 x 114 in)
Weight	approx. 1,250 kg (2,756 lb)
Data preparation	
Software	EOS RP Tools; EOSTATE; EOSPRINT; Materialise Magics RP
	with SG+ and further modules
CAD interface	STL. Optional: converter for all standard formats
Network	Ethernet

EOS M 400 and M 400-4

Proven quality, high productivity

- Increased productivity due to 1 kW laser
- Reduced non-productive time due recoating from both sides
- Reduced filter costs due to new recirculating filter system with automated cleaning function

Modular platform

- EOS M 400 consists of a Process Station and a Setup Station. This modular approach facilitates the easy integration of future innovations.

Enhanced monitoring

- Extensive monitoring features take quality management to a new level.

Sophisticated software

- Job preparation and calculation is separated from the building process: the job file prepared at your desk is transmitted via the network; the system focusses entirely on building parts.

Improved usability

- EOS M 400 supports the production of complex metal parts. Nonetheless, the system is extremely user-friendly.
- Quick and easy operation via touch screen.

Broad material portfolio

- EOS offers an increasing number of metal materials for the EOS M 400 system. With the corresponding ParameterSets, the system produces parts with standardized part property profiles (PPPs).
- The ParameterEditor enables you to modify parameters to meet your individual requirements.

EOS Material Metal

Product class	Product name	Material type*	Typical applications
Maraging steel	**EOS MaragingSteel MS1**	18 Mar 300 / 1.2709	Series injection molding tools; mechanical parts
Stainless steel	**EOS StainlessSteel GP1**	Stainless steel 17-4 / 1.4542	Functional prototypes and series-production parts; mechanical engineering and medical technology
	EOS StainlessSteel PH1	Hardenable stainless steel 15-5 / 1.4540	Functional prototypes and series-production parts; mechanical engineering and medical technology
	EOS stainlessSteel 316L	1.4404 / UNS S31673	Lifestyle: jewellery, functional elements in yachts, spectacle frames, etc. Aerospace: supports, brackets, etc. Medical: functional prototypes and series-production parts in e.g. endoscopy and orthopedics
	EOS StainlessSteel CX	Tooling grade steel	Manufacturing of injection moulding tools for medical products or products from corrosive plastics
	EOS StainlessSteel 17-4PH	Stainless steel 17-4PH / 1.4542 / X5CrNiCuNb17-4 ASTM F899-12b	Medical instruments (surgical tools, orthopedic instrumentation) Acid- and corrosion resistant parts.

Product class	Product name	Material type*	Typical applications
Nickel alloy	**EOS NickelAlloy IN718**	InconelTM 718, UNS N07718, AMS 5662, mat. # 2.4668	Functional prototypes and series-production parts; high-temperature turbine components
	EOS NickelAlloy IN625	InconelTM 625, UNS N06625, AMS 5666F, mat. # 2.4856 etc.	Functional prototypes and series-production parts; high-temperature turbine components
	EOS NickelAlloy HX	UNS N06002	Components with severe thermal conditions and high risk of oxidation, e.g. combustion chambers, burner components, fans, roller hearths and support members in industrial furnaces
Cobalt chrome	**EOS CobaltChrome MP1**	CoCrMo super alloy, UNS R31538, ASTM F75	Functional prototypes, series-production parts, mechanical engineering, medical technology, dental
	EOS CobaltChrome SP2	CoCrMo super alloy	Dental restorations (series-production)
	EOS CobaltChrome RPD	CoCrMo super alloy	Removable partial dentures

Product class	Product name	Material type*	Typical applications
Titanium	**EOS Titanium Ti64**	Ti6Al4V light metal	Functional prototypes and series-production parts; aerospace, motorsports etc.
	EOS Titanium Ti64ELI	Ti6Al4V ELI	Functional prototypes and series-production parts in medical technology
	EOS Titanium TiCP**	TiCP Grade 2, 3.7035, ASTM F67 (UNS R50400), ISO5832-2)	Medical implants (trauma plates, CMF Implants, spinal cages, dental implants)
Aluminium	**EOS Aluminium AlSi10Mg**	AlSi10Mg light metal	Functional prototypes and series-production parts; mechanical engineering, motorsports etc.

EOS NickelAlloy IN718 is a heat resistant nickel alloy powder for series production in aerospace

Characteristics and applications

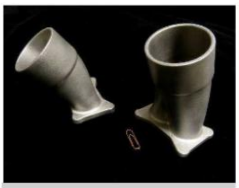
- Key characteristics
  - nickel based heat resistant alloy
  - outstanding corrosion resistance
  - high performance at temperatures up to 700°C, e.g. tensile strength, fatigue, creep and rupture
- Typical applications
  - aero and land based turbine engine parts
  - rocket and space application components
  - chemical and process industry parts
  - oil wells, petroleum and natural gas industry

Left: Turbine blade (demo part)
Top: Turbine wheel in EOS NickelAlloy IN718 built on EOSINT M 270 IM Xtended.

EOS CobaltChrome MP1 - CoCrMo superalloy material for prototyping and series production

Characteristics and applications

- Key characteristics
  - high strength, temperature and corrosion resistance
  - biocompatibility
  - fulfils ISO 5832-4 and ASTM F75 (cast CoCrMo implant alloys), and most of ISO 5832-12 and ASTM F1537 (wrought CoCrMo implants)
- Typical applications
  - high-temperature engineering applications, e.g. turbines
  - medical implants [1]



Engine exhausts in EOS CobaltChrome MP1

Knee implant in EOS CobaltChrome MP1

EOS CobaltChrome SP2 - special purpose CoCrMo superalloy for veneered dental restorations

Characteristics and applications

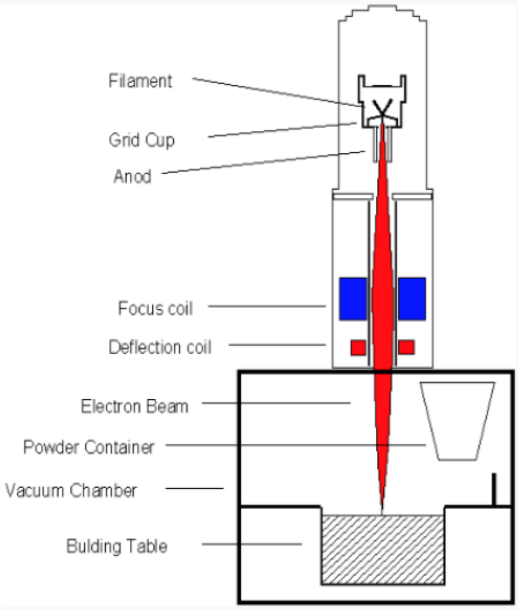
- Key characteristics
  - high strength, temperature and corrosion resistance
  - biocompatibility
  - thermal characterisitcs suitable for veneering with dental ceramic
- Application
  - dental restorations (crowns, bridges etc.)

Dental restorations in EOS CobaltChrome SP2

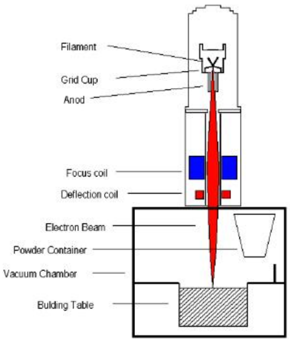
Job in EOS CobaltChrome SP2 with 384 units of dental restorations. Building time 20h.

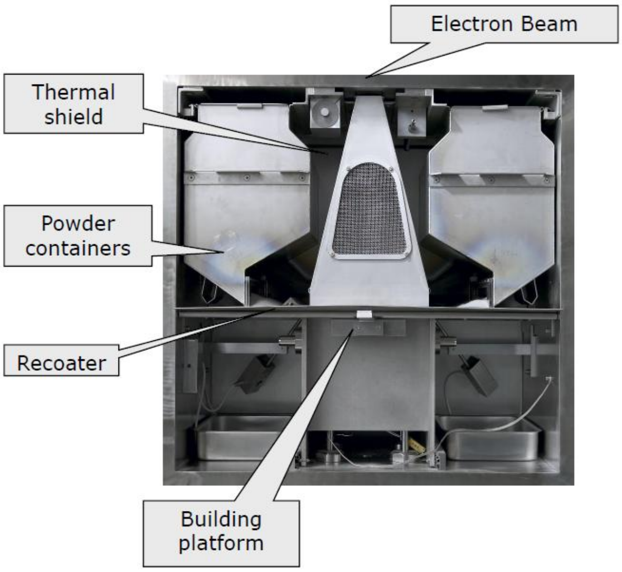
Electron Beam Melting

- **Electrons** are emitted from a filament which is heated to > 2500° C
- The electrons are **accelerated** through the anode
- A magnetic field lens brings the beam into **focus**
- Another magnetic field **controls the deflection** of the beam
- When the electrons hit the powder **kinetic energy** is transformed to **heat**.
- The heat **melts** the metal powder
- Power is controlled by altering the current in the beam.



No moving parts!





EBM Characteristic

- Ability to achieve **high power** (4 kW available) in a narrow beam.
- **High power utilization**
- **High build temperature**
- Beam Deflection with **no moving parts**
- Vacuum melt quality **eliminates impurities** and yields high strength properties of the material.
- Good thermal environment, leading to **good form stability** and **low residual stress** in the part
- Permits melting of **refractory metals** and combinations of dissimilar metals
- **Low operating costs**

Arcam – A2X

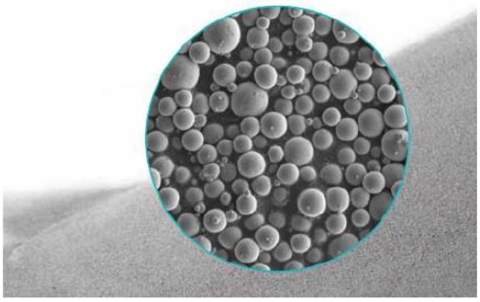
The Arcam A2X is designed to process titanium alloys as well as materials that require elevated process temperatures, e.g. titanium aluminide and Inconel, which makes it suited for both production and materials R&D. This EBM platform offers a build envelope of 200x200x380 mm.

Max. build size	200 x 200 x 380
Max. beam power	3000 W
Cathode type	Tungsten filament
Min. beam diameter	250μm
Max. EB translation speed	8000 m/s
Active cooling	No
Vacuum base pressure	5 x 10-4 mbar (chamber pressure before start of process)
Build atmosphere	2 x 10-3 mbar (partial pressure of He)
He consumption, build process	1 litre/h
He consumption, build cool down	50-75 litres/build cycle
Power supply	3 x 400 V, 32 A, 7 Kw
Size Approx.	1850 x 900 x 2200 mm (W x D x H)
Weight	1 700 kg
CAD interface Standard:	STL

EBM – Built Materials

Achieving target material properties is important for any demanding application, for orthopaedic implants and aerospace applications it is absolutely crucial. Arcam is committed to ensure first-class mechanical properties on all materials in our portfolio of standard materials.

- ExtensivetestinghasverifiedthatEBM-builtmaterialfulfillsallrelevantstandardswith regards to:
  - Chemical composition
  - Mechanical properties (static as well as fatigue)
  - Microstructure
- Standard Materials:
  - TitaniumTi6Al4V
  - TitaniumTi6Al4V ELI
  - Titanium Grade 2
  - Arcam ASTM F75
  - Cobalt-Chrome
  - Inconel718



EBM Technology – Fields of application

- Aerospace
  - Functional Parts
  - Prototypes
- Medical
  - Implants
  - Prosthesis
  - Instruments
  - Prototypes
- Automotive
  - Functional Parts
  - Prototypes

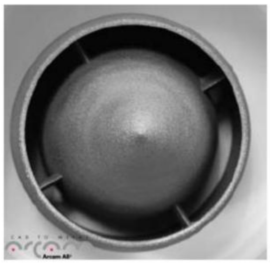
EBM Technology – Best – practice examples

Landing Gear Component

Material: Ti6Al4V
Weight: 4,5 kg

Aerospace Prototype

Material: Ti6Al4V
Weight: 5,5 kg

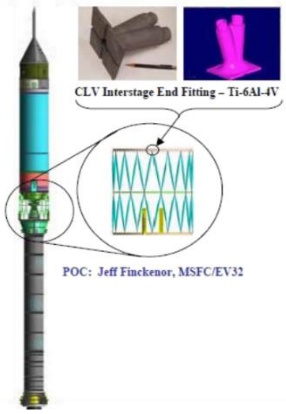


Rocket Engine Impeller

Material: Ti6Al4V ELI
Size: Ø 140 x 80 mm
Weight: 2,5 kg

CLV Interstage End Fitting

Manufactured by Synergeering for NASA Marshall Space Flight Center

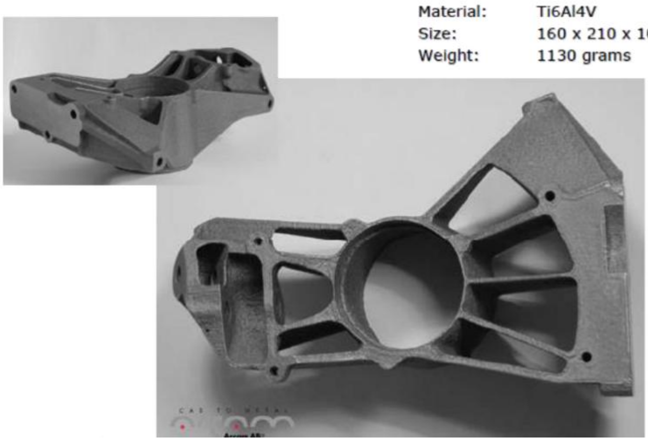


Race Car Gearbox Casing

Material: Ti6Al4V
Weight: 2,5 kg

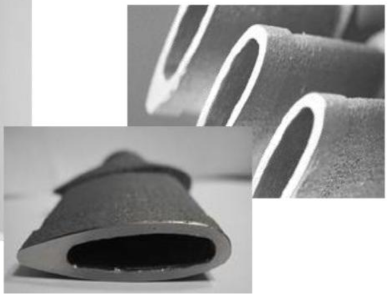
Race Car Suspension Parts

Material: Ti6Al4V
Size: 160 x 210 x 105 mm
Weight: 1130 grams



Race Car Suspension Parts

Material: Ti6Al4V
Size: 60 x 20 x 80 mm
Weight: 90 grams
Build time: 4.5 hours / 6 pieces



Spine Model for Crash Tests

Material: Ti6Al4V

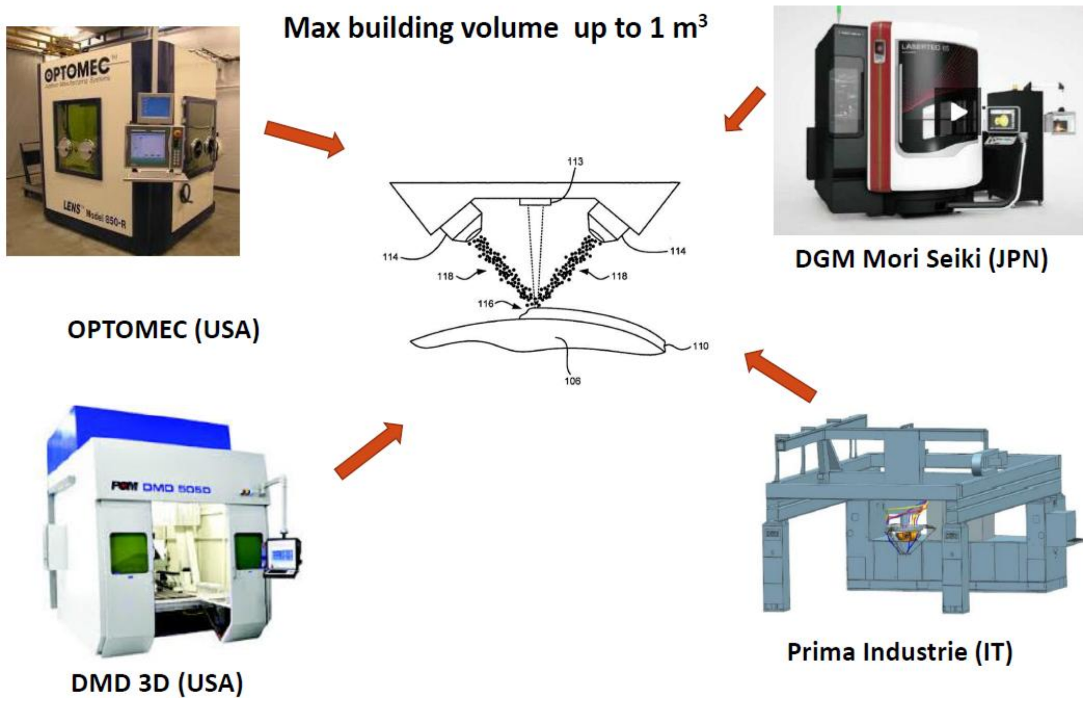
All components packed into one build.

Laser vs. Electron Beam

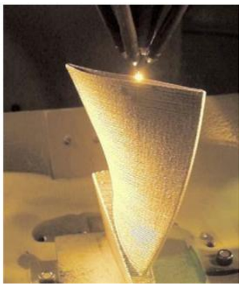
Table 5.1 Differences between EBM and SLM

Characteristic	Electron beam melting	Selective laser melting
Thermal source	Electron beam	Laser
Atmosphere	Vacuum	Inert gas
Scanning	Deflection coils	Galvanometers
Energy absorption	Conductivity-limited	Absorptivity-limited
Powder pre-heating	Use electron beam	Use infrared heaters
Scan speeds	Very fast, magnetically-driven	Limited by galvanometer inertia
Energy costs	Moderate	High
Surface finish	Moderate to poor	Excellent to moderate
Feature resolution	Moderate	Excellent
Materials	Metals (conductors)	Polymers, metals and ceramics

One of the most promising aspects of EBM is the ability to move the beam nearly instantaneously. Future improvements to scanning strategies may dramatically increase the build speed of EBM, helping to distinguish it even more from L-PBF for certain applications.



Examples:



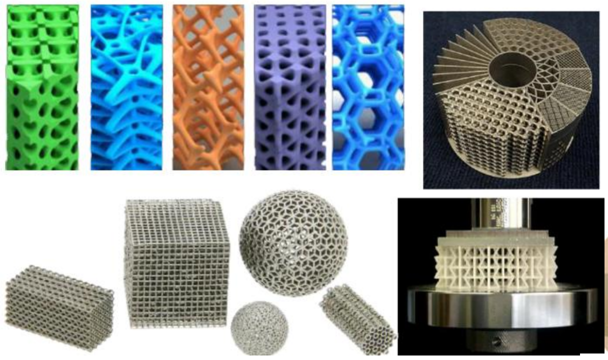
Wire

In the case of wire feeding, the volume of the deposit is always the volume of the wire that has been fed. This is effective for simple geometries, coating of surfaces, and/or deposits where porosity is acceptable. However, when complex, large, and/or fully dense parts are desired, geometry-related process parameters (such as hatch width, layer thickness, wire diameter, and wire feed rate) must be carefully controlled to achieve a proper deposit size and shape.

For certain geometries, it is not possible to control the geometry related process parameters accurately enough unless periodic subtractive processing (such as CNC machining) is done to reset the geometry to a known state.

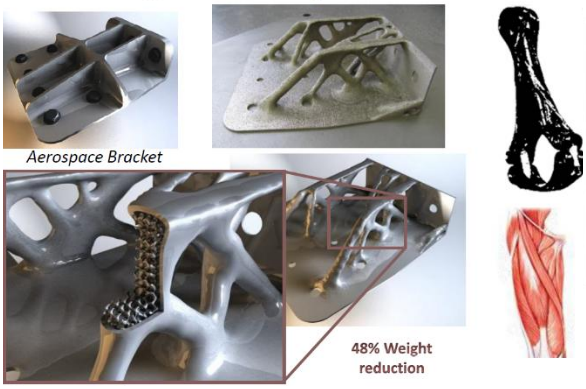
The selection of a wire feeding system versus a powder feeding system is best done after determining what type of deposit geometries are required and whether a subtractive milling system will be integrated with the additive deposition head.

Lattice Structures and Filters

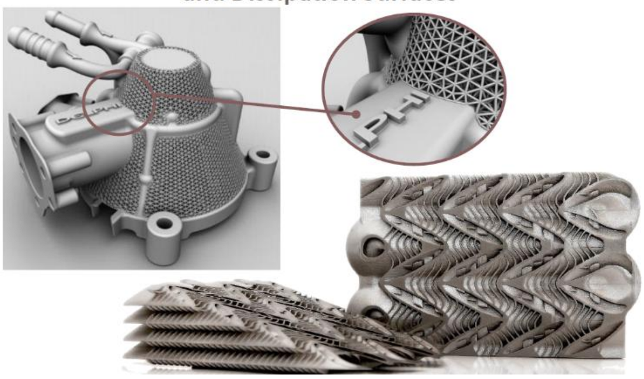


Living Hinges and Assemblies

Design from Biological Structures



Optimisation of Heat Exchangers and Dissipation Surfaces



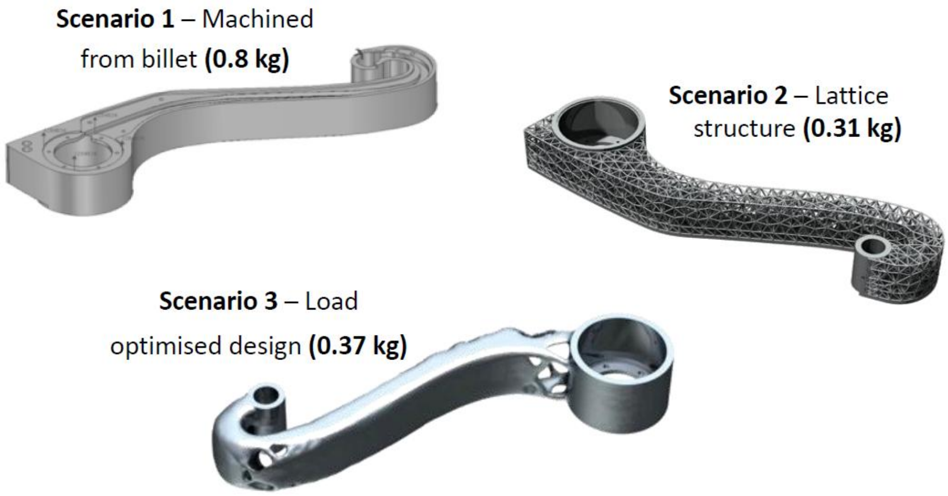
New Opportunites for Fluid Dynamics

SUMMING UP:

- Aerospace;
- Automotive;
- Medical and Dental;
- Jewellery;
- Architectural;
- Design and Fornitures;
- Fashion;
- Food industry;
- Lattice Structures and Filters;
- Living Hinges and Assemblies;
- Design from Biological Structures;
- Optimisation of Heat Exchangers and Dissipation Surfaces;
- New Opportunities for Fluid Dynamics.

Freeform design optimisation

Upper class monitor arm of Aluminum



Environment Impact

Example based on 90M km (Long haul) application

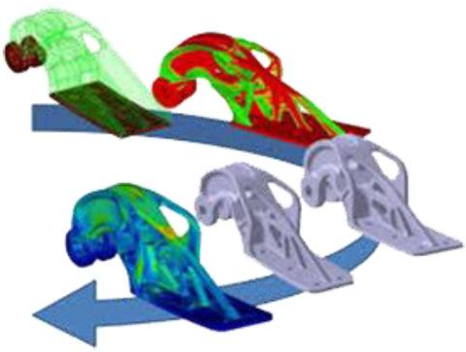
Process	Raw Materials CO_2	Manufacture CO_2	Distribution CO_2	Usage CO_2	Life cycle CO_2
Machining	100	2	5	43,779	43,886
SLM lattice	16	5	1	16,238	16,260
SLM optimal	18	7	2	20,339	20,366

(CO_2 values in kg)

Data courtesy of Loughborough University

Example – life cycle economic benefits

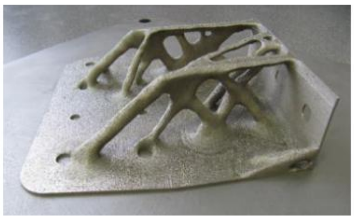
- 0.49 kg saving per monitor arm
- $1,500 per year in fuel savings (today's prices)
- $45,000 over 30-year aircraft life
- Product life span 5-7 years *(estimate)*
- Life-cycle economic saving $6.5K -$9K
- Machined part -$500
- AM Part -$2,500
- **Capital investment repaid in 2 years…**



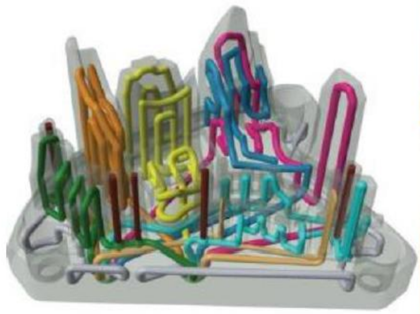
Original design

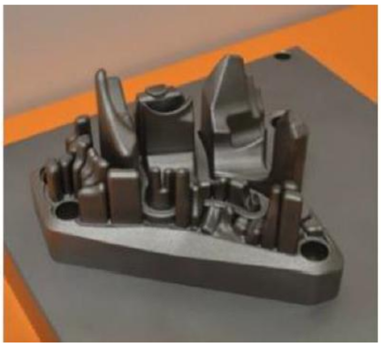
Aerospace Brackets

Designed for AM

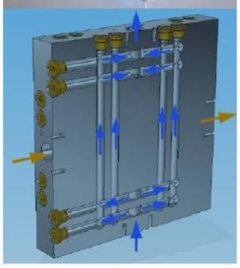


CONFORMAL COOLING RENISHAW

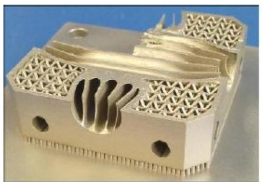


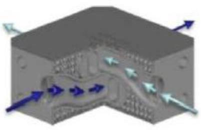


HEAT EXCHANGER HYDROVISION



2.900 cm^3 vs 244 cm^3
19.2 kg vs 1,2 kg
210 mm vs 85 mm





FLYING CAM

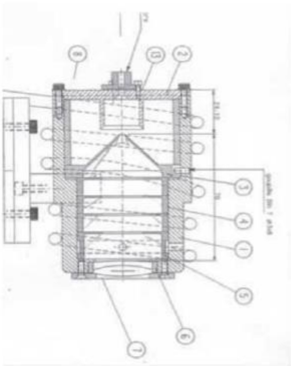
530g vs 392g (-26%)

7 components vs 2 components

3 materials vs 1 material (1 technology)

Much smaller carbon foot print

COLLIMATOR Sirris-CSL



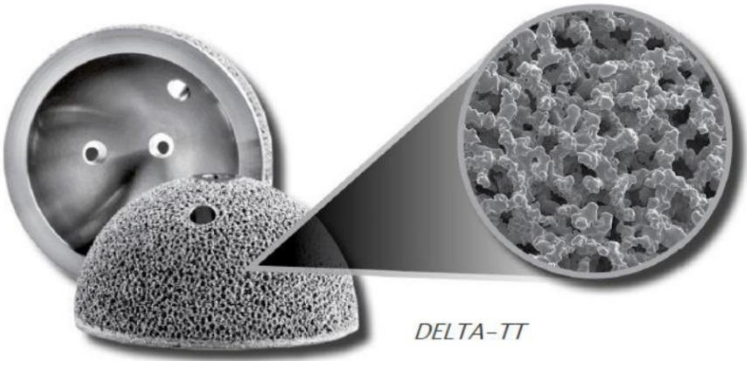
13 parts vs 2 parts

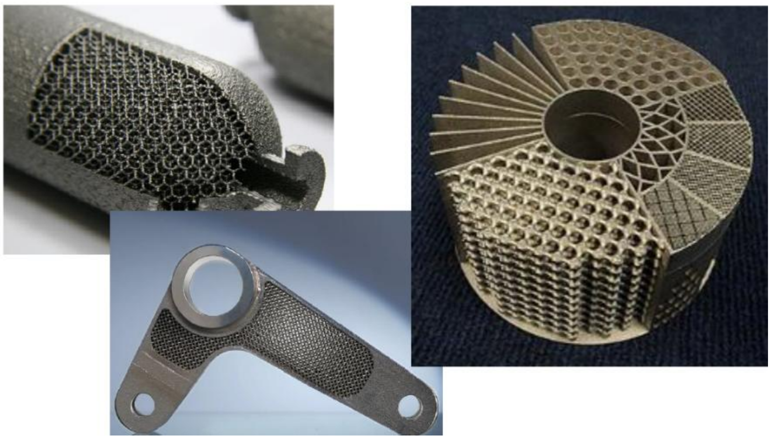
Internal cooling channels

Tollerances ok

Custom made porosities

What if … we can add porous structures to our part?





A8.6 CURRENT TRENDS AND FUTURE PERSPECTIVES

Multifunctional Technology Platforms

AM enabled multiple functionality to be manufactured using a single process.

- Replacing surface coatings & textures;
- Modifying physical behaviour by designing “*mechanical properties*”;
- Embedding secondary materials (*optical / electrical*).

Additive Manufacturing Sustainability

Product lifecycle improvements in economic and environmental sustainability.

- Reduced raw material consumption;
- Optimised product efficiency;
- Lighter weights components;
- Reduces the need for tooling (moulds/ cutters);
- Reduced capital investment & inventory;
- Efficient supply chains and new retail models (*Simplified and with reduced lead times*).

Forecast of future trends

Parameters	Trend	Main aspects
Chamber Volume	↗	• Problems with process reliability will keep chamber volume increase at a moderate rate
Build rates	↑	• Optimized layer structure (different layer thicknesses) • Process parallelization (simultaneous powder dispensing and laser melting) • Increased process stability (online monitoring systems)
Machine prices	↗	• Increasing addition of process and quality control electronics as well as number of lasers will raise the machine price, partly offset by economies of scales
Material prices	↘	• Powder prices set by AM system providers do not reflect production costs • With increasing market volume, metal powder producers will sell to end customers directly
Labour costs	↘	• Reliable systems will reduce effort for troubleshooting • Automated removal of excess powder

Future Challenges

- Filled Materials
- Multi material
- Local alloying
- Designed Anisotropy
- Designed local property
- Optimized metallurgical structures
- Ceramics and composite
- Nano Materials
- Micro parts
- Memory shape alloys in AM

What's next?

4D Printing…

If you're wondering how you can print in the 4thdimension (time), think of the ability to print out materials that are able to independently shape themselves and self-assemble over time.
There is a huge market
for such a technology.

Developments in the History of Automation and Control of Manufacturing Processes

Date	Development
1500-1600	Water power for metalworking; rolling mills for coinage strips.
1600-1700	Hand lathe for wood; mechanical calculator.
1700-1800	Boring, turning, and screw cutting lathe, drill press.
1800-1900	Copying lathe, turret lathe, universal milling machine; advanced mechanical calculators.
1808	Sheet-metal cards with punched holes for automatic control of weaving patterns in looms.
1863	Automatic piano player (Pianola).
1900-1920	Geared lathe; automatic screw machine; automatic bottle-making machine.
1920	First use of the word robot.
1920-1940	Transfer machines; mass production.
1940	First electronic computing machine.
1943	First digital electronic computer.
1945	First use of the word automation.
1947	Invention of the transistor.
1952	First prototype numerical control machine tool.
1954	Development of the symbolic language APT (Automatically Programmed Tool); adaptive control.
1957	Commercially available NC machine tools.
1959	Integrated circuits; first use of the term group technology.
1960	Industrial robots.
1965	Large-scale integrated circuits.
1968	Programmable logic controllers.
1970s	First integrated manufacturing system; spot welding of automobile bodies with robots; microprocessors; minicomputer-controlled robot; flexible manufacturing system; group technology.
1980s	Artificial intelligence; intelligent robots; smart sensors; untended manufacturing cells.
1990-2000s	Integrated manufacturing systems; intelligent and sensor-based machines; telecommunications and global manufacturing networks; fuzzy-logic devices; artificial neural networks; Internet tools; virtual environments; high-speed information systems.

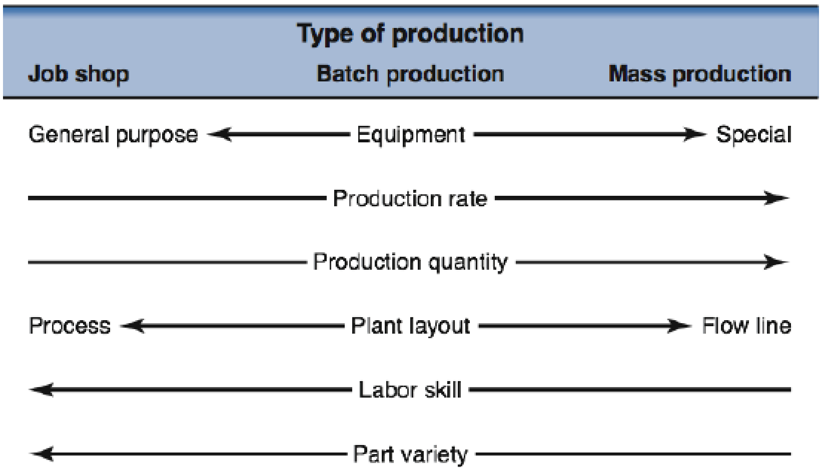
Production Quality

- The quantity of products Qmade by a factory has an important influence on the way its people, facilities, and procedures are organized

- Annual production quantities can be classified into three ranges

Production range:	**Annual Quantity, Q**
Low production	1 to 100 units
Medium production	100 to 10000 units
High production	10000 to millions of units

Hard Automation vs. Soft Automation



Hard Automation
Machines designed to produce a standardized product, thus specialized and lacking flexibility.
Transfer mechanisms and transfer lines used to move work pieces from one station to another.
Soft Automation
Flexible automation;
Programmable automation.

Goals of Automation

Automation has the following primary goals:

- integrating various aspects of manufacturing operations so as to improve product quality and uniformity, minimize cycle times and effort involved, and reduce labor costs.
- improving productivity by reducing manufacturing costs through better control of production. Raw materials and parts are loaded, fed, and unloaded on machines faster and more efficiently; machines are used more effectively; and production is organized more efficiently.
- improving quality by improving the repeatability of manufacturing processes.
- reducing human involvement, boredom, and the possibility of human error.
- reducing work piece damage caused by manual handling of parts.
- economizing on floor space by arranging machines, material handling and movement, and auxiliary equipment more efficiently.
- raising the level of safety for personnel, especially under hazardous working conditions.

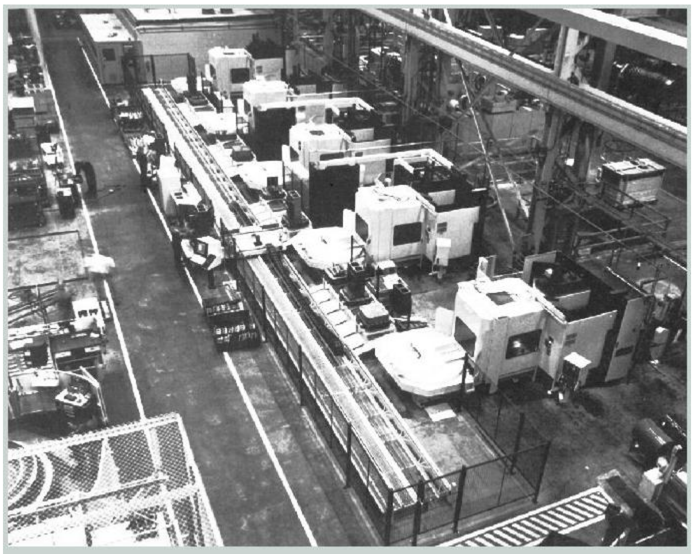
Application of Automation

The decision to automate a facility requires consideration of:

- type of product manufactured
- quantity and rate of production required
- manufacturing operation to be automated
- level of skill
- reliability and maintenance problems
- economics

A robotic arm performs unloading and loading operations in a turning center using a dual gripper.

Flexible Manufacturing Systems (FMS)



A general view of a flexible manufacturing system, showing several machine tools and an automated guided vehicle.

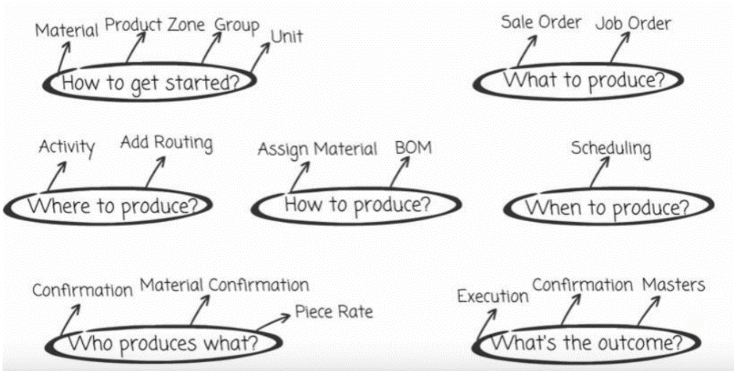
C1 PRODUCTION PLANNING

Generalities

The features of industrial evolution:

- Increasing of production volumes;
- Diversification of customer needs;
- Greater competition;
- Increasing availability of new technologies;
- Greater speed in transportation and communication;
- Presence of new services;
- A greater number of system components and relationships among them;

Production Planning questions:

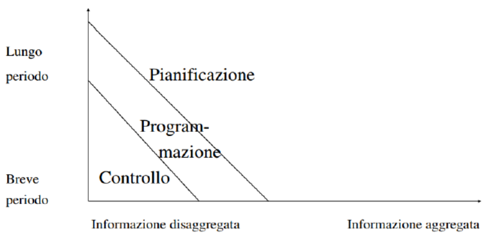


Production Management:

- It is the **decision-making process** through which the **productive resources** are organized in order to achieve certain goals.

- It is divided into three phases:

1. Production Planning
2. Production Programming
3. Production Control



Hierarchical Approach:

- Dividing the overall problem into simpler problems, so that within each problem the number of constrains and variables is limited.

Production Planning:

Definition:

Production planning is the process by which you define and commit the **amount of resources** (labour, equipment, machinery, materials) the company will need for its future productive activities, and the **resource allocation** in order to obtain the desired product, in the estimated quantities, at the expected time, and at the minimum possible cost.

Production Control:

Generally:

Production function that **controls** the performance of the **operations**, highlights the deviations from the production program and takes appropriate corrections.

Returning on the Production Planning…

2) Aggregate Production Planning (APP)

- It is medium-term plan;
- The level of accuracy of the available data is medium;
- It aims to **organize** and **allocate** existing resources and to **verify** their **adequacy to the expected and well-known forecast of demand** (from portfolio orders plus marketing goals).
- The **variables on which you can act** at the Aggregate Production Planning stage are:
    - Level of employment in the workforce;
    - Warehouse (magazzino);
    - Subcontracting in case of excess demand;
    - Investment in tools and equipment.

Input data:

1. **Long-term demand forecast**;
2. Human Resources available;
3. Inventory Level;
4. Production Costs;
5. Capacities Constraints;

Objectives:

1. Minimize costs;
2. Minimize inventory investments;
3. Minimize the variations in production levels / workforce;
4. Maximize profits;
5. Maximize Customer Service;
6. Maximize the use of plants and tools.

Actions:

Reactive alternatives: consist **of satisfying the given demand** that cannot be modified. They allow to change the production capacity to match the demand by using the following measures:

- Changes in the workforce;
- Use of extraordinary work;
- Use of the Warehouse;
- Subcontracting;
- Agreements with other companies;
- Accepting orders in advance;
- Possibility to postpone delivery;

Aggressive alternatives: consist **of changing the demand** and then the resource request.
- Price differentials in order to level the demand by reducing it in peak periods and by increasing it in times of lesser demand.
- Advertising to stimulate demand when it is less sustained.

The company Happy Colours produces and sells wholesale and retail paint products. The demand has a highly seasonal and has a peak in the third trimester. The production requires the best production plan for the current year and provides the following information:

Demand

I trim.: 300.000
II trim.: 850.000
III trim.: 1500.000
IV trim.: 350.000

Inventory:

Initial: 250.000
Final: 300.000

Costs:

Ordinary production: 1
Straordinary production: 1,50
External production: 1,90
Inventory cost (per trim.): 0,30

Constraints:

For each trimester
Straord. ≤ 0,2 Ordin.
No backorders

No stockout

Production Capacity (thousand):

Trimester	I trim	II trim	III trim	IV trim
Ordinary time:	450	450	750	450
Straordinary time:	90	90	150	90
External production:	200	200	200	200

Alternativs		Time Bucket 1	2	3	4	Unused Capacity	Total capacity
P	Inventory	0	0,30	0,60	0,90	250 / 0	250
1	Ordinary prod.	250 1.00	1,30	1,60	1,90	450 / 400 / 0	450
	Straordinary Prod.	50 1,50	400 1,80	2,10	2,40	90 / 0	90
	External Prod.	0 1,90	0 2,20	90 2,50	2,80	200 / 180	200
2	Ordinary Prod.	0	0 1.00	20 1,30	0 1,60	450 / 0	450
	Straordinary Prod.		450 1,50	1,80	2,10	90 / 0	90
	External Prod.		0 1,90	90 2,20	2,50	200 / 0	200
3	Ordinary Prod.		0	200 1.00	1,30	750 / 0	750
	Straordinary Prod.			750 1,50	1,80	150 / 0	150
	External Prod.			150 1,90	2,20	200 / 0	200
4	Ordinary Prod.			200	1.00	450 / 0	450
	Straordinary Prod.				450 1,50	90 / 0	90
	External Prod.				90 1,90	200 / 90	200
Demand		300	850	1500	110 650	270	3750

Consider the resolution algorithm provided by the Tableau method and identify the actions that ensure the optimum and the respect of constraints.

EXERCISE: Tableau Method (APP) (Personal Unwinding)

Demand
I trim.: 300.000
II trim.: 850.000
III trim.: 1500.000

IV trim.: 350.000

Inventory:
Initial: 250.000
Final: 300.000

Costs:
Ordinary production: 1
Straordinary production: 1,50
External production: 1,90
Inventory cost (per trim.): 0,30

Constraints:
For each trimester
Straord. ≤ 0,2 Ordin.
No backorders
No stockout

Production Capacity (thousand):

Trimester	I trim	II trim	III trim	IV trim
Ordinary time:	450	450	750	450
Straordinary time:	90	90	150	90
External production:	200	200	200	200

	1	2	3	4	Unused C	Used C
I_0	250 0	0,30	0,60	0,90	250	250
Q_{R1}	50 1,00	400 1,30	1,60	1,90	400/0	450
Q_{O1}	1,50	1,80	90 2,10	2,40	90/0	90
Q_{S1}	1,90	2,20	20 2,50	2,80	200/180	20
Q_{R2}		450 1,00	1,30	1,60	450/0	450
Q_{O2}		1,50	90 1,80	2,10	90/0	90
Q_{S2}		1,90	200 2,20	2,50	200/0	200
Q_{R3}			750 1,00	1,30	750/0	750
Q_{O3}			150 1,50	1,80	150/0	150
Q_{S3}			200 1,90	2,20	200/0	200
Q_{R4}				450 1	450/0	450
Q_{O4}				90 1,50	90/0	90
Q_{S4}				110 1,90	200/90	110
D	300	850	1500	350+300(I)		

$$\boldsymbol{I_t = I_{t-1} + Q_{Rt} + Q_{Ot} + Q_{St} - D_t}$$

$I_0 = 250$
$I_1 = 250 + 450 + 90 + 20 - 300 = \mathbf{510}$
$I_2 = 510 + 450 + 90 + 200 - 850 = \mathbf{400}$
$I_3 = 400 + 750 + 150 + 200 - 1500 = \mathbf{0}$

$$\boldsymbol{C_t = hI_t + rQ_{Rt} + cQ_{Ot} + sQ_{St}}$$

$C_1 = 0{,}30(510) + 1(450) + 1{,}5(90) + 1{,}9(20) = 776$
$C_2 = 0{,}30(400) + 1(450) + 1{,}5(90) + 1{,}9(200) = 1085$
$C_3 = 0{,}30(0) + 1(750) + 1{,}5(150) + 1{,}9(200) = 1355$
$C_4 = 0{,}30(300) + 1(450) + 1{,}5(90) + 1{,}9(110) = 884$
$C_T = 776 + 1085 + 1355 + 884 = \mathbf{4100}$

Production	1	2	3	4	5	6
Ordinary	200	200	350	200	150	150
Straordinary	30	40	70	40	30	30
External	0	0	0	0	30	100

Tableau Method (APP) (Personal Unwinding)

	1	2	3	4	5	6	Unused C	Used Q
I_0	30 0	0,20	0,40	0,60	0,80	1,00	30	30
Q_{R1}	120 1,10	80 1,30	1,50	1,70	1,90	2,10	200/80/0	200
Q_{O1}	1,50	30 1,70	1,90	2,10	2,30	2,50	40/10	30
Q_{S1}	2,00	2,20	2,40	2,60	2,80	3,00	100	0
Q_{R2}		200 1,10	1,30	1,50	1,70	1,90	200/0	200
Q_{O2}		40 1,50	1,70	1,90	2,10	2,30	40/0	40
Q_{S2}		2,00	2,20	2,40	2,60	2,80	100	0
Q_{R3}			200 1,10	50 1,30	80 1,50	20 1,70	350/150/100/20/0	350
Q_{O3}			1,50	1,70	1,90	70 2,10	70/0	70
Q_{S3}			2,00	2,20	2,40	2,60	100	0
Q_{R4}				200 1,10	1,30	1,50	200/0	200
Q_{O4}				1,50	40 1,70	1,90	40/0	40
Q_{S4}				2,00	2,20	2,40	100	0
Q_{R5}					150 1,10	1,30	150/0	150
Q_{O5}					30 1,50	1,70	30/0	30
Q_{S5}					2,00	30 2,20	100/70	30
Q_{R6}						150 1,10	150/0	150
Q_{O6}						30 1,50	30/0	30
Q_{S6}						100 2,00	100/0	100
D	150	350	200	250	300	350+50		

Provide some examples of product types that require a strategy: make stock, assembly to order or order or make to order.

PROJECTED ON HAND INVENTORY (2)

I_t provides an **estimation** of the **stocks available** in each period **after the satisfaction of the demand for that period.**

$$\boldsymbol{I_t = I_{t-1} + MPS_t - max\{F_t, O_t\}}$$

I_t: forecast of the stock availability in the period t (After the satisfaction of the demand for that period).
MPS_t: forecast of the produced quantity in the period t (Master Production Schedule).
F_t: forecast of the demand in the period t.
O_t: **new** orders in the period t.

- The maximum between the expected demand and the order already received is considered **in order to ensure the safety of the plane.**

- **The aim of the MPS** is to keep the **projected on-hand inventory non-negative** by identifying the moment and the quantities to produce.

	June				July			
I_o=45	1	2	3	4	5	6	7	8
F_t forecast	20	20	20	20	40	40	40	40
O_t orders	23	15	8	4	0	0	0	0
I_t Projected on-hand inventory	22	2	-18	...	...	...	...	...
MPS_t MPS Quantity								

45-23 | 22-20 | 2-20

	June				July			
I_o=45	1	2	3	4	5	6	7	8
F_t forecast	20	20	20	20	40	40	40	40
O_t Orders	23	15	8	4	0	0	0	0
I_t Projected on-hand inventory	22	2	62	42	2	42	2	42
MPS_t MPS Quantity			80			80		80

MPS_t Lot-size = 80

2+80-20

$$I_t = I_{t-1} + MPS_t - \max\{F_t, O_t\}$$

MPS_t Lot-size = 80	June				July			
I_o=45	1	2	3	4	5	6	7	8
F_t forecast	20	20	20	20	40	40	40	40
O_t orders	23	20	32	4	38	0	0	0
I_t Proj. on-hand invent.	22	2	50	30	-10	30	-10	30
MPS_t MPS Quantity			80			80		80
ATP_t Avail. to promise	2		6			80		80

CHANGES TO MPS

- MPS changes are expensive if they are introduced close to the delivery date:
  - Increasing the amount of MPS introduces delays in delivery, increased number of orders and shipping costs, possible stock outflows.
  - Decreasing the amount of MPS causes unused raw materials, components, under-assembled.

- MPS can be "**frozen**":
  - For a certain period of time, MPS cannot be updated automatically, but any modification must be authorized and executed manually.

- **Demand time fence**: Number of times (from the current one) during which the MPS cannot be modified without special permission.
- **Planning time fence**: Number of periods (from the current one) during which the MPS is not recalculated automatically but in which the MPS **quantities** can be changed manually by the manager.

ROUGHT CUT CAPACITY PLANNING (RCCP)

- **RCCP** is used to test the **feasibility of an MPS** by controlling the workload of some critical resources.

- RCCP uses a "**list of resources**" deployed by each finished product MPS.

- The list of resources (bill of resources or capacity bill) contains the **process time** on the critical resources needed to create a finished product.

Products \ Centers	10	20	30
1	4	4	2
2	8	0	4
3	4	8	6

[hours]

EXAMPLE (RCCP)

- We want to check the feasibility of the MPS of three End items, 1, 2, 3. The bill of resources of the Critical Workstations is 10, 20, 30 and the maximum workload on each workstation cannot exceed 3,000 hours.

- What objectives have emerged?

1. Keep the store level to the desired one.
2. Provide the right information about the materials and resources needed for APP.
3. Provide the right level of customer service.
4. Determine when and how to produce.

EXERCISE:

The prospectus describes the situation of a product whose production batch is 50 units.

I0=5	1	2	3	4	5	6	7	8	9	10
F_t	20	10	40	10	0	0	40	20	30	10
O_t	30	20	5	8	0	0	0	0	0	0
I_t										
MPS_t										
ATP_t										

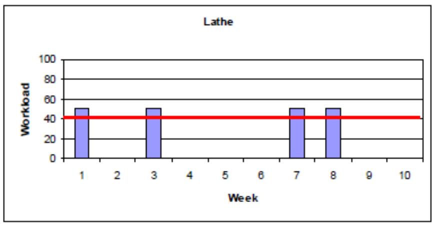
- Calculate the master production schedule.
- Determine the quantities available to promise.
- Decide to accept or reject the following orders:

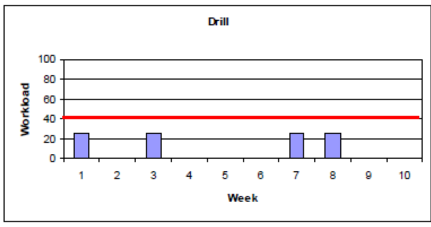
Order	Quantity	Due date
1	15	6
2	4	2
3	32	3

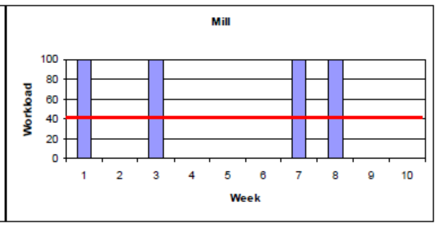
- Assess the feasibility of the plan knowing that the availability of Lathe, Drill and Mill is 40 h /week and their use for the production of a product unit (in hours) is shown in the table:

Lathe	Drill	Mill
1	0,5	2

	Week									
	1	2	3	4	5	6	7	8	9	10
MPSt (MPS Quantity)	50		50				50	50		
Lathe Used	50	0	50	0	0	0	50	50	0	0
Drill Used	25	0	25	0	0	0	25	25	0	0
Mill Used	100	0	100	0	0	0	100	100	0	0
Machine availability	40	40	40	40	40	40	40	40	40	40







- The Master Production Schedule is clearly unacceptable.
- It is therefore necessary to anticipate or postpone production.

(Personal Unwinding)

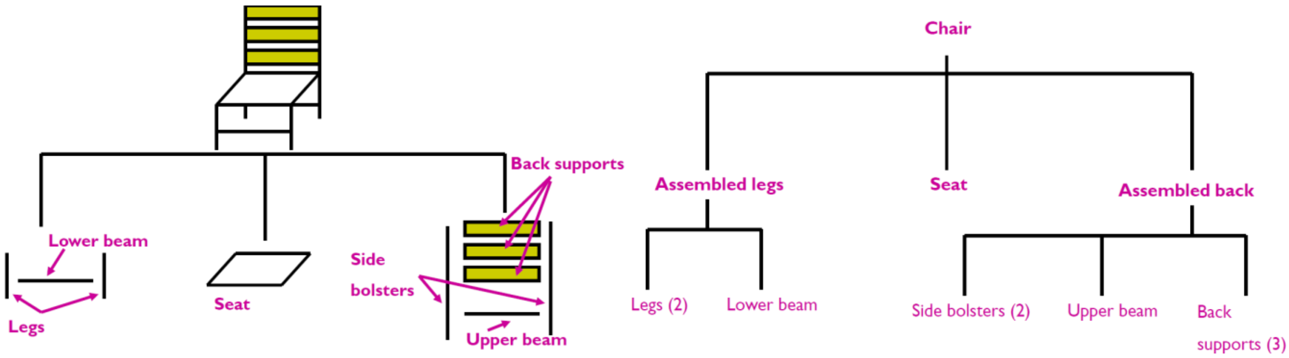
I0=5	1	2	3	4	5	6	7	8	9	10
F_t	20	10	40	10	0	0	40	20	30	10
O_t	30	20	5	8	0	0	0	0	0	0
I_t										
MPS_t										
ATP_t										

Order	Quantity	Due date
1	15	6
2	4	2
3	32	3

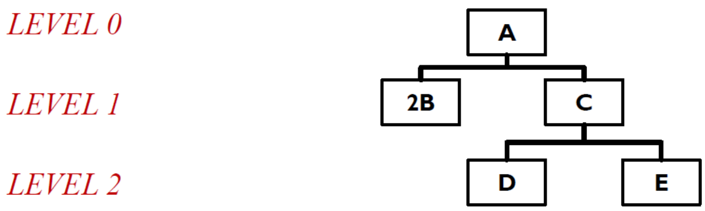
Lathe	Drill	Mill
1	0,5	2

- Calculate the master production schedule MPS_t
- Determine the quantities available to promise ATP_t
- Decide to accept or reject the following orders:
- Assess the feasibility of the plan knowing that the availability of Lathe, Drill and Mill is 40 h /week.

$I_0 = 5$	1	2	3	4	5	6	7	8	9	10
F_t	20	10	40	10	0	0	40	20	30	10
O_t	30	20	5	8	0	0	0	0	0	0
I_t	25	5	15	5	5	5	15	45	15	5
MPS_t	**50**		**50**				**50**	**50**		
ATP_t	**5**		**37**				**50**	**50**		

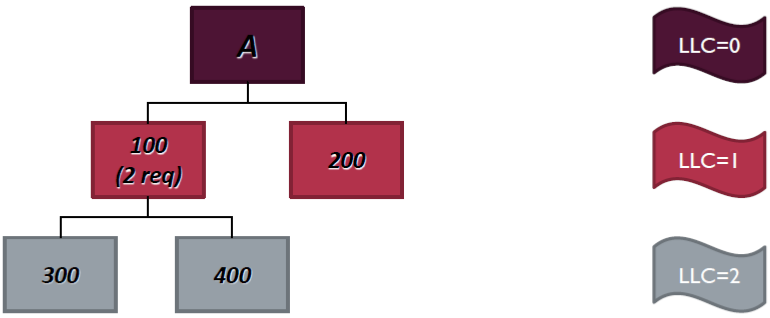


- The **level** represents the **vertical position** of an element of the BOM, in other words, it represents the **distance** between the element and the final product.
- Conventionally, the level of the final product is equal to **zero**.
- The next level down to zero level is the level 1 and so on ...



Lower-Level Code

- MRP (Material Requirement Planning) works with both finished products, or **end items**, and their **constituent parts**, called **"Lower-Level items" (LLI). The relationships** between **end items** and **lower-level items is described by the bill of material (BOM).**
- Let's consider the following product tree for product A.



[Rif. 1]

- Therefore, the LLC indicates the lowest level in a bill of material that a particular part is ever used.
- End items have LLC equal to **zero.**

Schematically – MRP Procedure

The MRP procedure can be summarized in the following points:

1. The **demand for finished products** (**independent demand**) must be given with a **predeterminate time** of the delivery;
2. It is required to know:
   the "**product tree**";
   the **on-hand inventory level**;
   the **status of the scheduled receipts**;
3. Then, we can proceed to **calculate the time** at which **each order must be released** in order to complete the production in accordance with the delivery date.

Item X	1	2	3	4	5	6	7	8
Gross requirements								
Scheduled receipts								
Projected on-hand inventory								
Net requirements								
Planned receipts								
Planned order releases								

Notations:

D_t: is the **gross demand (requirement)** for period t.
S_t: is the quantity of the **scheduled receipts** in period t.
AS: adjusted **scheduled receipts** in period t.
I_t: is the **projected on-hand inventory** to complete the p. in period t; current on-hand inventory is I_0.
N_t: is the **Net requirement** for period t.
$\boldsymbol{Planned\ order\ receipts}$
$\boldsymbol{Planned\ order\ releases}$

MRP Procedure:

For each level of the BOM, **beginning with the end items**, the MRP procedure consists of the following steps:

1. Netting

- Determines the **net demand** for **a** Material.
- So Netting is used to determine **net requirements**.
- Net requirement is determined in a very simple way by first determining the **current stock level**:

$I_t = I_{t-1} - D_t + S_t \; Current\ Stock\ Level$

- I_0 equal to the initial warehouse.

$N_t = min\{max(-I_t, 0), D_t\} \; Net\ requirements$

- Let's assume that the covers take place by first using the warehouse and then ordering already scheduled.

Part A		1	2	3	4	5	6	7	8
Gross requirements		15	20	50	10	30	30	30	30
Scheduled Receipts		10	10		100				
Adjusted SRs			20	Expedite					
Projected on-hand	20	5	5	-45					
Net requirements									
Planned Order Receipts									
Planned Order Releases									

Netting – NET REQUIREMENTS

Part A		1	2	3	4	5	6	7	8
Gross requirements		15	20	50	10	30	30	30	30
Scheduled Receipts		10	10		100				
Adjusted SRs			20	100					
Projected on-hand	20	5	5	55	45	15	-15		
Net requirements							15	30	30
Planned Order Receipts									
Planned Order Releases									

(To better understand the Net Requirement function Look "EXAMPLE 1: Personal Unwinding)

2. Lot Sizing

- Dismantles the **net demand** for production batches.
- Once we have computed the net requirements, we must schedule **production quantities** to satisfy them.
- Let us consider three lot-sizing **rules**:

2.1. Lot-for-Lot (LFL)
2.2. Fixed Order Quantity (FOQ)
2.3. Fixed Order Period (FOP)

2.1- Lot-For-Lot (LFL) Rule

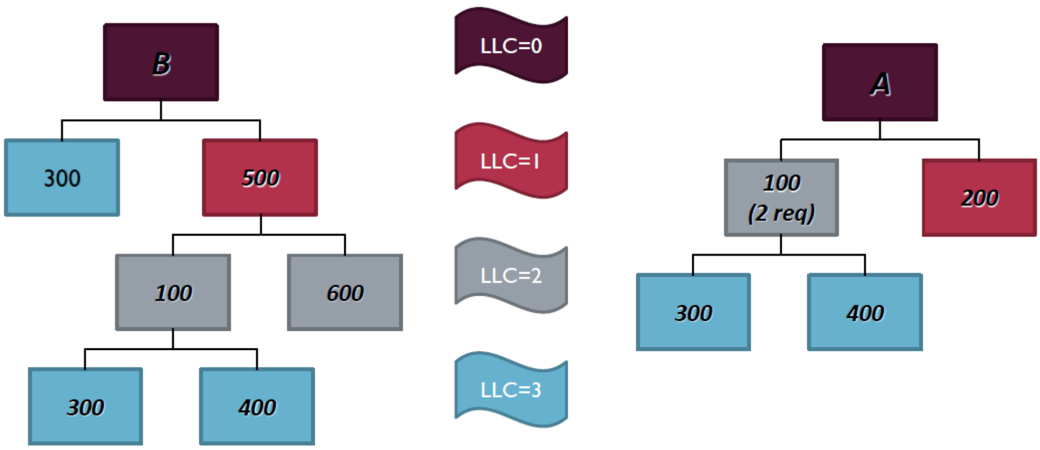
It is the simplest of the lot-sizing rules: simply produce in period t the net requirements for period t.

ADVANTAGES:
- Since this leaves no inventory at the end of any period, **this rule minimizes inventory.**
- It is consistent with the **Just in Time philosophy.**

Part A	1	2	3	4	5	6	7	8
Gross requirements	15	20	50	10	30	30	30	30
Scheduled Receipts	10	10		100				
Adjusted SRs		20	100					
Projected on-hand 20	5	5	55	45	15	-15		
Net requirements	0	0	0	0	0	15	30	30
Planned Order Receipts						45		30
Planned Order Releases				45		30		

4. BOM Explosion

- Calculates the **gross demand** for the component materials.
- The Type A product is made up of 2 units of type 100 components and a component of type 200 components.
- Therefore, the release of orders generated for the A-type product generates a gross requirement for component types 100 and 200.



- But first we need to apply the procedure to all products with LLC=0.

EXAMPLE 1: Part B (LLC=0)

- So, let's suppose the master production schedule of B-type components has the following data:

Part B	1	2	3	4	5	6	7	8
Gross requirements	10	15	10	20	20	15	15	15

Part 500		1	2	3	4	5	6	7	8
Gross requirements			35		30		15		
Scheduled Receipts									
Adjusted SRs									
Projected on-hand	40	40	5	5	-25				
Net requirements					25		15		
Planned Order Receipts					25		15		
Planned Order Releases		25*	15						

*Since the lead time for part 500 is 4 weeks, there is not enough time to finish the first 25 units before week 4. Therefore, a planned order release is scheduled for week 1 (as soon as possible) with an indication on an exception report that ti is expected to be late.

Part Number	Current On-Hand	SRs		Lot-Sizing Rule	Lead Time
		Due	Quantity		
500	40	0		Lot-for-lot	4 weeks

Since the **lead time** for part 500 is 4 weeks, there is not enough time to finish the first units before week 4. -> We have to note this fact.

MRP FOR PART 100 (LLC=2)

Part 100		1	2	3	4	5	6	7	8
Required from A					90		60		
Required from 500		25	15						
Gross requirements		25	15		90		60		
Scheduled Receipts									
Adjusted SRs									
Projected on-hand	40	15			-90				
Net requirements					90		60		
Planned Order Receipts					90		60		
Planned Order Releases			90		60				

Part Number	Current On-Hand	SRs		Lot-Sizing Rule	Lead Time
		Due	Quantity		
100	40	0		Lot-for-lot	2 weeks

MRP FOR PART 300 (LLC=3)

Part 300		1	2	3	4	5	6	7	8
Required from B			35		30		15		
Required from 100			90		60				
Gross requirements			125		90		15		
Scheduled Receipts			100						
Adjusted SRs									
Projected on-hand	50	50	25	25	-65				
Net requirements					65		15		
Planned Order Receipts					65		15		
Planned Order Releases				65		15			

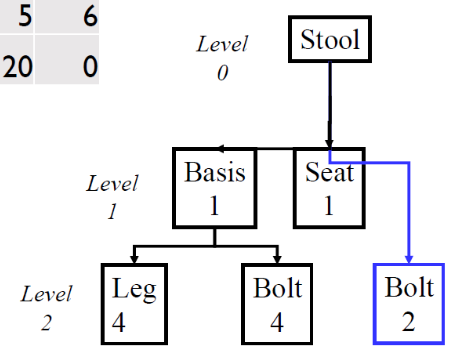
Part Number	Current On-Hand	SRs		Lot-Sizing Rule	Lead Time
		Due	Quantity		
300	50	2	100	Lot-for-lot	1 week

SUMMARY OF MRP OUTPUTS

EXERCISE

Week	1	2	3	4	5	6
Demand	0	0	0	0	120	0

Level	Name	Quantity	Lead Time	I_0	Lot Size
0	Sgabello	1	1	20	FOQ 100
1	Base	1	1	0	L4L
2	Gamba	4	2	0	FOP 2
2	Bullone	4	2	0	FOP 3
1	Sedile	1	1	0	L4L
2	Bullone	2	2	0	FOP 3



Unwinding from Slides:

MRP (LLC=0)

Week	1	2	3	4	5	6
Demand	0	0	0	0	120	0

LLC	Liv	Nome	Qty	LT	I0	LS
0	0	Stool	1	1	20	FOQ 100
1	.1	Seat	1	1	0	L4L
1	.1	Basis	1	1	0	L4L
2	..2	Leg	4	2	0	POQ 2
2	..2	Bolt	4	2	0	POQ 3
2	.1	Bolt	2	2	0	POQ 3

Pianificazione livello 0

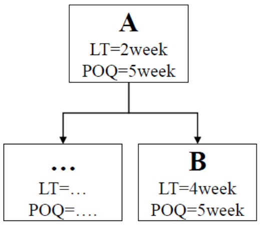
Item	Sgabello	Sgabello	t=0	1	2	3	4	5
I(0)	20	Gross requirement - *D(t)*		0	0	0	0	120
SS	0	Scheduled receipt						
		Adjusted Scheduled receipt - SR*(t)*						
Lot type	**FOQ**	Projected on-hand inventory - *I* (t)	20	20	20	20	20	0
Lot value	100	Net requirement - *N(t)*		0	0	0	0	100
		Planned order receipt - *PR* (t)						100
Lead time	1	Planned order release - *PO(t)*	0	0	0	0	100	0

Planning level 1 (LLC=1)

Item	Base	Base	t=0	1	2	3	4	5	6
I(0)	0	Gross requirement - *D(t)*		0	0	0	100	0	0
SS	0	Scheduled receipt							
		Adjusted Scheduled receipt - SR*(t)*							
Lot type	**L4L**	Projected on-hand inventory - *I* (t)	0	0	0	0	0	0	0
Lot value		Net requirement - *N(t)*		0	0	0	100	0	0
		Planned order receipt - *PR* (t)					100		
Lead time	1	Planned order release - *PO(t)*	0	0	0	100	0	0	0

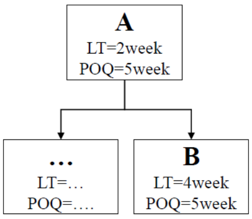
Item	Sedile	Sedile	t=0	1	2	3	4	5	6
I(0)	0	Gross requirement - *D(t)*		0	0	0	100	0	0
SS	0	Scheduled receipt							
		Adjusted Scheduled receipt - SR*(t)*							
Lot type	**L4L**	Projected on-hand inventory - *I* (t)	0	0	0	0	0	0	0
Lot value		Net requirement - *N(t)*		0	0	0	100	0	0
		Planned order receipt - *PR* (t)					100		
Lead time	1	Planned order release - *PO(t)*	0	0	0	100	0	0	0

MRP – Nervousness



Item A	1	2	3	4	5	6	7	8
GR	2	24	3	5	1	3	4	50
SR								
POH 28	26	2	-1	-6	-7	-10	-14	-64
NR			1	5	1	3	4	50
PR			14					50
POR	14					50		

Item B	1	2	3	4	5	6	7	8
GR	14	0	0	0	0	50	0	0
SR	14							
POH 2	2	2	2	2	2	-48	-48	-48
NR						48	0	0
PR						48		
POR		48						



Item A	1	2	3	4	5	6	7	8
GR	2	23	3	5	1	3	4	50
SR								
POH 28	26	3	0	-5	-6	-9	-13	-63
NR				5	1	3	4	50
PR				63				
POR		63						

Item B	1	2	3	4	5	6	7	8
GR	0	63	0	0	0	0	0	0
SR	14							
POH 2	16	-47	-47	-47	-47	-47	-47	-47
NR		47	0	0	0	0	0	0
PR		47						
POR	???							

MRP – Firm Planned Orders

An order which is treated as a planned order for the MRP calculation but one that will not be changed, either in date or quantity, by the computer. Firm Planned are raised manually and used for Master Scheduling and to override the computer settings of Order Quantity, Lead Times and Safety Stock, usually to overcome material or capacity problems.

MRP – Limits

1. **Integrity of the data**: If there are any errors in the: Inventory data, in the BOM data, or in the MPS, then the output data will also be incorrect.
2. **Lead time**: must be known in advance and it must be constant over time, regardless of the quantity to be produced and the state of the system.
3. **Resource Allocation**: **Physical location of the materials**: to have the availability of materials in a warehouse in kilometres not needed.
4. **Production Capacity**: If it is not considered, then you have production plans ineligible.
5. **Variability BOM**: Changes of the BOM must be recorded and preserved in time.
6. **Accounting**: There is no connection with the accounting aspects of the company.
7. **Forecast**: there is no system for forecasting demand.

Projected on hand I_t $(I_0 = 40)$	30	15	5	-15	(-35)	(-50)	(-65)	(-80)
Net Requirements N_t	0	0	0	15	20	15	15	15
Planned Order Receipts				35		30		15
Planned Order Releases		35		30		15		

Part 500 (LLC=1)	1	2	3	4	5	6	7	8
Gross Requirements D_t	0	35	0	30	0	15	0	0
Scheduled Receips S_t	0	0	0	0	0	0	0	0
Adjusted S_t	/	/	/	/	/	/	/	/
Projected on hand I_t $(I_0 = 40)$	40	5	5	-25	(-25)	(-40)	(-40)	-(40)
Net Requirements N_t	0	0	0	25	0	15	0	0
Planned Order Receipts				25		15		
Planned Order Releases	25	15						

Part 100 (LLC=2)	1	2	3	4	5	6	7	8
Required from A	0	0	0	2x45	0	2x30	0	0
Required from Part 500B	25	15	0	0	0	0	0	0
Gross Requirements D_t	25	15	0	90	0	60	0	0
Scheduled Receips S_t	0	0	0	0	0	0	0	0
Adjusted S_t	/	/	/	/	/	/	/	/
Projected on hand I_t $(I_0 = 40)$	15	0	0	-90	(-90)	(-150)	(-150)	(-150)
Net Requirements N_t	0	0	0	90	0	60	0	0
Planned Order Receipts				90		60		
Planned Order Releases		90		60				

Part 300 (LLC=3)	1	2	3	4	5	6	7	8
Required from B	0	35	0	30	0	15	0	0
Required from Part 100	0	90	0	60	0	0	0	0
Gross Requirements D_t	0	125	0	90	0	15	0	0
Scheduled Receips S_t	0	100	0	0	0	0	0	0
Adjusted S_t	/	/	/	/	/	/	/	/
Projected on hand I_t $(I_0 = 50)$	50	25	25	-65	(-65)	(-80)	(-80)	(-80)
Net Requirements N_t	0	0	0	65	0	15	0	0
Planned Order Receipts				65		15		
Planned Order Releases			65		15			

Summary of MRP Outputs:

Transaction	**Part**	**Old due date /Realise Date**	**New Due Date /Receipt Date**	**Quantity**	**Notice**
Change Notice	A	1	2	10	Defer
Change Notice	A	4	3	100	Expedite
Planned Order	A	4	6	45	Ok
Planned Order	A	6	8	30	Ok
Planned Order	B	2	4	35	Ok
Planned Order	B	4	6	30	Ok
Planned Order	B	6	8	15	Ok
Planned Order	500	1	4	25	Late
Planned Order	500	2	6	15	Ok
Planned Order	100	2	4	90	Ok
Planned Order	100	4	6	60	Ok
Planned Order	300	3	4	65	Ok
Planned Order	300	5	6	15	Ok

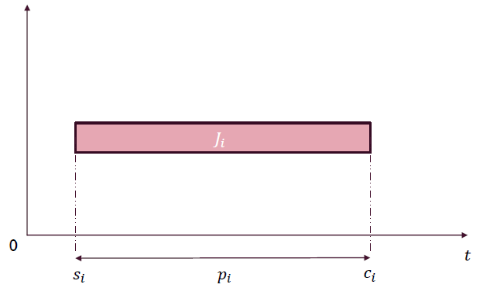
Bolt (LLC=2)	1	2	3	4	5	6
Required from Seat			2x100			
Required from Basis			4x100			
Gross Requirements D_t	0	0	600	0	0	0
Scheduled Receips S_t	0	0	0	0	0	0
Adjusted S_t	/	/	/	/	/	/
Projected on hand I_t ($I_0 = 00$)	0	0	-600	(-600)	(-600)	(-600)
Net Requirements N_t	0	0	600	0	0	0
Planned Order Receipts			600			
Planned Order Releases	600					

Summary of MRP Outputs:

Transaction	Part	Old Due Date /Realise Date	New Due Date /Receipt Date	Quantity	Notice
Planned Order	Stool	4	5	100	Ok
Planned Order	Basis	3	4	100	Ok
Planned Order	Seat	3	4	100	Ok
Planned Order	Leg	1	3	400	Ok
Planned Order	Bolt	1	3	600	Ok

Parameters $(c_i, L_i, T_i, n_T, C_{max})$

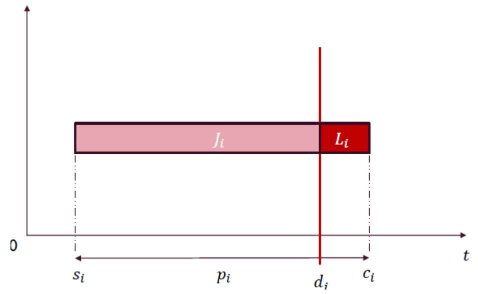
Completion time (c)



- The time when the **last operation** of the job ends.

$$c_i = s_i + p_i$$

Lateness (L)

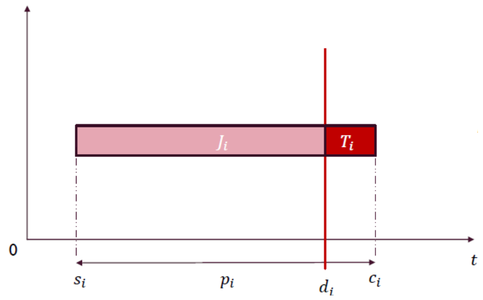


- Lateness indicates the **delay** or the **advance** of **completing a job** with respect to the **due date.**

$$L_i = c_i - d_i$$

$$if\ L_i > 0 \rightarrow delay$$
$$if\ L_i < 0 \rightarrow advance$$

Tardiness (T)



- Tardiness **coincides** with Lateness **if this is positive**, otherwise it is equal to **zero.**

$$T_i = max\{0, L_i\}$$

Number of Tardy Job (n_T)

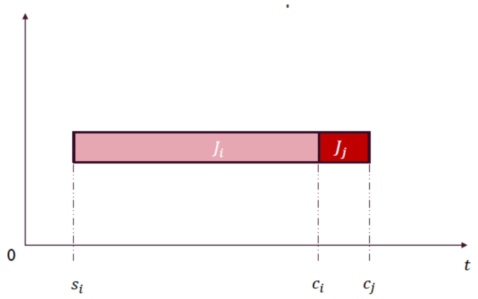
- U_i is **a binary variable** so defined:

$$U_i = \begin{cases} 1\ if\ L_i > 0 \\ 0\ if\ L_i \leq 0 \end{cases}$$

- The number of Tardy Job is equal to the number of jobs with lateness greater than zero.

$$n_T = \sum_{i=1}^{n} U_i$$

Makespan (C_{max})



- **Makespan, or Maximum Completion Time**, is the **instant** in which **the last operation of the last job ends.** It coincides with the completion time of the last job.

$$C_{max} = max\{c_i\}$$

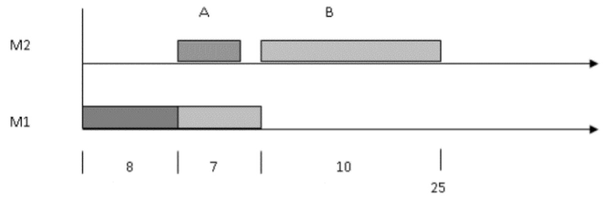
Scheduling – EXAMPLE (to better understand)

- Consider the data in the following table with only two jobs, A and B, which need to be scheduled on two machines, **M1 and M2, in series.**

JOB	Processing times	
	M1	M2
A	8	5
B	7	10

- Suppose we want to measure the effectiveness of the scheduling with the C_{max} indicator of the completion time of both jobs.

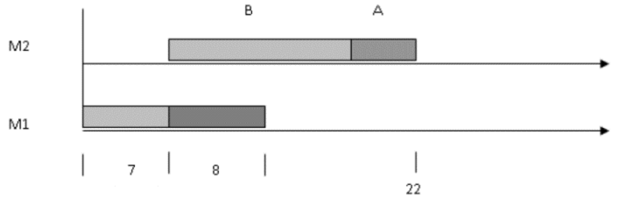
1) First eligible sequence: job A is loaded as first. $\boldsymbol{C_{max}} = \mathbf{25}$



Remember the Constrains:

- Each **Working Center** can work only **one job at a time**;
- Each **job cannot be worked simultaneously** by multiple machines.
+ M1, M2 are **in series**.

2) Second eligible sequence: job B is loaded as first. $\boldsymbol{C_{max}} = \mathbf{22}$



This simple example provides some information on the main features of scheduling problems:

- Note that each sequence contains information about the start and end time of each activity;
- The example provides a clear view of the performance indicator and how it changes the value by modifying the sequence.

Computational Complexity

- T**o find the solution of an Optimization Problem**, the **comparison of the possible solutions is necessary**, but the **number of alternatives** is influenced both by the **Number of Jobs** and by the **Type of System.**

Given n jobs it is possible to have $n! = n \cdot (n-1) \cdot (n-2) \ldots \cdot 3 \cdot 2 \cdot 1$ possible schedules/possibilities. If the evaluation of a schedule takes 1 second:

Number of job	Schedules	Time(s)	Time
5	5!	120	2 minutes
10	10!	3,63 10^6	42 days
20	20!	2,43 10^{18}	Centuries

By thinking again to your schedule activity example, can you formulate it in terms of a scheduling problem by identifying the type of the system, constraints and objective function?

EDD (Earliest Due Date) schedule: Minimizing Maximum Lateness on single machine (1 / / L_{max})

- In this second case, scheduling is typical of a manufacturer that has to respond to external customer orders with a well-defined delivery date.
- You want to minimize the maximum lateness.

Job	Due date	Processing time
A	d_A	p_A
B	d_B	p_B
C	d_C	p_C
D	d_D	p_D

In a problem 1 / / L_{max} the maximum lateness is minimized by a sequence so that:
$d_{[1]} < d_{[2]} < \cdots < d_{[n]}$
Where $d_{[k]}$ is the due date of job processed in the k position.
- A schedule made this way takes the name of EDD (Earliest Due Date) schedule.
- An EDD schedule **also solves the scheduling problem 1 / / T_{max}.**

EXAMPLE:

5 jobs (J_1,J_2,J_3,J_4,J_5) must be processed on a machine. The process times and the due dates are:

Job	Process Time	Due Date
J1	11	61
J2	29	45
J3	31	31
J4	1	33
J5	2	32

1) Determine the sequence that minimizes the maximum Lateness. (EDD Schedule)
2) Determine the sequence that minimizes the number of tardy jobs: -> Moore's Algorithm

Sequence	Comp. Time	D. Date	Tardiness
J1	11	61	0
J2	40	45	0
J3	71	31	40
J4	72	33	39
J5	74	32	42
Totals	268		121

- Average Completion time: (268)/5=53.4
- Average Tardiness: (121)/5=24.2
- Number of Tardy jobs: 3

By using the EDD method we obtain:

Sequence	Comp. Time	D. Date	Tardiness
J3	31	31	0
J5	33	32	1
J4	34	33	1
J2	63	45	18
J1	74	61	13
Totals	235		33

- Average Completion time: (235)/5=47
- Average Tardiness: (33)/5=6.6
- Number of Tardy jobs: 4

This is the sequence that minimizes the maximum Lateness (a) (33 vs 121, 43).

Karg-Thompson's Algorithm: Minimizing the Global Set-up Time

TSP (Traveling Salesman Problem)

- This scheduling problem has the objective of minimizing the time lost in the set-up at every change of job.
- The goal of the scheduling is to get a job sequence such that the overall time of setup S is minimum.
- The **available data** for the scheduler are **sij the Setup Time for each pair of jobs** <i, j>.
- This scheduling problem is also known as "**traveling salesman problem**" (**TSP**).
- The approximate solution can be obtained by applying the following rule: "reached a chosen city, choose as the next destination the closest city not yet visited."

TSP (Traveling Salesman Problem) – KARG – THOMPSON'S ALGORITHM

Step 1: Select a couple of jobs among the n jobs;
Step 2: Choose as next job the one with minimum set-up time from the last job in the sequence without considering the already ordered jobs;
Step 3: Iterate point 2 until all the jobs are ordered in the sequence;
Step 4: Evaluate the global set-up time;
Step 5: Go back to point 1;
Step 6: Select, as solution, the sequence corresponding to the **Minimum Global Set-up Time** among the evaluated sequences.

EXAMPLE:

- In a production system with one machine, the manager has to schedule 4 jobs all independent and all available at t=0.
- The set-up times for each pair of jobs are:

	J1	J2	J3	J4
J1	12	2	3	5
J2	1	15	4	3
J3	2	3	9	3
J4	5	4	2	11

1) Determine the sequence that minimize the global set-up time.

- We can choose jobs J_2 and J_1 as the initial jobs of the sequence.
- Choose as third job the one with the minimum set-up time from J_1 by excluding J_2. (=> $J_3 = mins_{1k}$)
- The final sequence is: $J_2 \rightarrow J_1 \rightarrow J_3 \rightarrow J_4$
- The global set-up time is: $s_{21} + s_{13} + s_{34} = 1 + 3 + 3 = 7$

- We can choose jobs J_2 and J_3 as the initial jobs of the sequence.
- Choose as third job the one with the minimum set-up time from J_3 by excluding J_2. (=> $J_1 = mins_{3k}$)
- The final sequence is: $J_2 \rightarrow J_3 \rightarrow J_1 \rightarrow J_4$
- The global set-up time is: $s_{23} + s_{31} + s_{14} = 4 + 2 + 5 = 11$

- We can choose jobs J_1 and J_3 as the initial jobs of the sequence.
- Choose as third job the one with the minimum set-up time from J_3 by excluding J_1. ($J_4 = J_2 = mins_{3k}$)
- The final sequence is: $J_1 \rightarrow J_3 \rightarrow J_2 \rightarrow J_4 \quad or \quad J_1 \rightarrow J_3 \rightarrow J_4 \rightarrow J_2 \quad (because \quad J_4 = J_2 = mins_{3k})$
- The global set-up time is: $s_{13} + s_{32} + s_{24} = 3 + 3 + 3 = 9 \quad or \quad s_{13} + s_{34} + s_{42} = 3 + 3 + 4 = 10$

- We can choose jobs J_4 and J_3 as the initial jobs of the sequence.
- Choose as third job the one with the minimum set-up time from J_3 by excluding J_4. (=> $J_1 = mins_{3k}$)
- The final sequence is: $J_4 \rightarrow J_3 \rightarrow J_1 \rightarrow J_2$
- The global set-up time is: $s_{43} + s_{31} + s_{12} = 2 + 2 + 2 = 6$

Case 2: $P_M \, / \, / \sum C_i$ Minimizing the total Waiting Time ($\sum C_i$)

- Consider a scheduling problem with identical machines in parallel. The procedure minimizes the total waiting time is:

Step 1: Order the jobs according to the **LPT** rule;
Step 2: Assign progressively the job to the machine with the shortest completion time;
Step 3: Once the allocation to the machines is completed, sort the jobs of each machine according to the **SPT** rule.

Note: that this rule acts on each queue by minimizing the waiting time.

EXAMPLE: $P_2 \, / \, / \sum C_i$

- Consider two parallel identical machines and a set of 5 jobs with the following processing times on the machines:

Job	1	2	3	4	5
P_i	2	3	6	1	4

- Find the assignment of the jobs to the two machines that minimizes the overall waiting time $\sum C_i$.

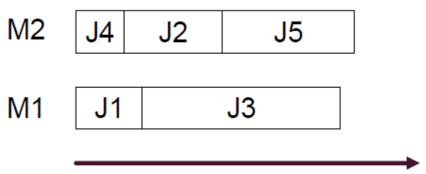
- Order the jobs according to the LPT rule (Step 1):

$J_3 \rightarrow J_5 \rightarrow J_2 \rightarrow J_1 \rightarrow J_4$

- Job's assignment (Step 2):

M1 $\leftarrow J_3, J_1$
M2 $\leftarrow J_5, J_2, J_4$

- On each machine, sequencing the jobs according the **SPT** rule (Step 3):



$C_{max} = 8$
$\sum C_i = 1 + (1 + 3) + (4 + 4) + 2 + (2 + 6) = 23$

Scheduling on Machines in Series - $(F_M \; / \; / \; C_{max})$

- The organization in series of work centers is probably the most common configuration in the productive systems of any size.
- Just think of the production lines or assembly.
- The scheduling problems on machines in series, in order to be processed with a reasonable complexity, require the introduction of some simplifications:
- Consider M Work Centers connected in series and N job to be processed. Assume that:

h1: Each job can be processed from a single center at a time.
h2: Each center cannot begin processing a job before it has finished to be processed in the previous work center.

- These scheduling problems generally have as key **performance indicator** the Maximum Completion Time of all jobs in the C_{max} queue.
- Each job in the queue will be loaded on the first machining center and then moved from that center to the next one only after it has finished the working operation.
- Once the work sequence is chosen, it will remain unchanged along the line, in other words, the jobs will be processed in the last work center with the same sequence as they were uploaded to the first center.

- The problem presents different complexity depending on the number of work centers in the line.
- This characteristic derives from the fact that each center should reserve a work interval for each job with a start time immediately subsequent to the time of completion of the previous job.
- In addition, the start time of the processing of a job on a work center depends on the completion of the previous processing time.
- The presence of these two constraints is due to a complex formulation of the problem.

Scheduling on a line of two Machines – Johnson Algorithm

- Scheduling a line with **two machining centers** is one of the few problems that admits an optimal solution in the form of constructive procedure: the **algorithm of Johnson.**
- For a simple interpretation, note that the Minimization of the Completion Time of the jobs is equivalent to maximize the use of the centers.
- From here it follows that the first center of the line, finding jobs in the queue, can work without interruption. Consequently, to reduce the time of completion, it will be necessary to avoid as much as possible that the second center presents dead time between completion of a job and the beginning of the subsequent processing. So, it would seem reasonable to have as the first in the queue a job with a short time to work on the first center, because at that time the second center is forcibly stopped waiting.
- For similar reason, it is reasonable to have as the last job in the queue that which has a short working time at the second center, in order to reduce the "queue" of the scheduling (the first center is in fact stopped, having no more jobs to be processed).

JOHNSON ALGORITHM

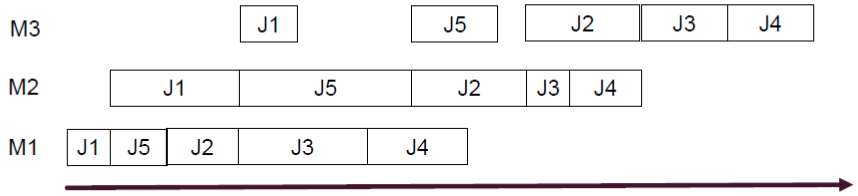
Step1: Separate the jobs into **two sets, G_1 and G_2**, such that the jobs in G_1 are those whose process time on the first machine is less than or equal to the process time on the second machine. The set G_2 contains the remaining jobs.
$G_1 = \{J_i, p_{i1} \leq p_{i2}\}$ $\qquad$ $G_2 = \{J_i, p_{i1} > p_{i2}\}$

Step 2: Order the jobs in G_1 in a non-decreasing order of their process times (**SPT rule);**

Johnson's Algorithm to the two machines:

Job	M1	M2
J1	3	13
J2	5	16
J3	9	10
J4	7	11
J5	4	18

$J_1 \rightarrow J_5 \rightarrow J_2 \rightarrow J_3 \rightarrow J_4$ (first possibility) (in my opinion there is an error: $J_1 \rightarrow J_5 \rightarrow J_2 \rightarrow J_4 \rightarrow J_3$)



Makespan = 53 (Calculated with the original processing times)

- Step 2:

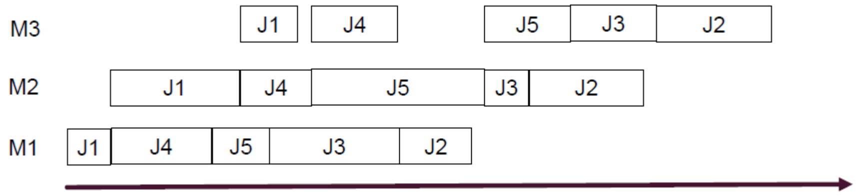
$$t'_{11} = \sum_{k=1}^{2} t_{11} + t_{12} = 12 \qquad t'_{12} = 4$$

$$t'_{21} = 13 \quad t'_{22} = 8$$
$$t'_{31} = 12 \quad t'_{32} = 7$$
$$t'_{41} = 12 \quad t'_{42} = 6$$
$$t'_{51} = 16 \quad t'_{52} = 6$$

- Johnson's Algorithm to the two machines:

Job	M1	M2
J1	12	4
J2	13	8
J3	12	7
J4	12	6
J5	16	6

$J_1 \rightarrow J_4 \rightarrow J_5 \rightarrow J_3 \rightarrow J_2$ (second possibility)



Makespan = 3+9+5+12+6+7+8=50 (Calculated with the original processing times)

Step 2: Johnson in G_{21}:

Job	pj2	pj1
J1	4	5
J6	3	2
J8	4	3

Schedule:

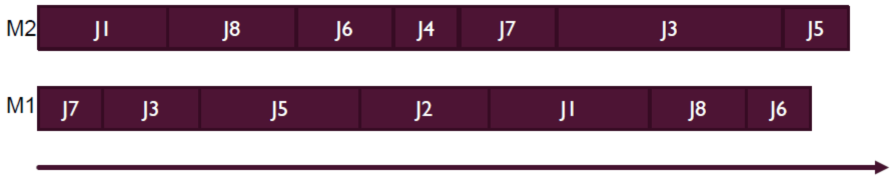
1	2	3
J1	J8	J6

Step 3: Sort the job on the M_1 machine according to the sequence:

$J_7 \rightarrow J_3 \rightarrow J_5 \rightarrow J_2 \rightarrow J_1 \rightarrow J_8 \rightarrow J_6$

Step 4: Sort the job on the M_2 machine according to the sequence:

$J_1 \rightarrow J_8 \rightarrow J_6 \rightarrow J_4 \rightarrow J_7 \rightarrow J_3 \rightarrow J_5$



Remarks:

- The logic behind this algorithm is to try to occupy the two centers as much as possible, thereby increasing their rate of utilization and reducing the time of completion of the job.
- Analysing the steps 3 and 4, it can be noted that the center M1, in its initial stage, processes the job to be sent to the next center and the same happens to the center M2. In this way each center operates to feed the other.
- In the middle phase, each center processes the job of its core competence, in this way they both work without interruption.
- In the third stage each center processes the job received by the other.