CNC

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Chapter 1

Numerical control

"CNC" redirects here. For other uses, see CNC (disambiguation).

Numerical control (**NC**) is the automation of machine

A CNC turning center

tools that are operated by precisely programmed commands encoded on a storage medium, as opposed to controlled manually via hand wheels or levers, or mechanically automated via cams alone. Most NC today is **computer (or computerized) numerical control (CNC)**,[1] in which computers play an integral part of the control.

In modern CNC systems, end-to-end component design is highly automated using computer-aided design (CAD) and computer-aided manufacturing (CAM) programs. The programs produce a computer file that is interpreted to extract the commands needed to operate a particular machine via a post processor, and then loaded into the CNC machines for production. Since any particular component might require the use of a number of different tools – drills, saws, etc., modern machines often combine multiple tools into a single "cell". In other installations, a number of different machines are used with an external controller and human or robotic operators that move the component from machine to machine. In either case, the series of steps needed to produce any part is highly automated and produces a part that closely matches the original CAD design.

1.1 History

Main article: History of numerical control

The first NC machines were built in the 1940s and 1950s, based on existing tools that were modified with motors that moved the controls to follow points fed into the system on punched tape. These early servomechanisms were rapidly augmented with analog and digital computers, creating the modern CNC machine tools that have revolutionized the machining processes.

1.2 Description

Motion is controlled along multiple axes, normally at least two (X and Y),[2] and a tool spindle that moves in the Z (depth). The position of the tool is driven by motors through a series of step down gears in order to provide highly accurate movements, or in modern designs, direct-drive stepper motor or servo motors. Open-loop control works as long as the forces are kept small enough and speeds are not too great. On commercial metalworking machines closed loop controls are standard and required in order to provide the accuracy, speed, and repeatability demanded.

As the controller hardware evolved, the mills themselves also evolved. One change has been to enclose the entire mechanism in a large box as a safety measure, often with additional safety interlocks to ensure the operator is far enough from the working piece for safe operation. Most new CNC systems built today are completely electronically controlled.

CNC-like systems are now used for any process that can be described as a series of movements and operations. These include laser cutting, welding, friction stir welding, ultrasonic welding, flame and plasma cutting, bending, spinning, hole-punching, pinning, gluing, fabric cutting, sewing, tape and fiber placement, routing, picking and placing (PnP), and sawing.

1.3 Examples of CNC machines

1.3.1 Mills

CNC mills use computer controls to cut different materials. They are able to translate programs consisting of specific number and letters to move the spindle to various locations and depths. Many use G-code, which is a standardized programming language that many CNC machines understand, while others use proprietary languages created by their manufacturers. These proprietary languages while often simpler than G-code are not transferable to other machines. CNC mills have many functions including face milling, shoulder milling, tapping, drilling and some even offer turning. Standard CNC mills have 3 axes (X,Y and Z) but others may also have one or more rotational axes.

1.3.2 Lathes

Lathes are machines that cut workpieces while they are rotated. CNC lathes are able to make fast, precision cuts, generally using indexable tools and drills. They are particularly effective for complicated programs to make parts that would be more difficult to make on manual lathes. CNC lathes have similar control specifications to CNC mills and can often read G-code as well as the manufacturer's proprietary programming language. CNC lathes generally have 2 axes (X and Z), but newer models have more axes allowing for more advanced jobs to be machined.

1.3.3 Plasma cutters
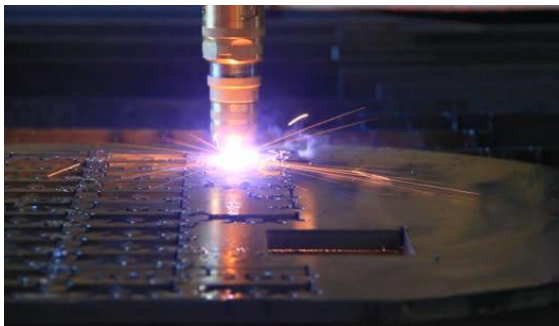
CNC plasma cutting

Plasma cutting involves cutting a material using a plasma torch. It is commonly used to cut steel and other metals, but can be used on a variety of materials. In this process, gas (such as compressed air) is blown at high speed out of a nozzle; at the same time an electrical arc is formed through that gas from the nozzle to the surface being cut, turning some of that gas to plasma. The plasma is sufficiently hot to melt the material being cut and moves sufficiently fast to blow molten metal away from the cut.

1.3.4 Electric discharge machining

Electric discharge machining (EDM), sometimes colloquially also referred to as spark machining, spark eroding, burning, die sinking, or wire erosion, is a manufacturing process in which a desired shape is obtained using electrical discharges (sparks). Material is removed from the workpiece by a series of rapidly recurring current discharges between two electrodes, separated by a dielectric fluid and subject to an electric voltage. One of the electrodes is called the tool-electrode, or simply the "tool" or "electrode," while the other is called the workpiece-electrode, or "workpiece."

When the distance between the two electrodes is reduced, the intensity of the electric field in the space between the electrodes becomes greater than the strength of the dielectric (at least in some point(s)), which breaks, allowing current to flow between the two electrodes. This phenomenon is the same as the breakdown of a capacitor. As a result, material is removed from both the electrodes. Once the current flow stops (or it is stopped – depending on the type of generator), new liquid dielectric is usually conveyed into the inter-electrode volume enabling the solid particles (debris) to be carried away and the insulating properties of the dielectric to be restored. Adding new liquid dielectric in the inter-electrode volume is commonly referred to as flushing. Also, after a current flow, a difference of potential between the two electrodes is restored to what it was before the breakdown, so that a new liquid dielectric breakdown can occur.

Wire EDM

Also known as wire cutting EDM, wire burning EDM, or traveling wire EDM, this process uses spark erosion to machine or remove material with a traveling wire electrode from any electrically conductive material. The wire electrode usually consists of brass or zinc-coated brass material.

Sinker EDM

Sinker EDM, also called cavity type EDM or volume EDM, consists of an electrode and workpiece submerged in an insulating liquid—often oil but sometimes other dielectric fluids. The electrode and workpiece are connected to a suitable power supply, which generates an electrical potential between the two parts. As the electrode approaches the workpiece, dielectric breakdown occurs in the fluid forming a plasma channel) and a small spark jumps.

1.3.5 Water jet cutters

A water jet cutter, also known as a waterjet, is a tool capable of slicing into metal or other materials (such as

granite) by using a jet of water at high velocity and pressure, or a mixture of water and an abrasive substance, such as sand. It is often used during fabrication or manufacture of parts for machinery and other devices. Waterjet is the preferred method when the materials being cut are sensitive to the high temperatures generated by other methods. It has found applications in a diverse number of industries from mining to aerospace where it is used for operations such as cutting, shaping, carving, and reaming.

1.3.6   Other CNC tools

Many other tools have CNC variants, including:

- Drills

- EDMs

- Embroidery machines

- Lathes

- Milling machines

- Canned cycle

- Wood routers

- Sheet metal works (Turret punch)

- Wire bending machines

- Hot-wire foam cutters

- Plasma cutters

- Water jet cutters

- Laser cutting

- Oxy-fuel

- Surface grinders

- Cylindrical grinders

- 3D Printing

- Induction hardening machines

- submerged welding

- knife cutting

- glass cutting

1.4   Tool / machine crashing

In CNC, a "crash" occurs when the machine moves in such a way that is harmful to the machine, tools, or parts being machined, sometimes resulting in bending or breakage of cutting tools, accessory clamps, vises, and fixtures, or causing damage to the machine itself by bending guide rails, breaking drive screws, or causing structural components to crack or deform under strain. A mild crash may not damage the machine or tools, but may damage the part being machined so that it must be scrapped.

Many CNC tools have no inherent sense of the absolute position of the table or tools when turned on. They must be manually "homed" or "zeroed" to have any reference to work from, and these limits are just for figuring out the location of the part to work with it, and aren't really any sort of hard motion limit on the mechanism. It is often possible to drive the machine outside the physical bounds of its drive mechanism, resulting in a collision with itself or damage to the drive mechanism. Many machines implement control parameters limiting axis motion past a certain limit in addition to physical limit switches. However, these parameters can often be changed by the operator.

Many CNC tools also don't know anything about their working environment. Machines may have load sensing systems on spindle and axis drives, but some do not. They blindly follow the machining code provided and it is up to an operator to detect if a crash is either occurring or about to occur, and for the operator to manually abort the cutting process. Machines equipped with load sensors can stop axis or spindle movement in response to an overload condition, but this does not prevent a crash from occurring. It may only limit the damage resulting from the crash. Some crashes may not ever overload any axis or spindle drives.

If the drive system is weaker than the machine structural integrity, then the drive system simply pushes against the obstruction and the drive motors "slip in place". The machine tool may not detect the collision or the slipping, so for example the tool should now be at 210mm on the X axis but is in fact at 32mm where it hit the obstruction and kept slipping. All of the next tool motions will be off by −178mm on the X axis, and all future motions are now invalid, which may result in further collisions with clamps, vises, or the machine itself. This is common in open loop stepper systems, but is not possible in closed loop systems unless mechanical slippage between the motor and drive mechanism has occurred. Instead, in a closed loop system, the machine will continue to attempt to move against the load until either the drive motor goes into an overcurrent condition or a servo following error alarm is generated.

Collision detection and avoidance is possible, through the use of absolute position sensors (optical encoder strips or disks) to verify that motion occurred, or torque sensors

or power-draw sensors on the drive system to detect abnormal strain when the machine should just be moving and not cutting, but these are not a common component of most hobby CNC tools.

Instead, most hobby CNC tools simply rely on the assumed accuracy of stepper motors that rotate a specific number of degrees in response to magnetic field changes. It is often assumed the stepper is perfectly accurate and never mis-steps, so tool position monitoring simply involves counting the number of pulses sent to the stepper over time. An alternate means of stepper position monitoring is usually not available, so crash or slip detection is not possible.

Commercial CNC metalworking machines use closed loop feedback controls for axis movement. In a closed loop system, the control is aware of the actual position of the axis at all times. With proper control programming, this will reduce the possibility of a crash, but it is still up to the operator and tool path programmer to ensure that the machine is operated in a safe manner. However, during the 2000s and 2010s, the software for machining simulation has been maturing rapidly, and it is no longer uncommon for the entire machine tool envelope (including all axes, spindles, chucks, turrets, toolholders, tailstocks, fixtures, clamps, and stock) to be modeled accurately with 3D solid models, which allows the simulation software to predict fairly accurately whether a cycle will involve a crash. Although such simulation is not new, its accuracy and market penetration are changing considerably because of computing advancements.[3]

1.5   Numerical precision vs equipment backlash

Within the numerical systems of CNC programming it is possible for the code generator to assume that the controlled mechanism is always perfectly accurate, or that precision tolerances are identical for all cutting or movement directions. This is not always a true condition of CNC tools. CNC tools with a large amount of mechanical backlash can still be highly precise if the drive or cutting mechanism is only driven so as to apply cutting force from one direction, and all driving systems are pressed tightly together in that one cutting direction. However a CNC device with high backlash and a dull cutting tool can lead to cutter chatter and possible workpiece gouging. Backlash also affects precision of some operations involving axis movement reversals during cutting, such as the milling of a circle, where axis motion is sinusoidal. However, this can be compensated for if the amount of backlash is precisely known by linear encoders or manual measurement.

The high backlash mechanism itself is not necessarily relied on to be repeatedly precise for the cutting process, but some other reference object or precision surface may be used to zero the mechanism, by tightly applying pressure against the reference and setting that as the zero reference for all following CNC-encoded motions. This is similar to the manual machine tool method of clamping a micrometer onto a reference beam and adjusting the Vernier dial to zero using that object as the reference.

1.6   See also

- Binary Cutter Location

- Computer-aided technologies

    - Computer-aided engineering (CAE)

- Coordinate-measuring machine (CMM)

- Direct numerical control (DNC)

- Design for Manufacturability for CNC machining

- Domotics

- Gerber format

- Multiaxis machining

- EIA RS-274

- EIA RS-494

- G-code

- Part program

- Robotics

- Wireless DNC

- Automatic Tool Changer

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[2] Mike Lynch, "Key CNC Concept #1—The Fundamentals Of CNC", *Modern Machine Shop*, 4 January 1997. Accessed 11 February 2015

[3] Zelinski, Peter (2014-03-14), "New users are adopting simulation software", *Modern Machine Shop*.

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1.9 External links

- Media related to Computer numerical control at Wikimedia Commons

Chapter 2

Milling (machining)

For asphalt milling machines, see Pavement milling.

Milling is the machining process of using rotary cutters to remove material[1] from a workpiece advancing (or *feeding*) in a direction at an angle with the axis of the tool.[2][3] It covers a wide variety of different operations and machines, on scales from small individual parts to large, heavy-duty gang milling operations. It is one of the most commonly used processes in industry and machine shops today for machining parts to precise sizes and shapes.

Milling can be done with a wide range of machine tools. The original class of machine tools for milling was the **milling machine** (often called a **mill**). After the advent of computer numerical control (CNC), milling machines evolved into **machining centers** (milling machines with automatic tool changers, tool magazines or carousels, CNC control, coolant systems, and enclosures), generally classified as **vertical machining centers** (**VMCs**) and **horizontal machining centers** (**HMCs**). The integration of milling into turning environments and of turning into milling environments, begun with live tooling for lathes and the occasional use of mills for turning operations, led to a new class of machine tools, **multitasking machines** (**MTMs**), which are purpose-built to provide for a default machining strategy of using any combination of milling and turning within the same work envelope.

2.1 Process

Milling is a cutting process that uses a milling cutter to remove material from the surface of a workpiece. The milling cutter is a rotary cutting tool, often with multiple cutting points. As opposed to drilling, where the tool is advanced along its rotation axis, the cutter in milling is usually moved perpendicular to its axis so that cutting occurs on the circumference of the cutter. As the milling cutter enters the workpiece, the cutting edges (flutes or teeth) of the tool repeatedly cut into and exit from the material, shaving off chips (swarf) from the workpiece with each pass. The cutting action is shear deformation; material is pushed off the workpiece in tiny clumps that
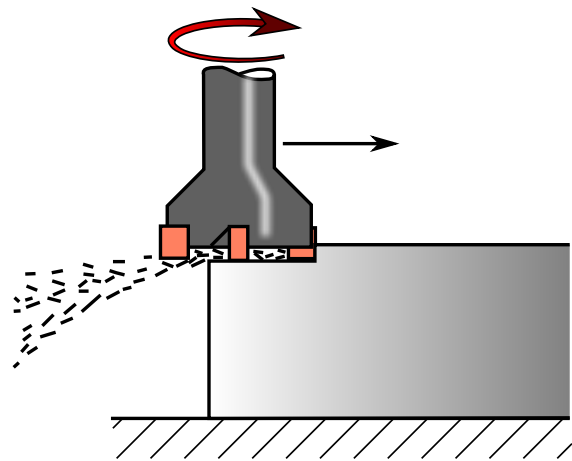
Face milling process (cutter rotation axis is vertical)

hang together to a greater or lesser extent (depending on the material) to form chips. This makes metal cutting somewhat different (in its mechanics) from slicing softer materials with a blade.

The milling process removes material by performing many separate, small cuts. This is accomplished by using a cutter with many teeth, spinning the cutter at high speed, or advancing the material through the cutter slowly; most often it is some combination of these three approaches.[2] The speeds and feeds used are varied to suit a combination of variables. The speed at which the piece advances through the cutter is called **feed rate**, or just **feed**; it is most often measured in length of material per full revolution of the cutter.

There are two major classes of milling process:

- In **face milling**, the cutting action occurs primarily at the end corners of the milling cutter. Face milling is used to cut flat surfaces (faces) into the workpiece, or to cut flat-bottomed cavities.

- In **peripheral milling**, the cutting action occurs primarily along the circumference of the cutter, so that the cross section of the milled surface ends up receiving the shape of the cutter. In this case the blades of the cutter can be seen as scooping out material from the work piece. Peripheral milling is well

suited to the cutting of deep slots, threads, and gear teeth.

2.1.1 Milling cutters

Main article: Milling cutter

Many different types of cutting tools are used in the milling process. Milling cutters such as endmills may have cutting surfaces across their entire end surface, so that they can be drilled into the workpiece (plunging). Milling cutters may also have extended cutting surfaces on their sides to allow for peripheral milling. Tools optimized for face milling tend to have only small cutters at their end corners.

The cutting surfaces of a milling cutter are generally made of a hard and temperature-resistant material, so that they wear slowly. A low cost cutter may have surfaces made of high speed steel. More expensive but slower-wearing materials include cemented carbide. Thin film coatings may be applied to decrease friction or further increase hardness.

They are cutting tools typically used in milling machines or machining centres to perform milling operations (and occasionally in other machine tools). They remove material by their movement within the machine (e.g., a ball nose mill) or directly from the cutter's shape (e.g., a form tool such as a hobbing cutter).

2.1.2 Surface finish
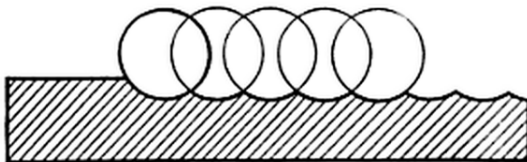
A diagram of revolution ridges on a surface milled by the side of the cutter, showing the position of the cutter for each cutting pass and how it corresponds with the ridges (cutter rotation axis is perpendicular to image plane)

As material passes through the cutting area of a milling machine, the blades of the cutter take swarfs of material at regular intervals. Surfaces cut by the side of the cutter (as in peripheral milling) therefore always contain regular ridges. The distance between ridges and the height of the ridges depend on the feed rate, number of cutting surfaces, the cutter diameter.[4] With a narrow cutter and rapid feed rate, these revolution ridges can be significant variations in the surface height.

The face milling process can in principle produce very flat surfaces. However, in practice the result always shows visible trochoidal marks following the motion of points on
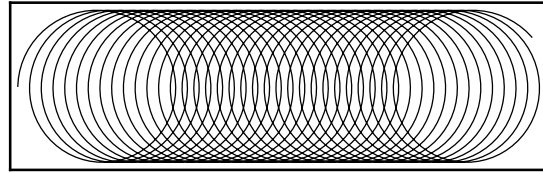
Trochoidal marks, characteristic of face milling.

the cutter's end face. These **revolution marks** give the characteristic finish of a face milled surface. Revolution marks can have significant roughness depending on factors such as flatness of the cutter's end face and the degree of perpendicularity between the cutter's rotation axis and feed direction. Often a final pass with a slow feed rate is used to compensate for a poor milling setup, in order to reduce the roughness of revolution marks. In a precise face milling operation, the revolution marks will only be microscopic scratches due to imperfections in the cutting edge.

2.1.3 Gang milling
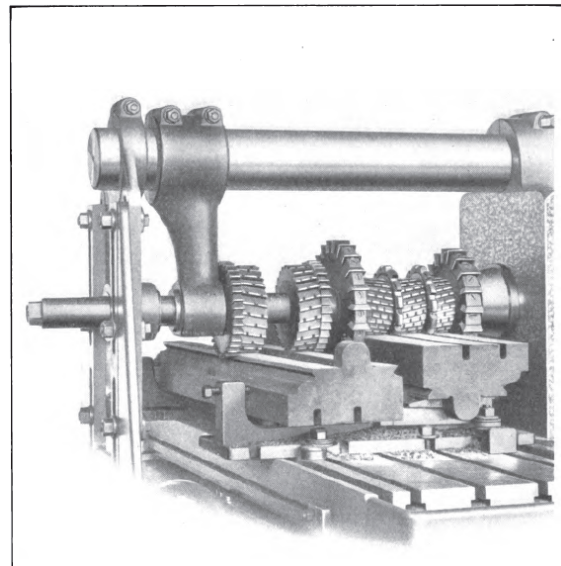
Heavy gang milling of milling machine tables

Gang milling refers to the use of two or more milling cutters mounted on the same arbor (that is, ganged) in a horizontal-milling setup. All of the cutters may perform the same type of operation, or each cutter may perform a different type of operation. For example, if several workpieces need a slot, a flat surface, and an angular groove, a good method to cut these (within a non-CNC context) would be gang milling. All the completed workpieces would be the same, and milling time per piece would be minimized.[5]

Gang milling was especially important before the CNC era, because for duplicate part production, it was a

substantial efficiency improvement over manual-milling one feature at an operation, then changing machines (or changing setup of the same machine) to cut the next op. Today, CNC mills with automatic tool change and 4- or 5-axis control obviate gang-milling practice to a large extent.

2.2   Equipment

Milling is performed with milling cutters attached to a milling machine.

2.2.1   Types and nomenclature

Mill orientation is the primary classification for milling machines. The two basic configurations are vertical and horizontal. However, there are alternate classifications according to method of control, size, purpose and power source.

Mill orientation

- Watch video
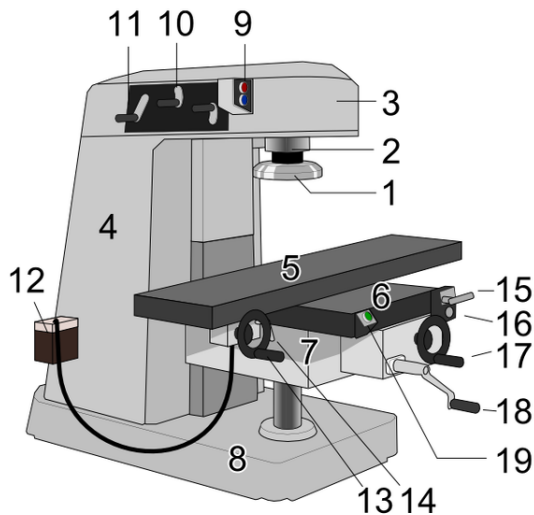
Vertical milling machine. 1: milling cutter 2: spindle 3: top slide or overarm 4: column 5: table 6: Y-axis slide 7: knee 8: base

Vertical mill   In the **vertical mill** the spindle axis is vertically oriented. Milling cutters are held in the spindle and rotate on its axis. The spindle can generally be extended (or the table can be raised/lowered, giving the same effect), allowing plunge cuts and drilling. There are two subcategories of vertical mills: the bed mill and the turret mill.

- A **turret mill** has a stationary spindle and the table is moved both perpendicular and parallel to the spindle axis to accomplish cutting. The most common

example of this type is the Bridgeport, described below. Turret mills often have a quill which allows the milling cutter to be raised and lowered in a manner similar to a drill press. This type of machine provides two methods of cutting in the vertical (Z) direction: by raising or lowering the quill, and by moving the knee.

- In the **bed mill**, however, the table moves only perpendicular to the spindle's axis, while the spindle itself moves parallel to its own axis.

Turret mills are generally considered by some to be more versatile of the two designs. However, turret mills are only practical as long as the machine remains relatively small. As machine size increases, moving the knee up and down requires considerable effort and it also becomes difficult to reach the quill feed handle (if equipped). Therefore, larger milling machines are usually of the bed type.

A third type also exists, a lighter machine, called a mill-drill, which is a close relative of the vertical mill and quite popular with hobbyists. A mill-drill is similar in basic configuration to a small drill press, but equipped with an X-Y table. They also typically use more powerful motors than a comparably sized drill press, with potentiometer-controlled speed and generally have more heavy-duty spindle bearings than a drill press to deal with the lateral loading on the spindle that is created by a milling operation. A mill drill also typically raises and lowers the entire head, including motor, often on a dove-tailed vertical, where a drill press motor remains stationary, while the arbor raises and lowers within a driving collar. Other differences that separate a mill-drill from a drill press may be a fine tuning adjustment for the Z-axis, a more precise depth stop, the capability to lock the X, Y or Z axis, and often a system of tilting the head or the entire vertical to allow angled cutting. Aside from size and precision, the principal difference between these hobby-type machines and larger true vertical mills is that the X-Y table is at a fixed elevation; the Z-axis is controlled in basically the same fashion as drill press, where a larger vertical or knee mill has a vertically fixed milling head, and changes the X-Y table elevation. As well, a mill-drill often uses a standard drill press-type Jacob's chuck, rather than an internally tapered arbor that accepts collets. These are frequently of lower quality than other types of machines, but still fill the hobby role well because they tend to be benchtop machines with small footprints and modest price tags.

Horizontal mill   A horizontal mill has the same sort but the cutters are mounted on a horizontal arbor (see Arbor milling) across the table. Many horizontal mills also feature a built-in rotary table that allows milling at various angles; this feature is called a *universal table*. While end-mills and the other types of tools available to a vertical mill may be used in a horizontal mill, their real advan-
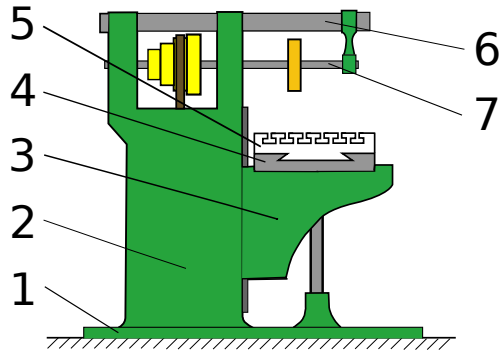
Horizontal milling machine. 1: base 2: column 3: knee 4 & 5: table (x-axis slide is integral) 6: overarm 7: arbor (attached to spindle)

tage lies in arbor-mounted cutters, called side and face mills, which have a cross section rather like a circular saw, but are generally wider and smaller in diameter. Because the cutters have good support from the arbor and have a larger cross-sectional area than an end mill, quite heavy cuts can be taken enabling rapid material removal rates. These are used to mill grooves and slots. Plain mills are used to shape flat surfaces. Several cutters may be ganged together on the arbor to mill a complex shape of slots and planes. Special cutters can also cut grooves, bevels, radii, or indeed any section desired. These specialty cutters tend to be expensive. Simplex mills have one spindle, and duplex mills have two. It is also easier to cut gears on a horizontal mill. Some horizontal milling machines are equipped with a power-take-off provision on the table. This allows the table feed to be synchronized to a rotary fixture, enabling the milling of spiral features such as hypoid gears.

Comparative merits The choice between vertical and horizontal spindle orientation in milling machine design usually hinges on the shape and size of a workpiece and the number of sides of the workpiece that require machining. Work in which the spindle's axial movement is normal to one plane, with an endmill as the cutter, lends itself to a vertical mill, where the operator can stand before the machine and have easy access to the cutting action by looking down upon it. Thus vertical mills are most favored for diesinking work (machining a mould into a block of metal).[6] Heavier and longer workpieces lend themselves to placement on the table of a horizontal mill.

Prior to numerical control, horizontal milling machines evolved first, because they evolved by putting milling tables under lathe-like headstocks. Vertical mills appeared in subsequent decades, and accessories in the form of add-on heads to change horizontal mills to vertical mills (and later vice versa) have been commonly used. Even in the CNC era, a heavy workpiece needing machining on multiple sides lends itself to a horizontal machining

center, while diesinking lends itself to a vertical one.

Alternate classifications

In addition to horizontal versus vertical, other distinctions are also important:

Variants
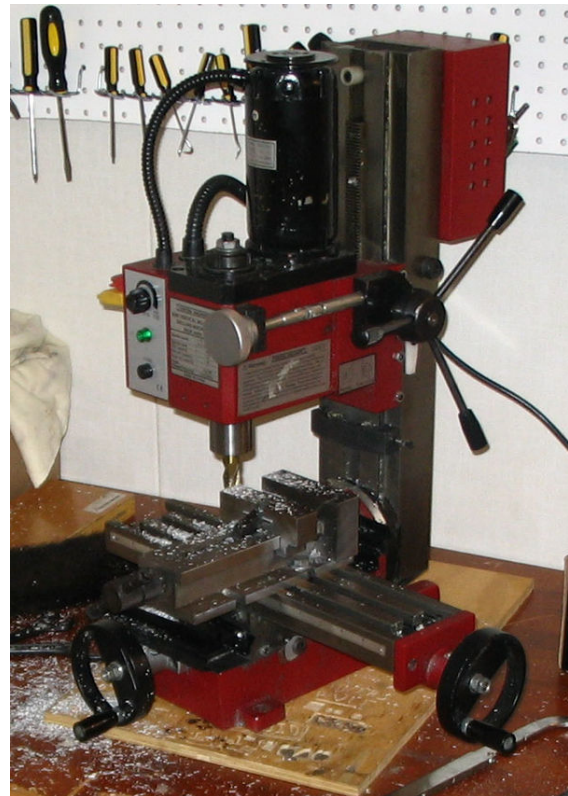
A Sieg X2 miniature hobbyist mill plainly showing the basic parts of a mill.

- **Bed mill** This refers to any milling machine where the spindle is on a *pendant* that moves up and down to move the cutter into the work, while the table sits on a stout *bed* that rests on the floor. These are generally more rigid than a knee mill. Gantry mills can be included in this bed mill category.

- **Box mill** or **column mill** Very basic hobbyist bench-mounted milling machines that feature a head riding up and down on a column or box way.

- **C-Frame mill** These are larger, industrial production mills. They feature a knee and fixed spindle head that is only mobile vertically. They are typically much more powerful than a turret mill, featuring a separate hydraulic motor for integral hydraulic power feeds in all directions, and a twenty to fifty horsepower motor. Backlash eliminators are almost always standard equipment. They use large NMTB

40 or 50 tooling. The tables on C-frame mills are usually 18" by 68" or larger, to allow multiple parts to be machined at the same time.

- **Floor mill** These have a row of rotary tables, and a horizontal pendant spindle mounted on a set of tracks that runs parallel to the table row. These mills have predominantly been converted to CNC, but some can still be found (if one can even find a used machine available) under manual control. The spindle carriage moves to each individual table, performs the machining operations, and moves to the next table while the previous table is being set up for the next operation. Unlike other mills, floor mills have movable floor units. A crane drops massive rotary tables, X-Y tables, etc., into position for machining, allowing large and complex custom milling operations.

- **Gantry mill** The milling head rides over two rails (often steel shafts) which lie at each side of the work surface.

- **Horizontal boring mill** Large, accurate bed horizontal mills that incorporate many features from various machine tools. They are predominantly used to create large manufacturing jigs, or to modify large, high precision parts. They have a spindle stroke of several (usually between four and six) feet, and many are equipped with a tailstock to perform very long boring operations without losing accuracy as the bore increases in depth. A typical bed has X and Y travel, and is between three and four feet square with a rotary table or a larger rectangle without a table. The pendant usually provides between four and eight feet of vertical movement. Some mills have a large (30" or more) integral facing head. Right angle rotary tables and vertical milling attachments are available for further flexibility.

- **Jig borer** Vertical mills that are built to bore holes, and very light slot or face milling. They are typically bed mills with a long spindle throw. The beds are more accurate, and the handwheels are graduated down to .0001" for precise hole placement.

- **Knee mill** or **knee-and-column mill** refers to any milling machine whose x-y table rides up and down the column on a vertically adjustable knee. This includes Bridgeports.

- **Planer-style mill** Large mills built in the same configuration as planers except with a milling spindle instead of a planing head. This term is growing dated as planers themselves are largely a thing of the past.

- **Ram-type mill** This can refer to any mill that has a cutting head mounted on a sliding ram. The spindle can be oriented either vertically or horizontally. In practice most mills with rams also involve swiveling

ability, whether or not it is called "turret" mounting. The Bridgeport configuration can be classified as a vertical-head ram-type mill. Van Norman specialized in ram-type mills through most of the 20th century. Since the wide dissemination of CNC machines, ram-type mills are still made in the Bridgeport configuration (with either manual or CNC control), but the less common variations (such as were built by Van Norman, Index, and others) have died out, their work being done now by either Bridgeport-form mills or machining centers.

- **Turret mill** More commonly referred to as Bridgeport-type milling machines. The spindle can be aligned in many different positions for a very versatile, if somewhat less rigid machine.

Alternate terminology

A milling machine is often called a **mill** by machinists. The archaic term **miller** was commonly used in the 19th and early 20th centuries.[7]

Since the 1960s there has developed an overlap of usage between the terms **milling machine** and **machining center**. NC/CNC machining centers evolved from milling machines, which is why the terminology evolved gradually with considerable overlap that still persists. The distinction, when one is made, is that a machining center is a mill with features that pre-CNC mills never had, especially an automatic tool changer (ATC) that includes a tool magazine (carousel), and sometimes an automatic pallet changer (APC). In typical usage, all machining centers are mills, but not all mills are machining centers; only mills with ATCs are machining centers.

2.2.2   Computer numerical control

Thin wall milling of aluminum using a water based cutting fluid on the milling cutter

Most CNC milling machines (also called *machining centers*) are computer controlled vertical mills with the ability to move the spindle vertically along the Z-axis. This extra degree of freedom permits their use in diesinking, engraving applications, and 2.5D surfaces such as relief sculptures. When combined with the use of conical tools or a ball nose cutter, it also significantly improves milling precision without impacting speed, providing a cost-efficient alternative to most flat-surface hand-engraving work.

Five-axis machining center with rotating table and computer interface

CNC machines can exist in virtually any of the forms of manual machinery, like horizontal mills. The most advanced CNC milling-machines, the multiaxis machine, add two more axes in addition to the three normal axes (XYZ).[8] Horizontal milling machines also have a C or Q axis, allowing the horizontally mounted workpiece to be rotated, essentially allowing asymmetric and eccentric turning. The fifth axis (B axis) controls the tilt of the tool itself. When all of these axes are used in conjunction with each other, extremely complicated geometries, even organic geometries such as a human head can be made with relative ease with these machines. But the skill to program such geometries is beyond that of most operators. Therefore, 5-axis milling machines are practically always programmed with CAM.

The operating system of such machines is a closed loop system and functions on feedback. These machines have developed from the basic NC (NUMERIC CONTROL) machines. A computerized form of NC machines is known as CNC machines. A set of instructions (called a program) is used to guide the machine for desired operations. Some very commonly used codes, which are used in the program are:

G00 - Rapid Traverse G01 - linear interpolation of tool. G21 - Dimensions in metric units. M03/M04 - spindle start (clockwise/counter clockwise). T01 M06 - Automatic tool change to tool 1 M30 - program end.

Various other codes are also used. A CNC machine is operated by a single operator called a programmer. This machine is capable of performing various operations automatically and economically.

With the declining price of computers and open source CNC software, the entry price of CNC machines has plummeted.

High speed steel with cobalt endmills used for cutting operations in a milling machine.

2.2.3 Tooling

The accessories and cutting tools used on machine tools (including milling machines) are referred to in aggregate by the mass noun "tooling". There is a high degree of standardization of the tooling used with CNC milling machines, and a lesser degree with manual milling machines. To ease up the organization of the tooling in CNC production many companies use a tool management solution.

Milling cutters for specific applications are held in various tooling configurations.

CNC milling machines nearly always use SK (or ISO), CAT, BT or HSK tooling. SK tooling is the most common in Europe, while CAT tooling, sometimes called V-Flange Tooling, is the oldest and probably most common type in the USA. CAT tooling was invented by Caterpillar Inc. of Peoria, Illinois, in order to standardize the tooling used on their machinery. CAT tooling comes in a range of sizes designated as CAT-30, CAT-40, CAT-50, etc. The number refers to the Association for Manufacturing Technology (formerly the National Machine Tool Builders Association (NMTB)) Taper size of the tool.

An improvement on CAT Tooling is BT Tooling, which looks similar and can easily be confused with CAT tooling. Like CAT Tooling, BT Tooling comes in a range of sizes and uses the same NMTB body taper. However, BT tooling is symmetrical about the spindle axis, which CAT tooling is not. This gives BT tooling greater stability and balance at high speeds. One other subtle difference between these two toolholders is the thread used to hold the pull stud. CAT Tooling is all Imperial thread and BT Tooling is all Metric thread. Note that this affects the pull stud only, it does not affect the tool that they can hold, both types of tooling are sold to accept both Imperial and metric sized tools.

2.2.4   Accessories

- Arbor support

- Stop block

2.3   History

2.3.1   1810s-1830s

A CAT-40 toolholder

A boring head on a Morse taper shank

This milling machine was long credited to Eli Whitney and dated to circa 1818. From the 1910s through the 1940s, this version of its provenance was widely published. In the 1950s and 1960s, various historians of technology mostly discredited the view of this machine as the first miller and possibly even of Whitney as its builder. Nonetheless, it is still an important early milling machine, regardless of its exact provenance details.
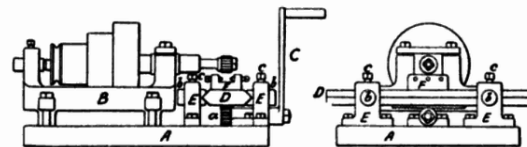
The Middletown milling machine of circa 1818, associated with Robert Johnson and Simeon North.

SK and HSK tooling, sometimes called "Hollow Shank Tooling", is much more common in Europe where it was invented than it is in the United States. It is claimed that HSK tooling is even better than BT Tooling at high speeds. The holding mechanism for HSK tooling is placed within the (hollow) body of the tool and, as spindle speed increases, it expands, gripping the tool more tightly with increasing spindle speed. There is no pull stud with this type of tooling.

For manual milling machines, there is less standardization, because a greater plurality of formerly competing standards exist. Newer and larger manual machines usually use NMTB tooling. This tooling is somewhat similar to CAT tooling but requires a drawbar within the milling machine. Furthermore, there are a number of variations with NMTB tooling that make interchangeability troublesome. The older a machine, the greater the plurality of standards that may apply (e.g., Morse, Jarno, Brown & Sharpe, Van Norman, and other less common builder-specific tapers). However, two standards that have seen especially wide usage are the Morse #2 and the R8, whose prevalence was driven by the popularity of the mills built by Bridgeport Machines of Bridgeport, Connecticut. These mills so dominated the market for such a long time that "Bridgeport" is virtually synonymous with "manual milling machine". Most of the machines that Bridgeport made between 1938 and 1965 used a Morse taper #2, and from about 1965 onward most used an R8 taper.

Milling machines evolved from the practice of rotary filing—that is, running a circular cutter with file-like teeth in the headstock of a lathe. Rotary filing and, later, true milling were developed to reduce time and effort spent hand-filing. The full story of milling machine development may never be known, because much early development took place in individual shops where few records were kept for posterity. However, the broad outlines are known, as summarized below. From a history-of-technology viewpoint, it is clear that the naming of this new type of machining with the term "milling" was an extension from that word's earlier senses of processing materials by abrading them in some way (cutting, grinding, crushing, etc.).
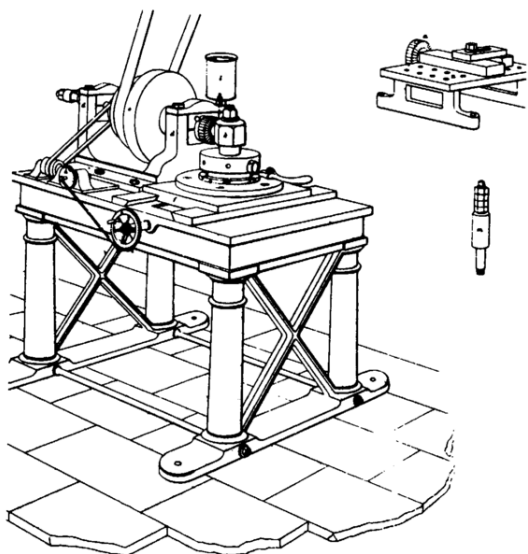
The milling machine built by James Nasmyth between 1829 and 1831 for milling the six sides of a hex nut using an indexing fixture.

Rotary filing long predated milling. A rotary file by Jacques de Vaucanson, circa 1760, is well known.[9][10] It is clear that milling machines as a distinct class of machine tool (separate from lathes running rotary files) first appeared between 1814 and 1818. The centers of earliest development of true milling machines were two federal armories of the U.S. (Springfield and Harpers Ferry) together with the various private armories and inside contractors that shared turnover of skilled workmen with them.

Between 1912 and 1916, Joseph W. Roe, a respected founding father of machine tool historians, credited Eli Whitney (one of the private arms makers mentioned above) with producing the first true milling machine.[11][12] By 1918, he considered it "Probably the first milling machine ever built—certainly the oldest now in existence […]."[13] However, subsequent scholars, including Robert S. Woodbury[14] and others,[15] have improved upon Roe's early version of the history and suggest that just as much credit—in fact, probably more—belongs to various other inventors, including Robert Johnson of Middletown, Connecticut; Captain John H. Hall of the Harpers Ferry armory; Simeon North of the Staddle Hill factory in Middletown; Roswell Lee of the Springfield armory; and Thomas Blanchard. (Several of the men mentioned above are sometimes described on the internet as "the inventor of the first milling machine" or "the inventor of interchangeable parts". Such claims are oversimplified, as these technologies evolved over time among many people.)

Peter Baida,[15] citing Edward A. Battison's article "Eli Whitney and the Milling Machine," which was published in the *Smithsonian Journal of History* in 1966, exemplifies the dispelling of the "Great Man" image of Whitney by

historians of technology working in the 1950s and 1960s. He quotes Battison as concluding that "There is no evidence that Whitney developed or used a true milling machine." Baida says, "The so-called Whitney machine of 1818 seems actually to have been made after Whitney's death in 1825." Baida cites Battison's suggestion that the first true milling machine was made not by Whitney, but by Robert Johnson of Middletown.[15]

The late teens of the 19th century were a pivotal time in the history of machine tools, as the period of 1814 to 1818 is also the period during which several contemporary pioneers (Fox, Murray, and Roberts) were developing the planer,[16] and as with the milling machine, the work being done in various shops was undocumented for various reasons (partially because of proprietary secrecy, and also simply because no one was taking down records for posterity).

James Nasmyth built a milling machine very advanced for its time between 1829 and 1831.[17] It was tooled to mill the six sides of a hex nut that was mounted in a six-way indexing fixture.

A milling machine built and used in the shop of Gay & Silver (aka Gay, Silver, & Co) in the 1830s was influential because it employed a better method of vertical positioning than earlier machines. For example, Whitney's machine (the one that Roe considered the very first) and others did not make provision for vertical travel of the knee. Evidently, the workflow assumption behind this was that the machine would be set up with shims, vise, etc. for a certain part design, and successive parts did not require vertical adjustment (or at most would need only shimming). This indicates that early thinking about milling machines was as production machines, not toolroom machines.

In these early years, milling was often viewed as only a roughing operation to be followed by finishing with a hand file. The idea of *reducing* hand filing was more important than *replacing* it.

2.3.2 1840s-1860

Some of the key men in milling machine development during this era included Frederick W. Howe, Francis A. Pratt, Elisha K. Root, and others. (These same men during the same era were also busy developing the state of the art in turret lathes. Howe's experience at Gay & Silver in the 1840s acquainted him with early versions of both machine tools. His machine tool designs were later built at Robbins & Lawrence, the Providence Tool Company, and Brown & Sharpe.) The most successful milling machine design to emerge during this era was the Lincoln miller, which rather than being a specific make and model of machine tool is truly a family of tools built by various companies on a common configuration over several decades. It took its name from the first company to put one on the market, George S. Lincoln & Company
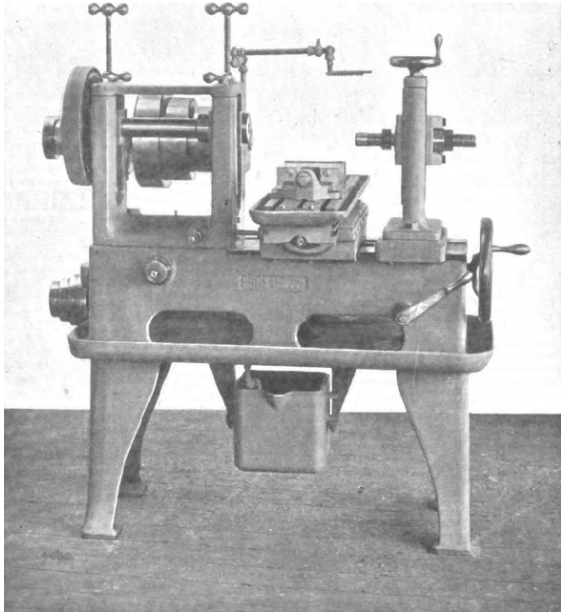
A typical Lincoln miller. The configuration was established in the 1850s. (This example was built by Pratt & Whitney, probably 1870s or 1880s.)

Brown & Sharpe's groundbreaking universal milling machine, 1861

(formerly the Phoenix Iron Works), whose first one was built in 1855 for the Colt armory.[18]

During this era there was a continued blind spot in milling machine design, as various designers failed to develop a truly simple and effective means of providing slide travel in all three of the archetypal milling axes (X, Y, and Z—or as they were known in the past, longitudinal, traverse, and vertical). Vertical positioning ideas were either absent or underdeveloped. The Lincoln miller's spindle could be raised and lowered, but the original idea behind its positioning was to be set up in position and then run, as oppose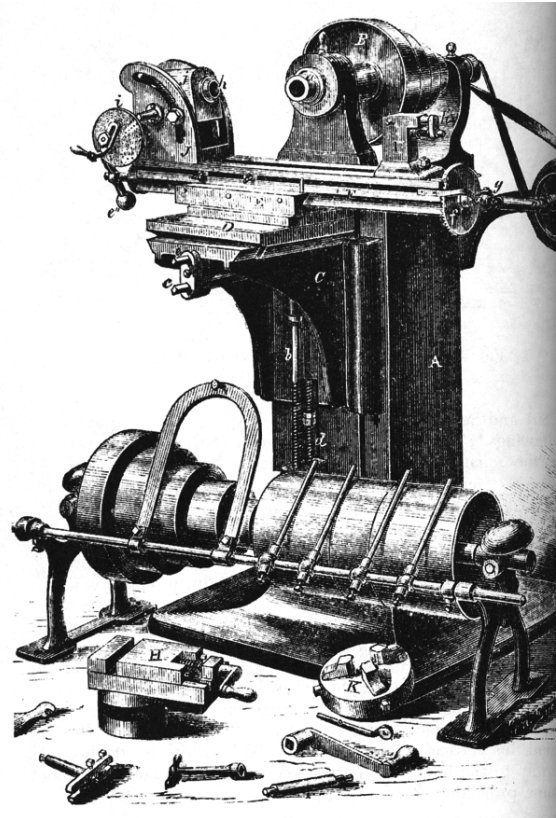d to being moved frequently while running. Like a turret lathe, it was a repetitive-production machine, with each skilled setup followed by extensive fairly low skill operation.

2.3.3   1860s

In 1861, Frederick W. Howe, while working for the Providence Tool Company, asked Joseph R. Brown of Brown & Sharpe for a solution to the problem of milling spirals, such as the flutes of twist drills. These were usually filed by hand at the time.[19] (Helical planing existed but was by no means common.) Brown designed a "universal milling machine" that, starting from its first sale in March 1862, was wildly successful. It solved the problem of 3-axis travel (i.e., the axes that we now call XYZ) much more elegantly than had been done in the past, and it allowed for the milling of spirals using an indexing head fed in coordination with the table feed. The term "universal" was applied to it because it was ready for any kind of work, including toolroom work, and was not as limited

in application as previous designs. (Howe had designed a "universal miller" in 1852, but Brown's of 1861 is the one considered a groundbreaking success.)[19]

Brown also developed and patented (1864) the design of formed milling cutters in which successive sharpenings of the teeth do not disturb the geometry of the form.[10]

The advances of the 1860s opened the floodgates and ushered in modern milling practice.

2.3.4   1870s to World War I

In these decades, Brown & Sharpe and the Cincinnati Milling Machine Company dominated the milling machine field. However, hundreds of other firms also built milling machines at the time, and many were significant in various ways. Besides a wide variety of specialized production machines, the archetypal multipurpose milling machine of the late 19th and early 20th centuries was a heavy knee-and-column horizontal-spindle design with power table feeds, indexing head, and a stout overarm to support the arbor. The evolution of machine design was driven not only by inventive spirit but also by the constant evolution of milling cutters that saw milestone after milestone from 1860 through World War I.[20][21]
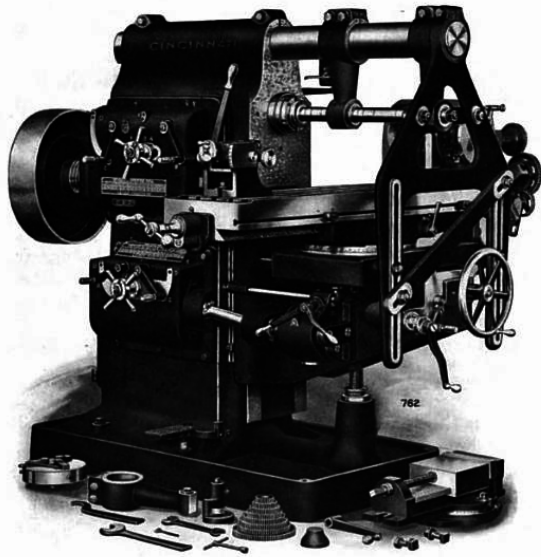
A typical universal milling machine of the early 20th century. Suitable for toolroom, jobbing, or production use.

2.3.5 World War I and interwar period

Around the end of World War I, machine tool control advanced in various ways that laid the groundwork for later CNC technology. The jig borer popularized the ideas of coordinate dimensioning (dimensioning of all locations on the part from a single reference point); working routinely in "tenths" (ten-thousandths of an inch, 0.0001") as an everyday machine capability; and using the control to go straight from drawing to part, circumventing jig-making. In 1920 the new tracer design of J.C. Shaw was applied to Keller tracer milling machines for diesinking via the three-dimensional copying of a template. This made diesinking faster and easier just as dies were in higher demand than ever before, and was very helpful for large steel dies such as those used to stamp sheets in automobile manufacturing. Such machines translated the tracer movements to input for servos that worked the machine leadscrews or hydraulics. They also spurred the development of antibacklash leadscrew nuts. All of the above concepts were new in the 1920s but became routine in the NC/CNC era. By the 1930s, incredibly large and advanced milling machines existed, such as the Cincinnati Hydro-Tel, that presaged today's CNC mills in every respect except for CNC control itself.

Bridgeport milling machine

In 1936, Rudolph Bannow (1897–1962) conceived of a major improvement to the milling machine.[22] His company commenced manufacturing a new knee-and-column vertical mill in 1938. This was the **Bridgeport milling machine**, often called a ram-type or turret-type mill because its head has sliding-ram and rotating-turret mounting. The machine became so popular that many other manufacturers created copies and variants. Furthermore, its name came to connote any such variant. The Bridgeport offered enduring advantages over previous models. It was small enough, light enough, and affordable enough to be a practical acquisition for even the smallest machine shop businesses, yet it was also smartly designed, versatile, well-built, and rigid. Its various directions of sliding and pivoting movement allowed the head to approach the work from any angle. The Bridgeport's design became the dominant form for manual milling machines used by several generations of small- and medium-enterprise machinists. By the 1980s an estimated quarter-million Bridgeport milling machines had been built,[22] and they (and their clones) are still being produced today.

Watch video

2.3.6 1940s-1970s

By 1940, automation via cams, such as in screw machines and automatic chuckers, had already been very well developed for decades. Beginning in the 1930s, ideas involving servomechanisms had been in the air, but it was especially during and immediately after World War II that they began to germinate (see also Numerical control > History). These were soon combined with the emerging technology of digital computers. This technological development milieu, spanning from the immediate pre–World War II period into the 1950s, was powered by the military capital expenditures that pursued contemporary advancements in the directing of gun and rocket artillery and in missile guidance—other applications in which humans wished to control the kinematics/dynamics of large machines quickly, precisely, and automatically. Sufficient R&D spending probably would not have happened within the machine tool industry alone; but it was for the latter applications that the will and ability to spend was available. Once the development was underway, it was eagerly applied to machine tool control in one of the many post-WWII instances of technology transfer.

In 1952, numerical control reached the developmental stage of laboratory reality. The first NC machine tool was a Cincinnati Hydrotel milling machine retrofitted with a scratch-built NC control unit. It was reported in *Scientific American*,[23] just as another groundbreaking milling machine, the Brown & Sharpe universal, had been in 1862.

During the 1950s, numerical control moved slowly from the laboratory into commercial service. For its first decade, it had rather limited impact outside of aerospace work. But during the 1960s and 1970s, NC evolved into CNC, data storage and input media evolved, computer processing power and memory capacity steadily increased, and NC and CNC machine tools gradually disseminated from an environment of huge corporations and mainly aerospace work to the level of medium-sized corporations and a wide variety of products. NC and CNC's drastic advancement of machine tool control

deeply transformed the culture of manufacturing.[24] The details (which are beyond the scope of this article) have evolved immensely with every passing decade.

2.3.7 1980s-present

Computers and CNC machine tools continue to develop rapidly. The personal computer revolution has a great impact on this development. By the late 1980s small machine shops had desktop computers and CNC machine tools. Soon after hobbyists began obtaining CNC mills and lathes. Manufacturers have started producing economically priced CNCs machines small enough to sit on a desktop which can cut at high resolution materials softer than stainless steel. They can be used to make anything from jewelry to printed circuit boards to gun parts.

2.4 See also

- Arbor milling
- CNC router
- Cryomilling
- Milling cutter
- Multiaxis machining
- Photo chemical milling
- Printed circuit board milling
- 3D printing
- CNC pocket milling

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2.5.1 Notes

[1] Brown & Sharpe 1914, p. 7.

[2] CMMC 1922, p. 122.

[3] Usher 1896, p. 142.

[4] CMMC 1992, pp. 125-127.

[5] "How to use a Milling Machine". American Machine Tools Co.

[6] Encyclopædia Britannica 2011

[7] Currently the term "miller" refers to machines built when that term was current, as with "phonograph" and "horseless carriage."

[8] "A Complete Guide To the CNC Milling Machine". CNC Machine HQ. 2014-10-20.

[9] Woodbury 1972, p. 23.

[10] Roe 1916, p. 206.

[11] Woodbury 1972, p. 17.

[12] Roe 1916, caption of figure facing p. 142.

[13] Roe 1918, p. 309.

[14] Woodbury 1972, pp. 16–26.

[15] Baida 1987

[16] Roe 1916, Chapter V: Inventors of the Planer, pp. 50–62.

[17] Woodbury 1972, pp. 24–26.

[18] Roe 1916, p. 165.

[19] Roe 1916, pp. 208–209.

[20] Woodbury 1972, pp. 51–55.

[21] Woodbury 1972, pp. 79–81.

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[23] Pease 1952

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Chapter 3

Lathe

Not to be confused with Lath, a thin piece of wood. For other uses, see Lathe (disambiguation).

A **lathe** /'leɪð/ is a machine tool which rotates the
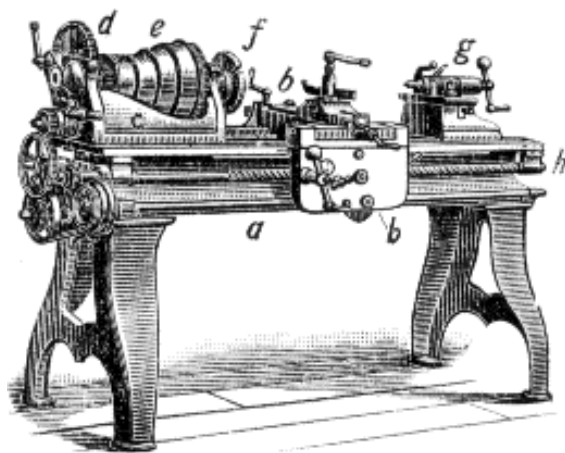
Lathe, p. 1218.

A metalworking lathe from 1911 showing component parts.
a = bed
b = carriage (with cross-slide and toolpost)
c = headstock
d = back gear (other geartrain nearby drives leadscrew)
e = cone pulley for a belt drive from an external power source
f = faceplate mounted on spindle
g = tailstock
h = leadscrew

A watchmaker using a lathe to prepare a component cut from copper.

workpiece on its axis to perform various operations such as cutting, sanding, knurling, drilling, or deformation, facing, turning, with tools that are applied to the workpiece to create an object which has symmetry about an axis of rotation.

Lathes are used in woodturning, metalworking, metal spinning, thermal spraying, parts reclamation, and glassworking. Lathes can be used to shape pottery, the best-known design being the potter's wheel. Most suitably equipped metalworking lathes can also be used to produce most solids of revolution, plane surfaces and screw threads or helices. Ornamental lathes can produce three-dimensional solids of incredible complexity. The workpiece is usually held in place by either one or two *centers*, at least one of which can typically be moved horizontally to accommodate varying workpiece lengths. Other workholding methods include clamping the work about the axis of rotation using a chuck or collet, or to a faceplate, using clamps or dogs.

Examples of objects that can be produced on a lathe include candlestick holders, gun barrels, cue sticks, table legs, bowls, baseball bats, musical instruments (especially woodwind instruments), crankshafts, and camshafts.

3.1 History

The lathe is an ancient tool, dating at least to ancient Egypt and known to be used in Assyria and ancient Greece. The lathe was very important to the Industrial Revolution.

The origin of turning dates to around 1300 BCE when the Ancient Egyptians first developed a two-person lathe. One person would turn the wood work piece with a rope while the other used a sharp tool to cut shapes in the wood. Ancient Rome improved the Egyptian design with the addition of a turning bow. In the Middle Ages a pedal replaced hand-operated turning, freeing both the craftsman's hands to hold the woodturning tools. The pedal was usually connected to a pole, often a straight-grained sapling. The system today is called the "spring pole" lathe. Spring pole lathes were in common use into the early 20th century.

Exact drawing made with camera obscura of horizontal boring machine by Jan Verbruggen in Woolwich Royal Brass Foundry approx 1778 (drawing 47 out of set of 50 drawings)

An important early lathe in the UK was the horizontal boring machine that was installed in 1772 in the Royal Arsenal in Woolwich. It was horse-powered and allowed for the production of much more accurate and stronger cannon used with success in the American Revolutionary War in the late 18th century. One of the key characteristics of this machine was that the workpiece was turning as opposed to the tool, making it technically a lathe (see attached drawing). Henry Maudslay who later developed many improvements to the lathe worked at the Royal Arsenal from 1783 being exposed to this machine in the Verbruggen workshop.[1]

During the Industrial Revolution, mechanized power generated by water wheels or steam engines was transmitted to the lathe via line shafting, allowing faster and easier work. Metalworking lathes evolved into heavier machines with thicker, more rigid parts. Between the late 19th and mid-20th centuries, individual electric motors at each lathe replaced line shafting as the power source. Beginning in the 1950s, servomechanisms were applied to the control of lathes and other machine tools via numerical control, which often was coupled with computers to yield computerized numerical control (CNC). Today manually controlled and CNC lathes coexist in the manufacturing industries.

3.2 Description

3.2.1 Parts

A lathe may or may not have legs which sit on the floor and elevate the lathe bed to a working height. A lathe may be small and sit on a workbench or table, and not require a stand.

Almost all lathes have a bed, which is (almost always) a horizontal beam (although CNC lathes commonly have an inclined or vertical beam for a bed to ensure that swarf,

or chips, falls free of the bed). Woodturning lathes specialized for turning large bowls often have no bed or tail stock, merely a free-standing headstock and a cantilevered tool rest.

At one end of the bed (almost always the left, as the operator faces the lathe) is a headstock. The headstock contains high-precision spinning bearings. Rotating within the bearings is a horizontal axle, with an axis parallel to the bed, called the spindle. Spindles are often hollow, and have exterior threads and/or an interior Morse taper on the "inboard" (i.e., facing to the right / towards the bed) by which work-holding accessories may be mounted to the spindle. Spindles may also have exterior threads and/or an interior taper at their "outboard" (i.e., facing away from the bed) end, and/or may have a hand-wheel or other accessory mechanism on their outboard end. Spindles are powered, and impart motion to the workpiece.

The spindle is driven either by foot power from a treadle and flywheel or by a belt or gear drive to a power source. In most modern lathes this power source is an integral electric motor, often either in the headstock, to the left of the headstock, or beneath the headstock, concealed in the stand.

In addition to the spindle and its bearings, the headstock often contains parts to convert the motor speed into various spindle speeds. Various types of speed-changing mechanism achieve this, from a cone pulley or step pulley, to a cone pulley with back gear (which is essentially a low range, similar in net effect to the two-speed rear of a truck), to an entire gear train similar to that of a manual-shift auto transmission. Some motors have electronic rheostat-type speed controls, which obviates cone pulleys or gears.

The counterpoint to the headstock is the tailstock, sometimes referred to as the loose head, as it can be positioned at any convenient point on the bed by sliding it to the required area. The tail-stock contains a barrel which does not rotate, but can slide in and out parallel to the axis of the bed, and directly in line with the headstock spindle. The barrel is hollow, and usually contains a taper to facilitate the gripping of various type of tooling. Its most common uses are to hold a hardened steel center, which is used to support long thin shafts while turning, or to hold drill bits for drilling axial holes in the work piece. Many other uses are possible.[2]

Metalworking lathes have a carriage (comprising a saddle and apron) topped with a cross-slide, which is a flat piece that sits crosswise on the bed, and can be cranked at right angles to the bed. Sitting atop the cross slide is usually another slide called a compound rest, which provides 2 additional axes of motion, rotary and linear. Atop that sits a toolpost, which holds a cutting tool which removes material from the workpiece. There may or may not be a leadscrew, which moves the cross-slide along the bed.

Woodturning and metal spinning lathes do not have cross-slides, but rather have banjos, which are flat pieces that

sit crosswise on the bed. The position of a banjo can be adjusted by hand; no gearing is involved. Ascending vertically from the banjo is a tool-post, at the top of which is a horizontal toolrest. In woodturning, hand tools are braced against the tool rest and levered into the workpiece. In metal spinning, the further pin ascends vertically from the tool rest, and serves as a fulcrum against which tools may be levered into the workpiece.

3.2.2 Accessories

A steady rest

See also: Lathe center

Unless a workpiece has a taper machined onto it which perfectly matches the internal taper in the spindle, or has threads which perfectly match the external threads on the spindle (two conditions which rarely exist), an accessory must be used to mount a workpiece to the spindle.

A workpiece may be bolted or screwed to a faceplate, a large, flat disk that mounts to the spindle. In the alternative, faceplate dogs may be used to secure the work to the faceplate.

A workpiece may be mounted on a mandrel, or circular work clamped in a three- or four-jaw chuck. For irregular shaped workpieces it is usual to use a four jaw (independent moving jaws) chuck. These holding devices mount directly to the Lathe headstock spindle.

In precision work, and in some classes of repetition work,

cylindrical workpieces are usually held in a collet inserted into the spindle and secured either by a draw-bar, or by a collet closing cap on the spindle. Suitable collets may also be used to mount square or hexagonal workpieces. In precision toolmaking work such collets are usually of the draw-in variety, where, as the collet is tightened, the workpiece moves slightly back into the headstock, whereas for most repetition work the dead length variety is preferred, as this ensures that the position of the workpiece does not move as the collet is tightened.

A soft workpiece (e.g., wood) may be pinched between centers by using a spur drive at the headstock, which bites into the wood and imparts torque to it.

Live center (top); dead center (bottom)

A soft dead center is used in the headstock spindle as the work rotates with the centre. Because the centre is soft it can be trued in place before use. The included angle is 60°. Traditionally, a hard dead center is used together with suitable lubricant in the tailstock to support the workpiece. In modern practice the dead center is frequently replaced by a live center, as it turns freely with the workpiece — usually on ball bearings — reducing the frictional heat, especially important at high speeds. When clear facing a long length of material it must be supported at both ends. This can be achieved by the use of a traveling or fixed steady. If a steady is not available, the end face being worked on may be supported by a dead (stationary) half center. A half center has a flat surface machined across a broad section of half of its diameter at the pointed end. A small section of the tip of the dead center is retained to ensure concentricity. Lubrication must be applied at this point of contact and tail stock pressure reduced. A lathe carrier or lathe dog may also be employed when turning between two centers.[3]

In woodturning, one variation of a live center is a cup center, which is a cone of metal surrounded by an annular ring of metal that decreases the chances of the workpiece splitting.

A circular metal plate with even spaced holes around the periphery, mounted to the spindle, is called an "index plate". It can be used to rotate the spindle to a precise

angle, then lock it in place, facilitating repeated auxiliary operations done to the workpiece.

Other accessories, including items such as taper turning attachments, knurling tools, vertical slides, fixed and traveling steadies, etc., increase the versatility of a lathe and the range of work it may perform.

3.2.3 Modes of use

When a workpiece is fixed between the headstock and the tail-stock, it is said to be "between centers". When a workpiece is supported at both ends, it is more stable, and more force may be applied to the workpiece, via tools, at a right angle to the axis of rotation, without fear that the workpiece may break loose.

When a workpiece is fixed only to the spindle at the headstock end, the work is said to be "face work". When a workpiece is supported in this manner, less force may be applied to the workpiece, via tools, at a right angle to the axis of rotation, lest the workpiece rip free. Thus, most work must be done axially, towards the headstock, or at right angles, but gently.

When a workpiece is mounted with a certain axis of rotation, worked, then remounted with a new axis of rotation, this is referred to as "eccentric turning" or "multi-axis turning". The result is that various cross sections of the workpiece are rotationally symmetric, but the workpiece as a whole is not rotationally symmetric. This technique is used for camshafts, various types of chair legs.

3.2.4 Varieties

The smallest lathes are "jewelers lathes" or "watchmaker lathes", which are small enough that they may be held in one hand. The workpieces machined on a jeweler's lathe are metal. Jeweler's lathes can be used with handheld "graver" tools or with compound rests that attach to the lathe bed. Graver tools are generally supported by a T-rest, not fixed to a cross slide or compound rest. The work is usually held in a collet. Common spindle bore sizes are 6 mm, 8 mm and 10 mm. The term W/W refers to the Webster/Whitcomb collet and lathe, invented by the American Watch Tool Company of Waltham, Massachusetts. Most lathes commonly referred to as watchmakers lathes are of this design. In 1909, the American Watch Tool company introduced the Magnus type collet (a 10-mm body size collet) using a lathe of the same basic design, the Webster/Whitcomb Magnus. (F.W.Derbyshire, Inc. retains the trade names Webster/Whitcomb and Magnus and still produces these collets.) Two bed patterns are common: the WW (Webster Whitcomb) bed, a truncated triangular prism (found only on 8 and 10 mm watchmakers' lathes); and the continental D-style bar bed (used on both 6 mm and 8 mm lathes by firms such as Lorch and Star). Other bed designs have been used, such a triangular prism on some Boley 6.5 mm lathes, and a V-edged bed on IME's 8 mm lathes.

Smaller metalworking lathes that are larger than jewelers' lathes and can sit on a bench or table, but offer such features as tool holders and a screw-cutting gear train are called hobby lathes, and larger versions, "bench lathes". Even larger lathes offering similar features for producing or modifying individual parts are called "engine lathes". Lathes of these types do not have additional integral features for repetitive production, but rather are used for individual part production or modification as the primary role.

Lathes of this size that are designed for mass manufacture, but not offering the versatile screw-cutting capabilities of the engine or bench lathe, are referred to as "second operation" lathes.

Lathes with a very large spindle bore and a chuck on both ends of the spindle are called "oil field lathes".

Fully automatic mechanical lathes, employing cams and gear trains for controlled movement, are called screw machines.

Lathes that are controlled by a computer are CNC lathes.

Lathes with the spindle mounted in a vertical configuration, instead of horizontal configuration, are called vertical lathes or vertical boring machines. They are used where very large diameters must be turned, and the workpiece (comparatively) is not very long.

A lathe with a cylindrical tail-stock that can rotate around a vertical axis, so as to present different tools towards the headstock (and the workpiece) are turret lathes.[4]

A lathe equipped with indexing plates, profile cutters, spiral or helical guides, etc., so as to enable ornamental turning is an ornamental lathe.

Various combinations are possible: for example, a vertical lathe can have CNC capabilities as well (such as a CNC VTL).

Lathes can be combined with other machine tools, such as a drill press or vertical milling machine. These are usually referred to as combination lathes.

3.3 Major categories

3.3.1 Woodworking lathes

Woodworking lathes are the oldest variety. All other varieties are descended from these simple lathes. An adjustable horizontal metal rail - the tool rest - between the material and the operator accommodates the positioning of shaping tools, which are usually hand-held. With wood, it is common practice to press and slide sandpaper against the still-spinning object after shaping to smooth

A modern woodworking lathe.

the surface made with the metal shaping tools.

There are also woodworking lathes for making bowls and plates, which have no horizontal metal rail, as the bowl or plate needs only to be held by one side from a metal face plate. Without this rail, there is very little restriction to the width of the piece being turned. Further detail can be found on the woodturning page.

Most woodworking lathes are designed to be operated at a rate of between 200 and 1,400 revolutions per minute, with a rate slightly over 1,000 rpms being considered optimal for most such work, and with larger workpieces requiring slower rates.[5]

3.3.2   Metalworking lathes

A CNC metalworking lathe

Main article: Lathe (metal)

In a metalworking lathe, metal is removed from the workpiece using a hardened cutting tool, which is usually fixed to a solid moveable mounting, either a tool-post or a turret, which is then moved against the workpiece using handwheels and/or computer controlled motors. These (cutting) tools come in a wide range of sizes and shapes depending upon their application. Some common styles are diamond, round, square and triangular.

The tool-post is operated by lead-screws that can accurately position the tool in a variety of planes. The tool-post may be driven manually or automatically to produce the roughing and finishing cuts required to *turn* the workpiece to the desired shape and dimensions, or for cut-

ting threads, worm gears, etc. Cutting fluid may also be pumped to the cutting site to provide cooling, lubrication and clearing of swarf from the workpiece. Some lathes may be operated under control of a computer for mass production of parts (see "Computer Numerical Control").

Manually controlled metalworking lathes are commonly provided with a variable ratio gear train to drive the main lead-screw. This enables different thread pitches to be cut. On some older lathes or more affordable new lathes, the gear trains are changed by swapping gears with various numbers of teeth onto or off of the shafts, while more modern or expensive manually controlled lathes have a **quick change box** to provide commonly used ratios by the operation of a lever. CNC lathes use computers and servomechanisms to regulate the rates of movement.

On manually controlled lathes, the thread pitches that can be cut are, in some ways, determined by the pitch of the lead-screw: A lathe with a metric lead-screw will readily cut metric threads (including BA), while one with an imperial lead-screw will readily cut imperial unit based threads such as BSW or UTS (UNF,UNC). This limitation is not insurmountable, because a 127-tooth gear, called a transposing gear, is used to translate between metric and inch thread pitches. However, this is optional equipment that many lathe owners do not own. It is also a larger change-wheel than the others, and on some lathes may be larger than the change-wheel mounting banjo is capable of mounting.

The workpiece may be supported between a pair of points called centres, or it may be bolted to a faceplate or held in a chuck. A chuck has movable jaws that can grip the workpiece securely.

There are some effects on material properties when using a metalworking lathe. There are few chemical or physical effects, but there are many mechanical effects, which include residual stress, micro-cracks, work-hardening, and tempering in hardened materials.

3.3.3   Cue lathes

Cue lathes function similar to turning and spinning lathes allowing for a perfectly radially-symmetrical cut for billiard cues. They can also be used to refinish cues that have been worn over the years.

3.3.4   Glass-working lathes

Glass-working lathes are similar in design to other lathes, but differ markedly in how the workpiece is modified. Glass-working lathes slowly rotate a hollow glass vessel over a fixed or variable temperature flame. The source of the flame may be either hand-held, or mounted to a banjo/cross slide that can be moved along the lathe bed. The flame serves to soften the glass being worked, so that the glass in a specific area of the workpiece be-

comes ductile, and subject to forming either by inflation ("glassblowing"), or by deformation with a heat resistant tool. Such lathes usually have two head-stocks with chucks holding the work, arranged so that they both rotate together in unison. Air can be introduced through the headstock chuck spindle for glassblowing. The tools to deform the glass and tubes to blow (inflate) the glass are usually handheld.

In diamond turning, a computer-controlled lathe with a diamond-tipped tool is used to make precision optical surfaces in glass or other optical materials. Unlike conventional optical grinding, complex aspheric surfaces can be machined easily. Instead of the dovetailed ways used on the tool slide of a metal turning lathe, the ways typically float on air bearings and the position of the tool is measured by optical interferometry to achieve the necessary standard of precision for optical work. The finished work piece usually requires a small amount subsequent polishing by conventional techniques to achieve a finished surface suitably smooth for use in a lens, but the rough grinding time is significantly reduced for complex lenses.

3.3.5 Metal spinning lathes

Main article: metal spinning

In metal spinning, a disk of sheet metal is held perpendicularly to the main axis of the lathe, and tools with polished tips (*spoons*) or roller tips are hand held, but levered by hand against fixed posts, to develop pressure that deforms the spinning sheet of metal.

Metal spinning lathes are almost as simple as wood turning lathes, and usually are. Typically, metal spinning requires a mandrel, usually made of wood, which serves as the template onto which the workpiece is formed (asymmetric shapes can be made, but it is a very advanced technique). For example, to make a sheet metal bowl a solid block of wood in the shape of the bowl is required, similarly to make a vase a solid template of the vase is required.

Given the advent of high speed, high pressure, industrial die forming, metal spinning is less common now than it once was, but still a valuable technique for producing one-off prototypes or small batches where die forming would be uneconomical.

3.3.6 Ornamental turning lathes

Main article: Ornamental turning

The ornamental turning lathe was developed around the same time as the industrial screw-cutting lathe in the nineteenth century. It was used not for making practical objects, but for decorative work - *ornamental turning*. By using accessories such as the horizontal and vertical cutting frames, eccentric chuck and elliptical chuck, solids of extraordinary complexity may be produced by various generative procedures.

A special purpose lathe, the Rose engine lathe is also used for ornamental turning, in particular for engine turning, typically in precious metals, for example to decorate pocket watch cases. As well as a wide range of accessories, these lathes usually have complex dividing arrangements to allow the exact rotation of the mandrel. Cutting is usually carried out by rotating cutters, rather than directly by the rotation of the work itself. Because of the difficulty of polishing such work, the materials turned, such as wood or ivory, are usually quite soft, and the cutter has to be exceptionally sharp. The finest ornamental lathes are generally considered to be those made by Holtzapffel around the turn of the 19th century.

3.3.7 Reducing lathe

Many types of lathes can be equipped with accessory components to allow them to reproduce an item: the original item is mounted on one spindle, the blank is mounted on another, and as both turn in synchronized manner, one end of an arm "reads" the original and the other end of the arm "carves" the duplicate.

A **reduction lathe** is a specialized lathe that is designed with this feature, and which incorporates a mechanism similar to a pantograph, so that when the "reading" end of the arm reads a detail that measures one inch (for example), the cutting end of the arm creates an analogous detail that is (for example) one quarter of an inch (a 4:1 reduction, although given appropriate machinery and appropriate settings, any reduction ratio is possible).

Reducing lathes are used in coin-making, where a plaster original (or an epoxy master made from the plaster original, or a copper shelled master made from the plaster original, etc.) is duplicated and reduced on the reducing lathe, generating a master die.

3.3.8 Rotary lathes

A lathe in which softwood, like spruce or pine, or hardwood, like birch, logs are turned against a very sharp blade and peeled off in one continuous or semi-continuous roll. Invented by Immanuel Nobel (father of the more famous Alfred Nobel). The first such lathes were set up in the United States in the mid-19th century. The product is called wood veneer and it is used for making plywood and as a cosmetic surface veneer on some grades of chipboard.

3.3.9 Watchmaker's lathes

Watchmakers lathes are delicate but precise metalworking lathes, usually without provision for screwcutting, and

are still used by horologists for work such as the turning of balance shafts. A handheld tool called a graver is often used in preference to a slide mounted tool. The original watchmaker's turns was a simple dead-center lathe with a moveable rest and two loose head-stocks. The workpiece would be rotated by a bow, typically of horsehair, wrapped around it.

3.3.10 Transcription or Recording lathes

Transcription or Recording lathes are used to make grooves on a surface for recording sounds. These were used in creating sound grooves on wax cylinders and then on flat recording discs. Originally the cutting lathes were driven by sound vibrations through a horn and then later driven by electric current when microphones were used in recording. Many of these were professional models, but there were some used for home recording and were popular before the advent of home tape recording.

3.4 Gallery

3.4.1 Examples of lathes

- Small metalworking lathe

- Large old lathe

- Belt-driven metalworking lathe in the machine shop at Hagley Museum

3.4.2 Examples of work produced from a lathe

- Lathe exercise

- Turned chess pieces

3.5 Performance Evaluation

National and international standards are used to standardize the definitions, environmental requirements, and test methods used for the performance evaluation of lathes. Selection of the standard to be used is an agreement between the supplier and the user and has some significance in the design of the lathe. In the United States, ASME has developed the B5.57 Standard entitled Methods for Performance Evaluation of Computer Numerically Controlled Lathes and Turning Centers, which establishes requirements and methods for specifying and testing the performance of CNC lathes and turning centers. [6]

3.6 See also

- Arbor support

- Diamond turning

- Segmented turning

- Unimat

3.7 References

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3.9   External links

- Historical lathe archive

- Medieval and Renaissance lathes

- The history of the lathe

- Early Wood-Working

- Spring pole lathe

- On ye art and mystery of Turning

- Modern Machine Shop Practice a historic Victorian text describing lathe design, construction and use in 1880s.

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Chapter 4

Plasma cutting

For fictional weapons, see Plasma weapon (fiction) and directed-energy weapon.

Plasma cutting is a process that is used to cut steel and
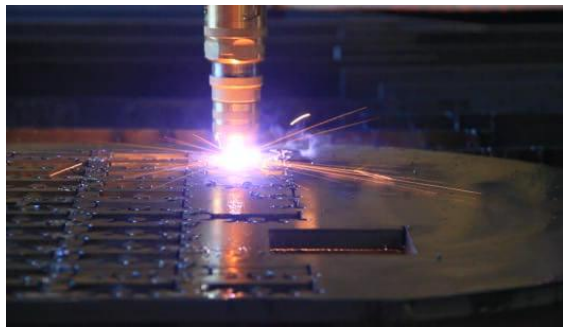
CNC Plasma Cutting

Plasma cutting performed by an industrial robot

other metals of different thicknesses (or sometimes other materials) using a plasma torch. In this process, a gas (oxygen, air, inert and others dependant on material) is blown at high speed out of a nozzle; at the same time an electrical arc is formed through that gas from the nozzle to the surface being cut, turning some of that gas to plasma. The plasma is hot enough to melt the metal being cut and moves fast enough to blow molten metal away from the cut.

4.1 Process

Freehand cut of a thick steel plate

A plasma torch requires you to start an arc between the electrode in the torch and the work you intend to cut. To start this arc there are various methods used, commonly High Frequency or Blow Back. HF (High Frequency) is used in most modern industrial plasma systems and in many older systems. The second common method is known as blow back, or short circuit start.

In a high frequency plasma system there are no moving parts in the torch. The electrode is connected to the power sources negative output and the work connected to the positive. The electrode is the conductor from which the arc starts and travels to the work piece. To start the arc the plasma initially connects the nozzle to positive. The nozzle is responsible for directing the gas flow, it wraps around the electrode and has a small output hole in which the gas flow and the plasma arc is directed. A DC potential between the nozzle an electrode is established and the HF circuit is turned on. The high frequency, high voltage causes a small low current arc to transfer between the nozzle and electrode in the torch. The low HF current

creates a path of ionized gas allowing the lower voltage DC output to conduct. The current established between the nozzle and electrode in the torch is known as a Pilot Arc.

In the blow back method the arc is started with the plasma torch's electrode and nozzle initially touching. The power source draws a current from the nozzle to the electrode. After the current is established the power source will turn on the gas flow. Due to the design of the torch when gas begins to flow the electrode will pull away from the nozzle. As the electrode retracts the current draw between it and the nozzle will create a spark. With this ionized path of gas, lower voltage DC current is allowed flow and once again have a Pilot Arc.

In both methods above you achieve a pilot arc, which is an ionized path of gas between the electrode and nozzle in the torch. Once this pilot arc is brought close to the work, which is at the same potential as the nozzle, current will transfer directly from the electrode to the work. The plasma source will detect the current into the work and disconnect the nozzle (in most cases) allowing full current flow from the electrode to nozzle.

Plasma is an effective means of cutting thin and thick materials alike. Hand-held torches can usually cut up to 38mm thick steel plate, and stronger computer-controlled torches can cut steel up to 150 mm thick. Since plasma cutters produce a very hot and very localized "cone" to cut with, they are extremely useful for cutting sheet metal in curved or angled shapes.

4.2 History

Plasma cutting with a tilting head

Plasma cutting grew out of plasma welding in the 1960s, and emerged as a very productive way to cut sheet metal and plate in the 1980s.[1] It had the advantages over traditional "metal against metal" cutting of producing no metal chips, giving accurate cuts, and producing a cleaner edge than oxy-fuel cutting. Early plasma cutters were large, somewhat slow and expensive and, therefore, tended to

be dedicated to repeating cutting patterns in a "mass production" mode.

As with other machine tools, CNC (computer numerical control) technology was applied to plasma cutting machines in the late 1980s into the 1990s, giving plasma cutting machines greater flexibility to cut diverse shapes "on demand" based on a set of instructions that were programmed into the machine's numerical control.[2] These CNC plasma cutting machines were, however, generally limited to cutting patterns and parts in flat sheets of steel, using only two axes of motion (referred to as X Y cutting).

4.3 Safety

Proper eye protection (but not gas welding goggles as these do not give UV protection) and face shields are needed to prevent eye damage called arc eye as well as damage from debris, as per Arc Welding. It is recommended to use green lens shade #8 or #9 safety glasses for cutting to prevent the retinas from being "flashed" or burned. OSHA recommends a shade 8 for Arc Current less than 300, but notes that "These values apply where the actual arc is clearly seen. Experience has shown that lighter filters may be used when the arc is hidden by the workpiece." Lincoln Electric, a manufacturer of plasma cutting equipment, says, "Typically a darkness shade of #7 to #9 is acceptable." Longevity Global, Inc., another manufacturer, offers this more specific table for Eye Protection for Plasma Arc Cutting at lower amperages :

Leather gloves, apron and jacket are also recommended to prevent burns from sparks and debris.

4.4 Starting methods

Plasma cutters use a number of methods to start the arc. In some units, the arc is created by putting the torch in contact with the work piece. Some cutters use a high voltage, high frequency circuit to start the arc. This method has a number of disadvantages, including risk of electrocution, difficulty of repair, spark gap maintenance, and the large amount of radio frequency emissions.[3] Plasma cutters working near sensitive electronics, such as CNC hardware or computers, start the pilot arc by other means. The nozzle and electrode are in contact. The nozzle is the cathode, and the electrode is the anode. When the plasma gas begins to flow, the nozzle is blown forward. A third, less common method is capacitive discharge into the primary circuit via a silicon controlled rectifier.

4.5 Inverter plasma cutters

Analog plasma cutters, typically requiring more than 2 kilowatts, use a heavy mains-frequency transformer. In-

Plasma cutting

4.7   CNC cutting methods

Plasma cutting with a CNC machine

Plasma cutting with a bevel head

verter plasma cutters rectify the mains supply to DC, which is fed into a high-frequency transistor inverter between 10 kHz to about 200 kHz. Higher switching frequencies give greater efficiencies in the transformer, allowing its size and weight to be reduced.

The transistors used were initially MOSFETs, but are now increasingly using IGBTs. With paralleled MOSFETs, if one of the transistors activates prematurely it can lead to a cascading failure of one quarter of the inverter. A later invention, IGBTs, are not as subject to this failure mode. IGBTs can be generally found in high current machines where it is not possible to parallel sufficient MOSFET transistors.

The switch mode topology is referred to as a dual transistor off-line forward converter. Although lighter and more powerful, some inverter plasma cutters, especially those without power factor correction, cannot be run from a generator (that means manufacturer of the inverter unit forbids doing so; it is only valid for small, light portable generators). However newer models have internal circuitry that allow units without power factor correction to run on light power generators.

4.6   Plasma gouging

Plasma gouging is a related process, typically performed on the same equipment as plasma cutting. Instead of cutting the material, plasma gouging uses a different torch configuration (torch nozzles and gas diffusers are usually different), and a longer torch-to-workpiece distance, to blow away metal. Plasma gouging can be used in a variety of applications, including removing a weld for rework. The additional sparks generated by the process requires the operator to wear a leather shield protecting their hand and forearm. Torch leads also can be protected by a leather sheath or heavy insulation.

Some plasma cutter manufacturers build CNC cutting tables, and some have the cutter built into the table. CNC tables allow a computer to control the torch head producing clean sharp cuts. Modern CNC plasma equipment is capable of multi-axis cutting of thick material, allowing opportunities for complex welding seams that are not possible otherwise. For thinner material, plasma cutting is being progressively replaced by laser cutting, due mainly to the laser cutter's superior hole-cutting abilities.

A specialized use of CNC Plasma Cutters has been in the HVAC industry. Software processes information on ductwork and creates flat patterns to be cut on the cutting table by the plasma torch. This technology has enormously increased productivity within the industry since its introduction in the early 1980s.

In recent years there has been even more development. Traditionally the machines' cutting tables were horizontal, but now vertical CNC plasma cutting machines are available, providing for a smaller footprint, increased flexibility, optimum safety and faster operation.

Hand held plasma cutter

High performance cut

4.8   New technology

In the past decade plasma torch manufacturers have engineered new models with a smaller nozzle and a thinner plasma arc. This allows near-laser precision on plasma cut edges. Several manufacturers have combined precision CNC control with these torches to allow fabricators to produce parts that require little or no finishing.

4.9   Costs

Plasma torches were once quite expensive. For this reason they were usually only found in professional welding shops and very well-stocked private garages and shops. However, modern plasma torches are becoming cheaper, and now are within the price range of many hobbyists. Older units may be very heavy, but still portable, while some newer ones with inverter technology weigh only a little, yet equal or exceed the capacities of older ones.

4.10   See also

- Laser cutting
- Air carbon arc cutting
- Plasma arc welding
- Water jet cutter
- Welding
- List of plasma (physics) articles

4.11   References

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4.12   External links

- HowStuffWorks on plasma cutting
- Plasma Cutter Safe Work Method Statement
- Torch Height Control through Arc Voltage Sensing

Chapter 5

Electrical discharge machining
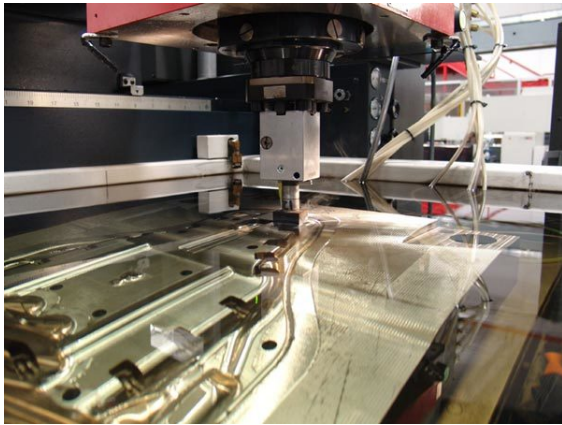
An electrical discharge machine

Electrical discharge machining (**EDM**), sometimes colloquially also referred to as **spark machining**, **spark eroding**, **burning**, **die sinking**, **wire burning** or **wire erosion**, is a manufacturing process whereby a desired shape is obtained using electrical discharges (sparks).[1] Material is removed from the workpiece by a series of rapidly recurring current discharges between two electrodes, separated by a dielectric liquid and subject to an electric voltage. One of the electrodes is called the tool-electrode, or simply the "tool" or "electrode", while the other is called the workpiece-electrode, or "workpiece".

When the distance between the two electrodes is reduced, the intensity of the electric field in the volume between the electrodes becomes greater than the strength of the dielectric (at least in some point(s)), which breaks, allowing current to flow between the two electrodes. This phenomenon is the same as the breakdown of a capacitor (condenser) (see also breakdown voltage). As a result, material is removed from both electrodes. Once the current stops (or is stopped, depending on the type of generator), new liquid dielectric is usually conveyed into the inter-electrode volume, enabling the solid particles (debris) to be carried away and the insulating properties of the dielectric to be restored. Adding new liquid dielectric in the inter-electrode volume is commonly referred to as "flushing". Also, after a current flow, the difference of potential between the electrodes is restored to what it was before the breakdown, so that a new liquid dielectric breakdown can occur.

5.1 History

The erosive effect of electrical discharges was first noted in 1770 by English physicist Joseph Priestley.[2]

5.1.1 Die-sink EDM

Two Russian scientists, B. R. Lazarenko and N. I. Lazarenko, were tasked in 1943 to investigate ways of preventing the erosion of tungsten electrical contacts due to sparking. They failed in this task but found that the erosion was more precisely controlled if the electrodes were immersed in a dielectric fluid. This led them to invent an EDM machine used for working difficult-to-machine materials such as tungsten. The Lazarenkos' machine is known as an R-C-type machine, after the RC circuit used to charge the electrodes.[3]

Simultaneously but independently, an American team, Harold Stark, Victor Harding, and Jack Beaver, developed an EDM machine for removing broken drills and taps from aluminium castings. Initially constructing their machines from feeble electric-etching tools, they were not very successful. But more powerful sparking units, combined with automatic spark repetition and fluid replacement with an electromagnetic interrupter arrangement produced practical machines. Stark, Harding, and Beaver's machines were able to produce 60 sparks per second. Later machines based on their design used vacuum tube circuits that were able to produce thousands of sparks per second, significantly increasing the speed of cutting.[4]

5.1.2 Wire-cut EDM

The wire-cut type of machine arose in the 1960s for the purpose of making tools (dies) from hardened steel. The tool electrode in wire EDM is simply a wire. To avoid the erosion of material from the wire causing it to break,

the wire is wound between two spools so that the active part of the wire is constantly changing. The earliest numerical controlled (NC) machines were conversions of punched-tape vertical milling machines. The first commercially available NC machine built as a wire-cut EDM machine was manufactured in the USSR in 1967. Machines that could optically follow lines on a master drawing were developed by David H. Dulebohn's group in the 1960s at Andrew Engineering Company[5] for milling and grinding machines. Master drawings were later produced by computer numerical controlled (CNC) plotters for greater accuracy. A wire-cut EDM machine using the CNC drawing plotter and optical line follower techniques was produced in 1974. Dulebohn later used the same plotter CNC program to directly control the EDM machine, and the first CNC EDM machine was produced in 1976[6]

5.2 Generalities

Electrical discharge machining is a machining method primarily used for hard metals or those that would be very difficult to machine with traditional techniques. EDM typically works with materials that are electrically conductive, although methods for machining insulating ceramics[7][8] with EDM have also been proposed. EDM can cut intricate contours or cavities in pre-hardened steel without the need for heat treatment to soften and reharden them. This method can be used with any other metal or metal alloy such as titanium, hastelloy, kovar, and inconel. Also, applications of this process to shape polycrystalline diamond tools have been reported.[9]

EDM is often included in the "non-traditional" or "non-conventional" group of machining methods together with processes such as electrochemical machining (ECM), water jet cutting (WJ, AWJ), laser cutting and opposite to the "conventional" group (turning, milling, grinding, drilling and any other process whose material removal mechanism is essentially based on mechanical forces).[10]

Ideally, EDM can be seen as a series of breakdown and restoration of the liquid dielectric in-between the electrodes. However, caution should be exerted in considering such a statement because it is an idealized model of the process, introduced to describe the fundamental ideas underlying the process. Yet, any practical application involves many aspects that may also need to be considered. For instance, the removal of the debris from the inter-electrode volume is likely to be always partial. Thus the electrical proprieties of the dielectric in the inter-electrodes volume can be different from their nominal values and can even vary with time. The inter-electrode distance, often also referred to as spark-gap, is the end result of the control algorithms of the specific machine used. The control of such a distance appears logically to be central to this process. Also, not all of the current between the dielectric is of the ideal type described

above: the spark-gap can be short-circuited by the debris. The control system of the electrode may fail to react quickly enough to prevent the two electrodes (tool and workpiece) from coming into contact, with a consequent short circuit. This is unwanted because a short circuit contributes to material removal differently from the ideal case. The flushing action can be inadequate to restore the insulating properties of the dielectric so that the current always happens in the point of the inter-electrode volume (this is referred to as arcing), with a consequent unwanted change of shape (damage) of the tool-electrode and workpiece. Ultimately, a description of this process in a suitable way for the specific purpose at hand is what makes the EDM area such a rich field for further investigation and research.[11]

To obtain a specific geometry, the EDM tool is guided along the desired path very close to the work; ideally it should not touch the workpiece, although in reality this may happen due to the performance of the specific motion control in use. In this way, a large number of current discharges (colloquially also called sparks) happen, each contributing to the removal of material from both tool and workpiece, where small craters are formed. The size of the craters is a function of the technological parameters set for the specific job at hand. They can be with typical dimensions ranging from the nanoscale (in micro-EDM operations) to some hundreds of micrometers in roughing conditions.

The presence of these small craters on the tool results in the gradual erosion of the electrode. This erosion of the tool-electrode is also referred to as wear. Strategies are needed to counteract the detrimental effect of the wear on the geometry of the workpiece. One possibility is that of continuously replacing the tool-electrode during a machining operation. This is what happens if a continuously replaced wire is used as electrode. In this case, the correspondent EDM process is also called wire EDM. The tool-electrode can also be used in such a way that only a small portion of it is actually engaged in the machining process and this portion is changed on a regular basis. This is, for instance, the case when using a rotating disk as a tool-electrode. The corresponding process is often also referred to as EDM grinding.[12]

A further strategy consists in using a set of electrodes with different sizes and shapes during the same EDM operation. This is often referred to as multiple electrode strategy, and is most common when the tool electrode replicates in negative the wanted shape and is advanced towards the blank along a single direction, usually the vertical direction (i.e. z-axis). This resembles the sink of the tool into the dielectric liquid in which the workpiece is immersed, so, not surprisingly, it is often referred to as die-sinking EDM (also called conventional EDM and ram EDM). The corresponding machines are often called sinker EDM. Usually, the electrodes of this type have quite complex forms. If the final geometry is obtained using a usually simple-shaped electrode which is moved

along several directions and is possibly also subject to rotations, often the term EDM milling is used.[13]

In any case, the severity of the wear is strictly dependent on the technological parameters used in the operation (for instance: polarity, maximum current, open circuit voltage). For example, in micro-EDM, also known as μ-EDM, these parameters are usually set at values which generates severe wear. Therefore, wear is a major problem in that area.

The problem of wear to graphite electrodes is being addressed. In one approach, a digital generator, controllable within milliseconds, reverses polarity as electroerosion takes place. That produces an effect similar to electroplating that continuously deposits the eroded graphite back on the electrode. In another method, a so-called "Zero Wear" circuit reduces how often the discharge starts and stops, keeping it on for as long a time as possible.[14]

5.3   Definition of the technological parameters

Difficulties have been encountered in the definition of the technological parameters that drive the process.

Two broad categories of generators, also known as power supplies, are in use on EDM machines commercially available: the group based on RC circuits and the group based on transistor controlled pulses.

In the first category, the main parameters to choose from at setup time are the resistance(s) of the resistor(s) and the capacitance(s) of the capacitor(s). In an ideal condition these quantities would affect the maximum current delivered in a discharge which is expected to be associated with the charge accumulated on the capacitors at a certain moment in time. Little control, however, is expected over the time duration of the discharge, which is likely to depend on the actual spark-gap conditions (size and pollution) at the moment of the discharge. The RC circuit generator can allow the user to obtain short time durations of the discharges more easily than the pulse-controlled generator, although this advantage is diminishing with the development of new electronic components.[15] Also, the open circuit voltage (i.e. the voltage between the electrodes when the dielectric is not yet broken) can be identified as steady state voltage of the RC circuit.

In generators based on transistor control, the user is usually able to deliver a train of pulses of voltage to the electrodes. Each pulse can be controlled in shape, for instance, quasi-rectangular. In particular, the time between two consecutive pulses and the duration of each pulse can be set. The amplitude of each pulse constitutes the open circuit voltage. Thus, the maximum duration of discharge is equal to the duration of a pulse of voltage in the train. Two pulses of current are then expected not to occur for

a duration equal or larger than the time interval between two consecutive pulses of voltage.

The maximum current during a discharge that the generator delivers can also be controlled. Because other sorts of generators may also be used by different machine builders, the parameters that may actually be set on a particular machine will depend on the generator manufacturer. The details of the generators and control systems on their machines are not always easily available to their user. This is a barrier to describing unequivocally the technological parameters of the EDM process. Moreover, the parameters affecting the phenomena occurring between tool and electrode are also related to the controller of the motion of the electrodes.

A framework to define and measure the electrical parameters during an EDM operation directly on inter-electrode volume with an oscilloscope external to the machine has been recently proposed by Ferri *et al.*[16] These authors conducted their research in the field of μ-EDM, but the same approach can be used in any EDM operation. This would enable the user to estimate directly the electrical parameters that affect their operations without relying upon machine manufacturer's claims. When machining different materials in the same setup conditions, the actual electrical parameters of the process are significantly different.[16]

5.4   Material removal mechanism

The first serious attempt of providing a physical explanation of the material removal during electric discharge machining is perhaps that of Van Dijck.[17] Van Dijck presented a thermal model together with a computational simulation to explain the phenomena between the electrodes during electric discharge machining. However, as Van Dijck himself admitted in his study, the number of assumptions made to overcome the lack of experimental data at that time was quite significant.

Further models of what occurs during electric discharge machining in terms of heat transfer were developed in the late eighties and early nineties, including an investigation at Texas A&M University with the support of AGIE, now Agiecharmilles. It resulted in three scholarly papers: the first presenting a thermal model of material removal on the cathode,[18] the second presenting a thermal model for the erosion occurring on the anode[19] and the third introducing a model describing the plasma channel formed during the passage of the discharge current through the dielectric liquid.[20] Validation of these models is supported by experimental data provided by AGIE.

These models give the most authoritative support for the claim that EDM is a thermal process, removing material from the two electrodes because of melting and/or vaporization, along with pressure dynamics established in the spark-gap by the collapsing of the plasma channel. How-

ever, for small discharge energies the models are inadequate to explain the experimental data. All these models hinge on a number of assumptions from such disparate research areas as submarine explosions, discharges in gases, and failure of transformers, so it is not surprising that alternative models have been proposed more recently in the literature trying to explain the EDM process.

Among these, the model from Singh and Ghosh[21] reconnects the removal of material from the electrode to the presence of an electrical force on the surface of the electrode that could mechanically remove material and create the craters. This would be possible because the material on the surface has altered mechanical properties due to an increased temperature caused by the passage of electric current. The authors' simulations showed how they might explain EDM better than a thermal model (melting and/or evaporation), especially for small discharge energies, which are typically used in μ-EDM and in finishing operations.

Given the many available models, it appears that the material removal mechanism in EDM is not yet well understood and that further investigation is necessary to clarify it,[16] especially considering the lack of experimental scientific evidence to build and validate the current EDM models.[16] This explains an increased current research effort in related experimental techniques.[11]

5.5 Types

5.5.1 Sinker EDM
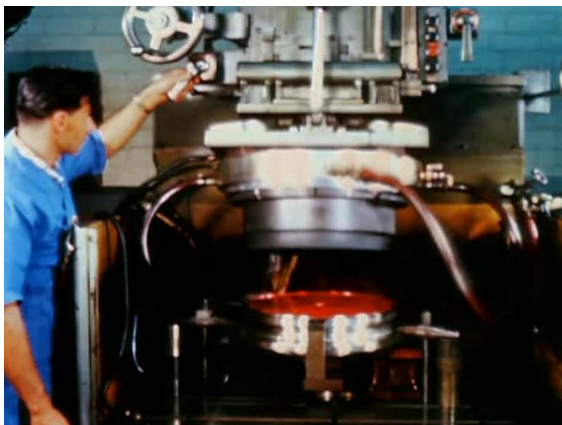
Sinker EDM allowed quick production of 614 uniform injectors for the J-2 rocket engine, six of which were needed for each trip to the moon.[22]

Sinker EDM, also called cavity type EDM or volume EDM, consists of an electrode and workpiece submerged in an insulating liquid such as, more typically,[23] oil or, less frequently, other dielectric fluids. The electrode and workpiece are connected to a suitable power supply. The power supply generates an electrical potential between

the two parts. As the electrode approaches the workpiece, dielectric breakdown occurs in the fluid, forming a plasma channel,[11][18][19][20] and a small spark jumps.

These sparks usually strike one at a time,[23] because it is very unlikely that different locations in the inter-electrode space have the identical local electrical characteristics which would enable a spark to occur simultaneously in all such locations. These sparks happen in huge numbers at seemingly random locations between the electrode and the workpiece. As the base metal is eroded, and the spark gap subsequently increased, the electrode is lowered automatically by the machine so that the process can continue uninterrupted. Several hundred thousand sparks occur per second, with the actual duty cycle carefully controlled by the setup parameters. These controlling cycles are sometimes known as "on time" and "off time", which are more formally defined in the literature.[11][16][24]

The on time setting determines the length or duration of the spark. Hence, a longer on time produces a deeper cavity for that spark and all subsequent sparks for that cycle, creating a rougher finish on the workpiece. The reverse is true for a shorter on time. Off time is the period of time that one spark is replaced by another. A longer off time, for example, allows the flushing of dielectric fluid through a nozzle to clean out the eroded debris, thereby avoiding a short circuit. These settings can be maintained in microseconds. The typical part geometry is a complex 3D shape,[23] often with small or odd shaped angles. Vertical, orbital, vectorial, directional, helical, conical, rotational, spin and indexing machining cycles are also used.

5.5.2 Wire EDM

CNC Wire-cut EDM machine

In *wire electrical discharge machining* (WEDM), also known as *wire-cut EDM* and *wire cutting*,[25] a thin single-

strand metal wire, usually brass, is fed through the work-piece, submerged in a tank of dielectric fluid, typically deionized water.[23] Wire-cut EDM is typically used to cut plates as thick as 300mm and to make punches, tools, and dies from hard metals that are difficult to machine with other methods. The wire, which is constantly fed from a spool, is held between upper and lower diamond guides. The guides, usually CNC-controlled, move in the x–y plane. On most machines, the upper guide can also move independently in the z–u–v axis, giving rise to the ability to cut tapered and transitioning shapes (circle on the bottom, square at the top for example). The upper guide can control axis movements in x–y–u–v–i–j–k–l–. This allows the wire-cut EDM to be programmed to cut very intricate and delicate shapes. The upper and lower diamond guides are usually accurate to 0.004 mm, and can have a cutting path or *kerf* as small as 0.021 mm using Ø 0.02 mm wire, though the average cutting kerf that achieves the best economic cost and machining time is 0.335 mm using Ø 0.25 brass wire. The reason that the cutting width is greater than the width of the wire is because sparking occurs from the sides of the wire to the work piece, causing erosion.[23] This "overcut" is necessary, for many applications it is adequately predictable and therefore can be compensated for (for instance in micro-EDM this is not often the case). Spools of wire are long — an 8 kg spool of 0.25 mm wire is just over 19 kilometers in length. Wire diameter can be as small as 20 micrometres and the geometry precision is not far from +/- 1 micrometre. The wire-cut process uses water as its dielectric fluid, controlling its resistivity and other electrical properties with filters and de-ionizer units. The water flushes the cut debris away from the cutting zone. Flushing is an important factor in determining the maximum feed rate for a given material thickness. Along with tighter tolerances, multi axis EDM wire-cutting machining centers have added features such as multi heads for cutting two parts at the same time, controls for preventing wire breakage, automatic self-threading features in case of wire breakage, and programmable machining strategies to optimize the operation. Wire-cutting EDM is commonly used when low residual stresses are desired, because it does not require high cutting forces for removal of material. If the energy/power per pulse is relatively low (as in finishing operations), little change in the mechanical properties of a material is expected due to these low residual stresses, although material that hasn't been stress-relieved can distort in the machining process. The work piece may undergo a significant thermal cycle, its severity depending on the technological parameters used. Such thermal cycles may cause formation of a recast layer on the part and residual tensile stresses on the work piece. If machining takes place after heat treatment, dimensional accuracy will not be affected by heat treat distortion.[26]

5.6   Applications

5.6.1   Prototype production

The EDM process is most widely used by the mold-making tool and die industries, but is becoming a common method of making prototype and production parts, especially in the aerospace, automobile and electronics industries in which production quantities are relatively low. In sinker EDM, a graphite, copper tungsten or pure copper electrode is machined into the desired (negative) shape and fed into the workpiece on the end of a vertical ram.

5.6.2   Coinage die making
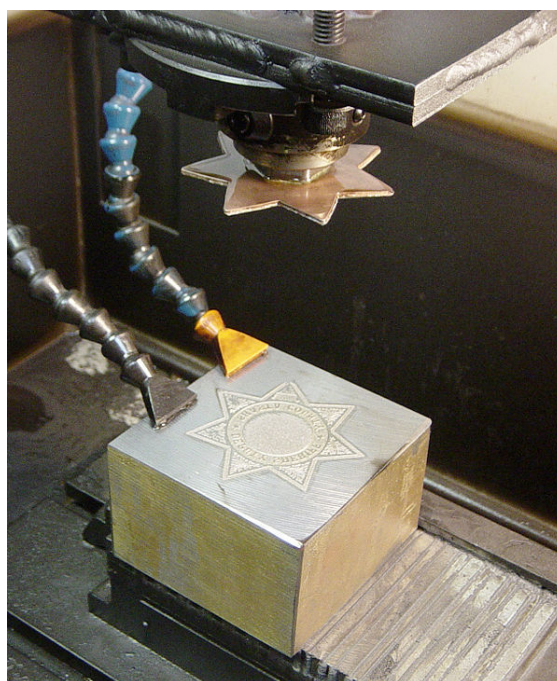
Master at top, badge die workpiece at bottom, oil jets at left (oil has been drained). Initial flat stamping will be "dapped" to give a curved surface.

For the creation of dies for producing jewelry and badges, or blanking and piercing (through use of a pancake die) by the coinage (stamping) process, the positive master may be made from sterling silver, since (with appropriate machine settings) the master is significantly eroded and is used only once. The resultant negative die is then hardened and used in a drop hammer to produce stamped flats from cutout sheet blanks of bronze, silver, or low proof gold alloy. For badges these flats may be further shaped to a curved surface by another die. This type of EDM is usually performed submerged in an oil-based dielectric. The finished object may be further refined by hard (glass) or soft (paint) enameling and/or electroplated with pure gold or nickel. Softer materials such as silver may be hand engraved as a refinement.
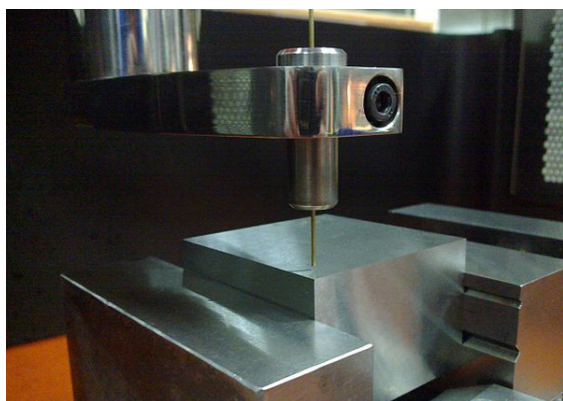
EDM control panel (Hansvedt machine). Machine may be adjusted for a refined surface (electropolish) at end of process.

5.6.3 Small hole drilling
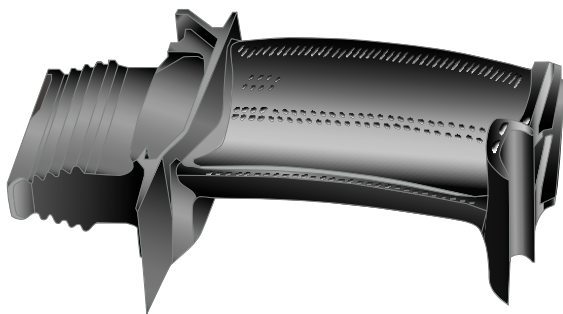
A turbine blade with internal cooling as applied in the high-pressure turbine.

Small hole drilling EDM machines.

Small hole drilling EDM is used in a variety of applications.

On wire-cut EDM machines, small hole drilling EDM is used to make a through hole in a workpiece in through which to thread the wire for the wire-cut EDM operation. A separate EDM head specifically for small hole drilling is mounted on a wire-cut machine and allows large hardened plates to have finished parts eroded from them as needed and without pre-drilling.

Small hole EDM is used to drill rows of holes into the leading and trailing edges of turbine blades used in jet engines. Gas flow through these small holes allows the engines to use higher temperatures than otherwise possible. The high-temperature, very hard, single crystal alloys employed in these blades makes conventional machining of these holes with high aspect ratio extremely difficult, if not impossible.

Small hole EDM is also used to create microscopic orifices for fuel system components, spinnerets for synthetic fibers such as rayon, and other applications.

There are also stand-alone small hole drilling EDM machines with an *x–y* axis also known as a super drill or *hole popper* that can machine blind or through holes. EDM drills bore holes with a long brass or copper tube electrode that rotates in a chuck with a constant flow of distilled or deionized water flowing through the electrode as a flushing agent and dielectric. The electrode tubes operate like the wire in wire-cut EDM machines, having a spark gap and wear rate. Some small-hole drilling EDMs are able to drill through 100 mm of soft or through hardened steel in less than 10 seconds, averaging 50% to 80% wear rate. Holes of 0.3 mm to 6.1 mm can be achieved in this drilling operation. Brass electrodes are easier to machine but are not recommended for wire-cut operations due to eroded brass particles causing "brass on brass" wire breakage, therefore copper is recommended.

5.6.4 Metal disintegration machining

Several manufacturers produce MDM machines for the specific purpose of removing broken tools (drill bits, taps, bolts and studs) from work pieces. In this application, the process is termed "metal disintegration machining" or MDM. The metal disintegration process removes only the center out of the tap, bolt or stud leaving the hole intact and allowing a part to be reclaimed.

5.6.5 Closed loop manufacturing

Closed loop manufacturing can improve the accuracy and reduce the tool costs

5.7 Advantages and disadvantages

Advantages of EDM include machining of:

- Complex shapes that would otherwise be difficult to

produce with conventional cutting tools.

- Extremely hard material to very close tolerances.

- Very small work pieces where conventional cutting tools may damage the part from excess cutting tool pressure.

- There is no direct contact between tool and work piece. Therefore delicate sections and weak materials can be machined without any distortion.

- A good surface finish can be obtained.

- very fine holes can be drilled.

Disadvantages of EDM include:

- The slow rate of material removal.

- Potential fire hazard associated with use of combustible oil based dielectrics.

- The additional time and cost used for creating electrodes for ram/sinker EDM.

- Reproducing sharp corners on the workpiece is difficult due to electrode wear.

- Specific power consumption is very high.

- Power consumption is high.

- "Overcut" is formed.

- Excessive tool wear occurs during machining.

- Electrically non-conductive materials can be machined only with specific set-up of the process.[27]

5.8   See also

- Electro chemical machining

5.9   References

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5.11 External links

- New Arc Detection Technology for Highly Efficient Electro-Discharge Machining

- Engineering Design For Electrical Discharge Machining

Chapter 6

Water jet cutter

Not to be confused with pressure washer.

 A **water jet cutter**, also known as a **water jet** or **water-jet**, is an industrial tool capable of cutting a wide variety of materials using a very high-pressure jet of water, or a mixture of water and an abrasive substance. The term **abrasivejet** refers specifically to the use of a mixture of water and abrasive to cut hard materials such as metal or granite, while the terms **pure waterjet** and **water-only cutting** refer to waterjet cutting without the use of added abrasives, often used for softer materials such as wood or rubber.[1]

Waterjet cutting is often used during fabrication of machine parts. It is the preferred method when the materials being cut are sensitive to the high temperatures generated by other methods. Waterjet cutting is used in various industries, including mining and aerospace, for cutting, shaping, and reaming.

6.1 History

6.1.1 Waterjet

While using high-pressure water for erosion dates back as far as the mid-1800s with hydraulic mining, it was not until the 1930s that narrow jets of water started to appear as an industrial cutting device. In 1933, the Paper Patents Company in Wisconsin developed a paper metering, cutting, and reeling machine that used a diagonally moving waterjet nozzle to cut a horizontally moving sheet of continuous paper.[2] These early applications were at a low pressure and restricted to soft materials like paper.

Waterjet technology evolved in the post-war era as researchers around the world searched for new methods of efficient cutting systems. In 1956, Carl Johnson of Durox International in Luxembourg developed a method for cutting plastic shapes using a thin stream high-pressure waterjet, but those materials, like paper, were soft materials.[3] In 1958, Billie Schwacha of North American Aviation developed a system using ultra-high-pressure liquid to cut hard materials.[4] This system used a 100,000 psi (690 MPa) pump to deliver a hypersonic liquid jet that could cut high strength alloys such as PH15-

7-MO stainless steel. Used as a honeycomb laminate on the Mach 3 North American XB-70 Valkyrie, this cutting method resulted in delaminating at high speed, requiring changes to the manufacturing process.[5]

While not effective for the XB-70 project, the concept was valid and further research continued to evolve waterjet cutting. In 1962, Philip Rice of Union Carbide explored using a pulsing waterjet at up to 50,000 psi (345 MPa) to cut metals, stone, and other materials.[6] Research by S.J. Leach and G.L. Walker in the mid-1960s expanded on traditional coal waterjet cutting to determine ideal nozzle shape for high-pressure waterjet cutting of stone,[7] and Norman Franz in the late 1960s focused on waterjet cutting of soft materials by dissolving long chain polymers in the water to improve the cohesiveness of the jet stream.[8] In the early 1970s, the desire to improve the durability of the waterjet nozzle led Ray Chadwick, Michael Kurko, and Joseph Corriveau of the Bendix Corporation to come up with the idea of using corundum crystal to form a waterjet orifice,[9] while Norman Franz expanded on this and created a waterjet nozzle with an orifice as small as 0.002 inches (0.05 mm) that operated at pressures up to 70,000 psi (483 MPa).[10] John Olsen, along with George Hurlburt and Louis Kapcsandy at Flow Research (later Flow Industries), further improved the commercial potential of the waterjet by showing that treating the water beforehand could increase the operational life of the nozzle.[11]

6.1.2 High pressure

High-pressure vessels and pumps became affordable and reliable with the advent of steam power. By the mid-1800s, steam locomotives were common and the first efficient steam-driven fire engine was operational.[12] By the turn of the century, high-pressure reliability improved, with locomotive research leading to a sixfold increase in boiler pressure, some reaching 1600 psi (11 MPa). Most high-pressure pumps at this time, though, operated around 500–800 psi (3–6 MPa).
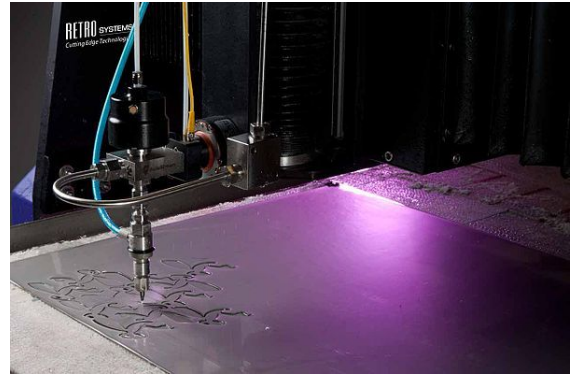
High-pressure systems were further shaped by the aviation, automotive, and oil industries. Aircraft manufacturers such as Boeing developed seals for hydraulically

38

Waterjet CNC cutting machine.

A diagram of a water jet cutter. #1: high-pressure water inlet. #2: jewel (ruby or diamond). #3: abrasive (garnet). #4: mixing tube. #5: guard. #6: cutting water jet. #7: cut material

ing Company in Baxter Springs, Kansas, began manufacturing these high-pressure pumps in 1960 for the polyethylene industry.[17] Flow Industries in Kent, Washington set the groundwork for commercial viability of waterjets with John Olsen's development of the high-pressure fluid intensifier in 1973,[18] a design that was further refined in 1976.[19] Flow Industries then combined the high-pressure pump research with their waterjet nozzle research and brought waterjet cutting into the manufacturing world.

6.1.3 Abrasive waterjet
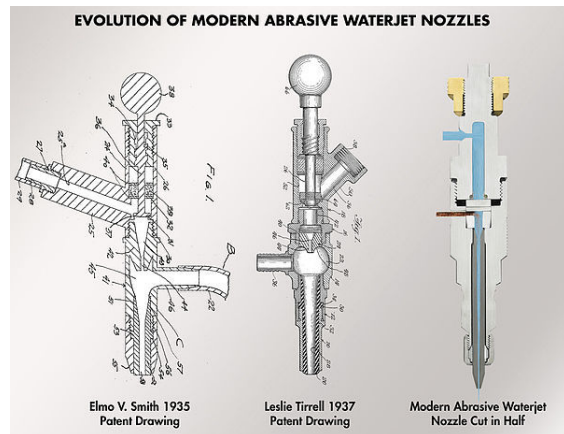
The Evolution of the Abrasive Waterjet Nozzle

boosted control systems in the 1940s,[13] while automotive designers followed similar research for hydraulic suspension systems.[14] Higher pressures in hydraulic systems in the oil industry also led to the development of advanced seals and packing to prevent leaks.[15]

These advances in seal technology, plus the rise of plastics in the post-war years, led to the development of the first reliable high-pressure pump. The invention of Marlex by Robert Banks and John Paul Hogan of the Phillips Petroleum company required a catalyst to be injected into the polyethylene.[16] McCartney Manufactur-

While cutting with water is possible for soft materials, the addition of an abrasive turned the waterjet into a modern machining tool for all materials. This began in 1935 when the idea of adding an abrasive to the water stream was developed by Elmo Smith for the liquid abrasive blasting.[20] Smith's design was further refined by Leslie Tirrell of the Hydroblast Corporation in 1937, resulting in a nozzle design that created a mix of high-pressure water and abrasive for the purpose of wet blasting.[21] Producing a commercially viable abrasive waterjet nozzle for precision cutting came next by Dr. Mohamed Hashish who invented and led an engineering research team at Flow

Industries to develop the modern abrasive waterjet cutting technology.[22] Dr. Hashish, who also coined the new term "Abrasive Waterjet" AWJ, and his team continued to develop and improve the AWJ technology and its hardware for many applications which is now in over 50 industries worldwide. A most critical development was creating a durable mixing tube that could withstand the power of the high-pressure AWJ, and it was Boride Products (now Kennametal) development of their ROCTEC line of ceramic tungsten carbide composite tubes that significantly increased the operational life of the AWJ nozzle.[23] Current work on AWJ nozzles is on micro abrasive waterjet so cutting with jets smaller than 0.015 inch in diameter can be commercialized.

6.1.4   Waterjet control

As waterjet cutting moved into traditional manufacturing shops, controlling the cutter reliably and accurately was essential. Early waterjet cutting systems adapted traditional systems such as mechanical pantographs and CNC systems based on John Parsons' 1952 NC milling machine and running G-code.[24] Challenges inherent to waterjet technology revealed the inadequacies of traditional G-Code, as accuracy depends on varying the speed of the nozzle as it approaches corners and details.[25] Creating motion control systems to incorporate those variables became a major innovation for leading waterjet manufacturers in the early 1990s, with Dr John Olsen of OMAX Corporation developing systems to precisely position the waterjet nozzle[26] while accurately specifying the speed at every point along the path,[27] and also utilizing common PCs as a controller. The largest waterjet manufacturer, Flow International (a spinoff of Flow Industries), recognized the benefits of that system and licensed the OMAX software, with the result that the vast majority of waterjet cutting machines worldwide are simple to use, fast, and accurate.[28]

6.2   Operation

The cutter is commonly connected to a high-pressure water pump where the water is then ejected from the nozzle, cutting through the material by spraying it with the jet of high-speed water. Additives in the form of suspended grit or other abrasives, such as garnet and aluminium oxide, can assist in this process.

6.3   Benefits

An important benefit of the water jet is the ability to cut material without interfering with its inherent structure, as there is no "heat-affected zone" (HAZ). Minimizing the effects of heat allows metals to be cut without harming or

changing intrinsic properties.[29]

Water jet cutters are also capable of producing intricate cuts in material. With specialized software and 3-D machining heads, complex shapes can be produced.[30]

The kerf, or width, of the cut can be adjusted by swapping parts in the nozzle, as well as changing the type and size of abrasive. Typical abrasive cuts have a kerf in the range of 0.04″ to 0.05″ (1.016 to 1.27 mm), but can be as narrow as 0.02″ (0.508 mm). Non-abrasive cuts are normally 0.007″ to 0.013″ (0.178 to 0.33 mm), but can be as small as 0.003″ (0.076 mm), which is approximately that of a human hair. These small jets can permit small details in a wide range of applications.

Water jets are capable of attaining accuracies down to 0.005″ (0.13 mm) and repeatabilities down to 0.001″ (0.025 mm).[30]

Due to its relatively narrow kerf, water jet cutting can reduce the amount of scrap material produced, by allowing uncut parts to be nested more closely together than traditional cutting methods. Water jets use approximately one half to one gallon (2 to 4 liters) per minute (depending on the cutting head's orifice size), and the water can be recycled using a closed-loop system. Waste water usually is clean enough to filter and dispose of down a drain. The garnet abrasive is a non-toxic material that can be recycled for repeated use; otherwise, it can usually be disposed in a landfill. Water jets also produce fewer airborne dust particles, smoke, fumes, and contaminants,[30] reducing operator exposure to hazardous materials.[31]

Meatcutting using waterjet technology eliminates the risk of cross contamination since there is no contact medium (namely, a blade) between different animals in the slaughterhouse.

6.4   Versatility

A water jet cutting a metal tool

Because the nature of the cutting stream can be easily modified the water jet can be used in nearly every industry; there are many different materials that the water jet can cut. Some of them have unique characteristics that

require special attention when cutting.

Materials commonly cut with a water jet include textiles, rubber, foam, plastics, leather, composites, stone, tile, metals, food, paper and much more. Examples of materials that cannot be cut with a water jet are tempered glass, diamonds and certain ceramics.[31] Water is capable of cutting materials over eighteen inches (45 cm) thick.

6.5 Availability

Commercial water jet cutting systems are available from manufacturers all over the world, in a range of sizes, and with water pumps capable of a range of pressures. Typical water jet cutting machines have a working envelope as small as a few square feet, or up to hundreds of square feet. Ultra-high-pressure water pumps are available from as low as 40,000 psi (276 MPa) up to 100,000 psi (689 MPa).[30]

6.6 Process

There are six main process characteristics to water jet cutting:

1. Uses a high velocity stream of abrasive particles suspended in a stream of Ultra High Pressure Water (30,000–90,000 psi) which is produced by a water jet intensifier pump.

2. Is used for machining a large array of materials, including heat-sensitive, delicate or very hard materials.

3. Produces no heat damage to workpiece surface or edges.

4. Nozzles are typically made of sintered boride.

5. Produces a taper of less than 1 degree on most cuts, which can be reduced or eliminated entirely by slowing down the cut process.

6. Distance of nozzle from workpiece affects the size of the kerf and the removal rate of material. Typical distance is .125″ (3.175 mm).

Temperature is not as much of a factor.

6.7 Edge quality
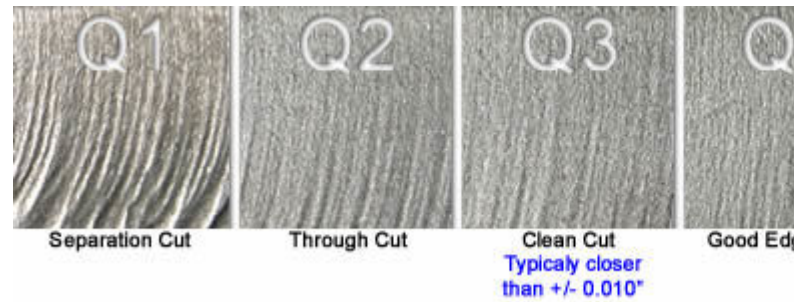
Edge quality for water jet cut parts is defined with the numbers 1 through 5. Lower numbers indicate rougher edge finish; higher numbers are smoother. For thin materials, the difference in cutting speed for quality 1 could be as much as 3 times faster than the speed for quality 5. For thicker materials, quality 1 could be 6 times faster than quality 5. For example, 4″ thick aluminium Q5 would be 0.72 ipm (18 mm/min) and Q1 would be 4.2 ipm (107 mm/min), 5.8 times faster.[32]

6.8 Multi-axis cutting

Main article: Multiaxis machining
With recent advances in control and motion technology,
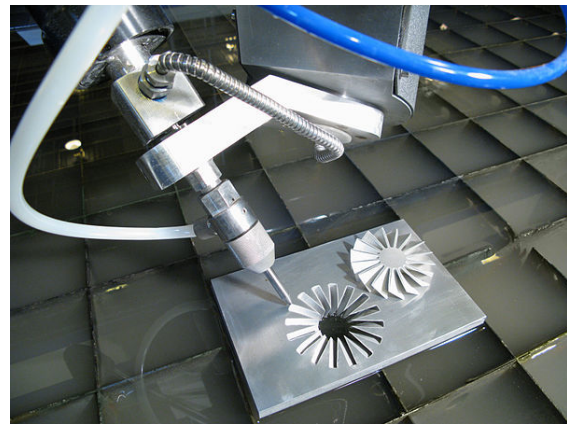
A 5-Axis Waterjet Cutting Head

5-axis water jet cutting (abrasive and pure) has become a reality. Where the normal axes on a water jet are named X (back/forth), Y(left/right) and Z (up/down), a 5-axis system will typically add an A axis (angle from perpendicular) and C axes (rotation around the Z-axis). Depending on the cutting head, the maximum cutting angle for the A axis can be anywhere from 55, 60, or in some cases even 90 degrees from vertical. As such, 5-axis cutting opens up a wide range of applications that can be machined on a water jet cutting machine.

A 5-axis cutting head can be used to cut 4-axis parts, where the bottom surface geometries are shifted a certain amount to produce the appropriate angle and the Z-axis
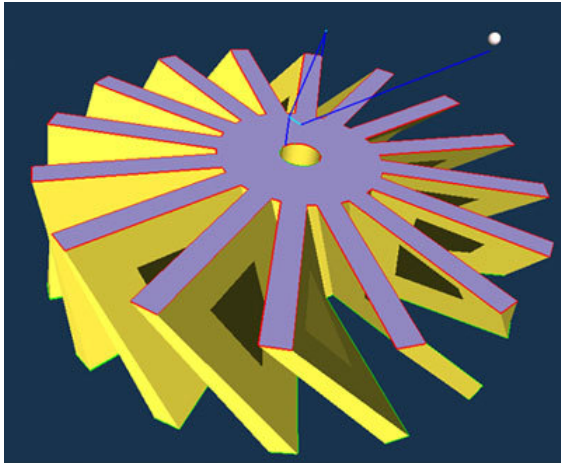
A 5-Axis Waterjet Part

remains at one height. This can be useful for applications like weld preparation where a bevel angle needs to be cut on all sides of a part that will later be welded, or for taper compensation purposes where the kerf angle is transferred to the waste material – thus eliminating the taper commonly found on water jet-cut parts. A 5-axis head can cut parts where the Z-axis is also moving along with all the other axis. This full 5-axis cutting could be used for cutting contours on various surfaces of formed parts.

Because of the angles that can be cut, part programs may need to have additional cuts to free the part from the sheet. Attempting to slide a complex part at a severe angle from a plate can be difficult without appropriate relief cuts.

6.9   See also

- CryoJet
- Laser cutting

6.10   References

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6.11 External links

- How Water Jets Work, HowStuffWorks.com video

Chapter 7

3D printing

For methods of applying a 2D image on a 3D surface, see pad printing. For methods of printing 2D parallax stereograms that seem 3D to the eye, see lenticular printing and holography.

3D printing (or **additive manufacturing, AM**) is any
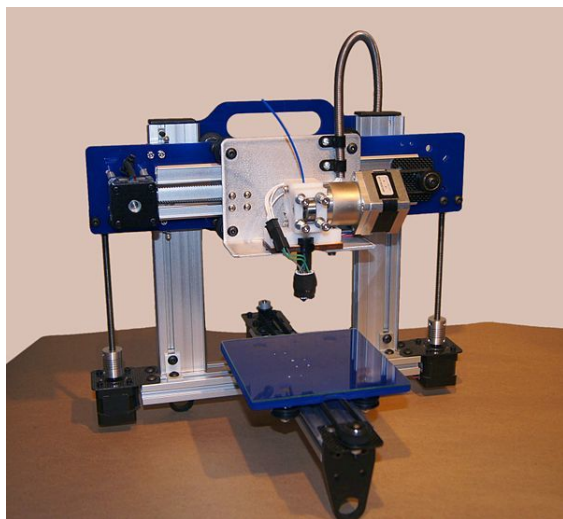
An ORDbot Quantum 3D printer

Timelapse video of a hyperboloid object (designed by George W. Hart) made of PLA using a RepRap "Prusa Mendel" 3 printer for molten polymer deposition

of various processes used to make a three-dimensional object.[1] In 3D printing, additive processes are used, in which successive layers of material are laid down under computer control.[2] These objects can be of almost any shape or geometry, and are produced from a 3D model

or other electronic data source. A 3D printer is a type of industrial robot.

3D printing in the term's original sense refers to processes that sequentially deposit material onto a powder bed with inkjet printer heads. More recently the meaning of the term has expanded to encompass a wider variety of techniques such as extrusion and sintering based processes. Technical standards generally use the term *additive manufacturing* for this broader sense.

7.1 History

7.1.1 Terminology and methods
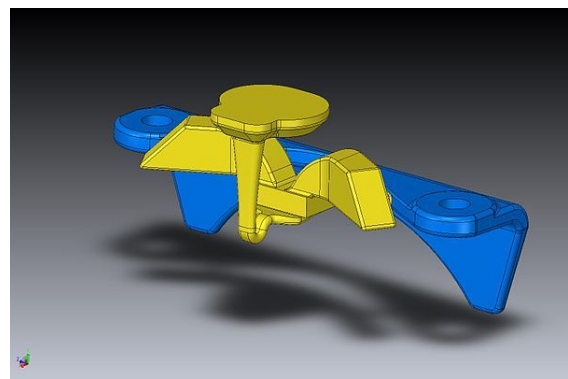
CAD Model used for 3D Printing

Earlier AM equipment and materials were developed in the 1980s.[3] In 1981, Hideo Kodama of Nagoya Municipal Industrial Research Institute invented two AM fabricating methods of a three-dimensional plastic model with photo-hardening polymer, where the UV exposure area is controlled by a mask pattern or the scanning fiber transmitter.[4][5] Then in 1984, Chuck Hull of 3D Systems Corporation,[6] developed a prototype system based on this process known as stereolithography, in which layers are added by curing photopolymers with ultraviolet light lasers. Hull defined the process as a "system for generating three-dimensional objects by creating a cross-sectional pattern of the object to be formed,"[7][8] but this had been already invented by Kodama. Hull's contribu-

tion is the design of STL (STereoLithography) file format widely accepted by 3D printing software as well as the digital slicing and infill strategies common to many processes today. The term *3D printing* originally referred to a process employing standard and custom inkjet print heads. The technology used by most 3D printers to date—especially hobbyist and consumer-oriented models—is fused deposition modeling, a special application of plastic extrusion.

AM processes for metal sintering or melting (such as selective laser sintering, direct metal laser sintering, and selective laser melting) usually went by their own individual names in the 1980s and 1990s. Nearly all metalworking production at the time was by casting, fabrication, stamping, and machining; even though plenty of automation was applied to those technologies (such as by robot welding and CNC), the idea of a tool or head moving through a 3D work envelope transforming a mass of raw material into a desired shape layer by layer was associated by most people only with processes that removed metal (rather than adding it), such as CNC milling, CNC EDM, and many others. But AM-type sintering was beginning to challenge that assumption. By the mid 1990s, new techniques for material deposition were developed at Stanford and Carnegie Mellon University, including microcasting[9] and sprayed materials.[10] Sacrificial and support materials had also become more common, enabling new object geometries.[11]

The umbrella term *additive manufacturing* gained wider currency in the decade of the 2000s[12] as the various additive processes matured and it became clear that soon metal removal would no longer be the only metalworking process done under that type of control (a tool or head moving through a 3D work envelope transforming a mass of raw material into a desired shape layer by layer). It was during this decade that the term *subtractive manufacturing* appeared as a retronym for the large family of machining processes with metal removal as their common theme. However, at the time, the term *3D printing* still referred only to the polymer technologies in most minds, and the term *AM* was likelier to be used in metalworking contexts than among polymer/inkjet/stereolithography enthusiasts. The term *subtractive* has not replaced the term *machining*, instead complementing it when a term that covers any removal method is needed.

By the early 2010s, the terms *3D printing* and *additive manufacturing* developed senses in which they were synonymous umbrella terms for all AM technologies. Although this was a departure from their earlier technically narrower senses, it reflects the simple fact that the technologies all share the common theme of sequential-layer material addition/joining throughout a 3D work envelope under automated control. (Other terms that have appeared, which are usually used as AM synonyms (although sometimes as hypernyms), have been *desktop manufacturing*, *rapid manufacturing* [as the logical production-level successor to *rapid prototyping*], and *on-*

demand manufacturing [which echoes *on-demand printing* in the 2D sense of *printing*].) The 2010s were the first decade in which metal parts such as engine brackets[13] and large nuts[14] would be grown (either before or instead of machining) in job production rather than obligately being machined from bar stock or plate.

7.1.2 Applications

Model of a turbine showing the benefits of 3d printing in industry

AM technologies found applications starting in the 1980s in product development, data visualization, rapid prototyping, and specialized manufacturing. Their expansion into production (job production, mass production, and distributed manufacturing) has been under development in the decades since. Industrial production roles within the metalworking industries[15] achieved significant scale for the first time in the early 2010s. Since the start of the 21st century there has been a large growth in the sales of AM machines, and their price has dropped substantially.[16] According to Wohlers Associates, a consultancy, the market for 3D printers and services was worth $2.2 billion worldwide in 2012, up 29% from 2011.[17] There are many applications for AM technologies, including architecture, construction (AEC), industrial design, automotive, aerospace,[18] military, engineering, dental and medical industries, biotech (human tissue replacement), fashion, footwear, jewelry, eyewear, education, geographic information systems, food, and many other fields.

In 2005, a rapidly expanding hobbyist and home-use market was established with the inauguration of the open-source RepRap and Fab@Home projects. Virtually all home-use 3D printers released to-date have their technical roots in the ongoing RepRap Project and associated open-source software initiatives.[19] In distributed manufacturing, one study has found[20] that 3D printing could

become a mass market product enabling consumers to save money associated with purchasing common household objects.[21] For example, instead of going to a store to buy an object made in a factory by injection molding (such as a measuring cup or a funnel), a person might instead print it at home from a downloaded 3D model.

7.2   General principles
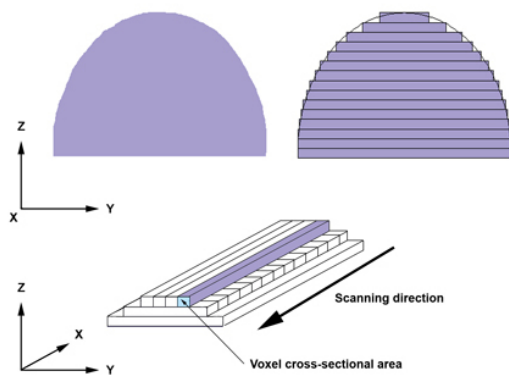
3D model slicing

7.2.1   Modeling

Main article: 3D modeling

3D printable models may be created with a computer aided design (CAD) package or via a 3D scanner or via a plain digital camera and photogrammetry software.

The manual modeling process of preparing geometric data for 3D computer graphics is similar to plastic arts such as sculpting. 3D scanning is a process of analysing and collecting digital data on the shape and appearance of a real object. Based on this data, three-dimensional models of the scanned object can then be produced.

Regardless of the 3D modelling software used, the 3D model (often in .skp, .dae, .3ds or some other format) then needs to be converted to either a.STL or a .OBJ format, to allow the printing (a.k.a. "CAM") software to be able to read it.

7.2.2   Printing

Before printing a 3D model from an STL file, it must first be examined for "manifold errors", this step being called the "fixup". Especially STL's that have been produced from a model obtained through 3D scanning often have

many manifold errors in them that need to be fixed. Examples of manifold errors are surfaces that do not connect, gaps in the models, ... Examples of software that can be used to fix these errors are netfabb and Meshmixer, or even Cura, or Slic3r.[22][23]

Once that's done, the .STL file needs to be processed by a piece of software called a "slicer" which converts the model into a series of thin layers and produces a G-code file containing instructions tailored to a specific type of 3D printer (FDM printers). This G-code file can then be printed with 3D printing client software (which loads the G-code, and uses it to instruct the 3D printer during the 3D printing process). It should be noted here that often, the client software and the slicer are combined into one software program in practice. Several open source slicer programs exist, including Skeinforge, Slic3r, and Cura as well as closed source programs including Simplify3D and KISSlicer. Examples of 3D printing clients include Repetier-Host, ReplicatorG, Printrun/Pronterface, ...
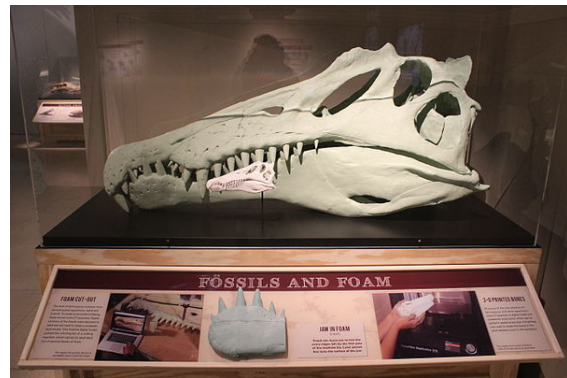
Scanned skull of Spinosaurus *printed in two sizes*

Note that there is one other piece of software that is often used by people using 3D printing, namely a GCode viewer. This software lets one examine the route of travel of the printer nozzle. By examining this, the user can decide to modify the GCode to print the model a different way (for example in a different position, e.g. standing versus lying down) so as to save plastic (depending on the position and nozzle travel, more or less support material may be needed). Examples of GCode viewers are Gcode Viewer for Blender and Pleasant3D.

The 3D printer follows the G-code instructions to lay down successive layers of liquid, powder, paper or sheet material to build the model from a series of cross sections. These layers, which correspond to the virtual cross sections from the CAD model, are joined or automatically fused to create the final shape. The primary advantage of this technique is its ability to create almost any shape or geometric feature.

Printer resolution describes layer thickness and X-Y resolution in dots per inch (dpi) or micrometres (μm). Typical layer thickness is around 100 μm (250 DPI), although some machines such as the *Objet Connex* series and 3D Systems' *ProJet* series can print layers as thin as 16 μm

(1,600 DPI).[24] X-Y resolution is comparable to that of laser printers. The particles (3D dots) are around 50 to 100 µm (510 to 250 DPI) in diameter.

Construction of a model with contemporary methods can take anywhere from several hours to several days, depending on the method used and the size and complexity of the model. Additive systems can typically reduce this time to a few hours, although it varies widely depending on the type of machine used and the size and number of models being produced simultaneously.

Traditional techniques like injection moulding can be less expensive for manufacturing polymer products in high quantities, but additive manufacturing can be faster, more flexible and less expensive when producing relatively small quantities of parts. 3D printers give designers and concept development teams the ability to produce parts and concept models using a desktop size printer.

7.2.3 Finishing

Though the printer-produced resolution is sufficient for many applications, printing a slightly oversized version of the desired object in standard resolution and then removing material[25] with a higher-resolution subtractive process can achieve greater precision.

Some printable polymers allow the surface finish to be smoothed and improved using chemical vapour processes.

Some additive manufacturing techniques are capable of using multiple materials in the course of constructing parts. These techniques are able to print in multiple colors and color combinations simultaneously, and would not necessarily require painting.

Some printing techniques require internal supports to be built for overhanging features during construction. These supports must be mechanically removed or dissolved upon completion of the print.

All of the commercialized metal 3-D printers involve cutting the metal component off of the metal substrate after deposition. A new process for the GMAW 3-D printing allows for substrate surface modifications to remove aluminum components manually with a hammer.[26]

7.3 Processes

Several different 3D printing processes have been invented since the late 1970s. The printers were originally large, expensive, and highly limited in what they could produce.[3]

A large number of additive processes are now available. The main differences between processes are in the way layers are deposited to create parts and in the materials that are used. Some methods melt or soften material to

Legend:
- Motor vehicles
- Consumer products
- Business machines
- Medical
- Academic
- Aerospace
- Government/Military
- Others

31.7% — 18.4% — 11.2% — 8.8% — 8.6% — 8.2% — 5.5% — 7.7%
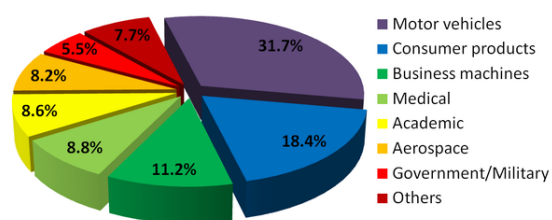
Rapid prototyping worldwide 2001[27]
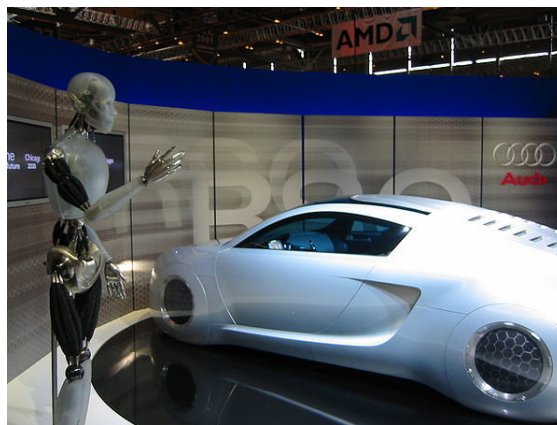
The Audi RSQ was made with rapid prototyping industrial KUKA robots

produce the layers, e.g. selective laser melting (SLM) or direct metal laser sintering (DMLS), selective laser sintering (SLS), fused deposition modeling (FDM),[28] or fused filament fabrication (FFF), while others cure liquid materials using different sophisticated technologies, e.g. stereolithography (SLA). With laminated object manufacturing (LOM), thin layers are cut to shape and joined together (e.g. paper, polymer, metal). Each method has its own advantages and drawbacks, which is why some companies consequently offer a choice between powder and polymer for the material used to build the object.[29] Other companies sometimes use standard, off-the-shelf business paper as the build material to produce a durable prototype. The main considerations in choosing a machine are generally speed, cost of the 3D printer, cost of the printed prototype, cost and choice of materials, and color capabilities.[30]

Printers that work directly with metals are expensive. In some cases, however, less expensive printers can be used to make a mould, which is then used to make metal parts.[31]

7.3.1 Extrusion deposition

Main article: Fused deposition modeling

Fused deposition modeling (FDM) was developed by S. Scott Crump in the late 1980s and was commercialized in 1990 by Stratasys.[33] After the patent on this technology
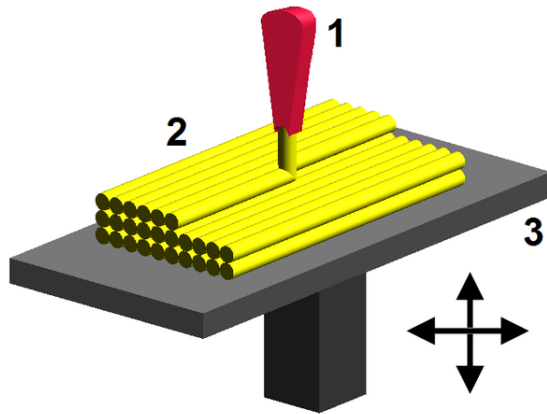
Fused deposition modeling: 1 – nozzle ejecting molten plastic, 2 – deposited material (modeled part), 3 – controlled movable table
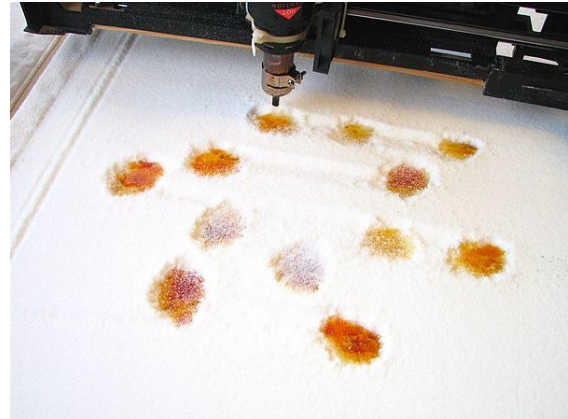
The CandyFab granular printing system uses heated air and granulated sugar to produce food-grade art objects

expired, a large open-source development community developed and both commercial and DIY variants utilizing this type of 3D printer appeared. As a result, the price of this technology has dropped by two orders of magnitude since its creation.

In fused deposition modeling the model or part is produced by extruding small beads of material which harden immediately to form layers. A thermoplastic filament or metal wire that is wound on a coil is unreeled to supply material to an extrusion nozzle head. The nozzle head heats the material and turns the flow on and off. Typically stepper motors or servo motors are employed to move the extrusion head and adjust the flow. The head can be moved in both horizontal and vertical directions, and control of the mechanism is typically done by a computer-aided manufacturing (CAM) software package running on a microcontroller.

Various polymers are used, including acrylonitrile butadiene styrene (ABS), polycarbonate (PC), polylactic acid (PLA), high density polyethylene (HDPE), PC/ABS, polyphenylsulfone (PPSU) and high impact polystyrene (HIPS). In general, the polymer is in the form of a filament fabricated from virgin resins. There are multiple projects in the open-sourced community aimed at processing post-consumer plastic waste into filament. These involve machines used to shred and extrude the plastic material into filament.

FDM is somewhat restricted in the variation of shapes that may be fabricated. For example, FDM usually cannot produce stalactite-like structures, since they would be unsupported during the build. Otherwise, a thin support must be designed into the structure which can be broken away during finishing.

7.3.2   Binding of granular materials

Another 3D printing approach is the selective fusing of materials in a granular bed. The technique fuses parts of

the layer and then moves downward in the working area, adding another layer of granules and repeating the process until the piece has built up. This process uses the unfused media to support overhangs and thin walls in the part being produced, which reduces the need for temporary auxiliary supports for the piece. A laser is typically used to sinter the media into a solid. Examples include selective laser sintering (SLS), with both metals and polymers (e.g. PA, PA-GF, Rigid GF, PEEK, PS, Alumide, Carbonmide, elastomers), and direct metal laser sintering (DMLS).[34]

Selective Laser Sintering (SLS) was developed and patented by Dr. Carl Deckard and Dr. Joseph Beaman at the University of Texas at Austin in the mid-1980s, under sponsorship of DARPA.[35] A similar process was patented without being commercialized by R. F. Housholder in 1979.[36]

Selective laser melting (SLM) does not use sintering for the fusion of powder granules but will completely melt the powder using a high-energy laser to create fully dense materials in a layer-wise method that has mechanical properties similar to those of conventional manufactured metals.

Electron beam melting (EBM) is a similar type of additive manufacturing technology for metal parts (e.g. titanium alloys). EBM manufactures parts by melting metal powder layer by layer with an electron beam in a high vacuum. Unlike metal sintering techniques that operate below melting point, EBM parts are fully dense, void-free, and very strong.[37][38]

Another method consists of an inkjet 3D printing system. The printer creates the model one layer at a time by spreading a layer of powder (plaster, or resins) and printing a binder in the cross-section of the part using an inkjet-like process. This is repeated until every layer has been printed. This technology allows the printing of full color prototypes, overhangs, and elastomer parts. The strength of bonded powder prints can be enhanced with wax or thermoset polymer impregnation.

7.3.3 Lamination

Main article: Laminated object manufacturing

In some printers, paper can be used as the build material, resulting in a lower cost to print. During the 1990s some companies marketed printers that cut cross sections out of special adhesive coated paper using a carbon dioxide laser and then laminated them together.

In 2005 Mcor Technologies Ltd developed a different process using ordinary sheets of office paper, a tungsten carbide blade to cut the shape, and selective deposition of adhesive and pressure to bond the prototype.[39]

There are also a number of companies selling printers that print laminated objects using thin plastic and metal sheets.

7.3.4 Photopolymerization
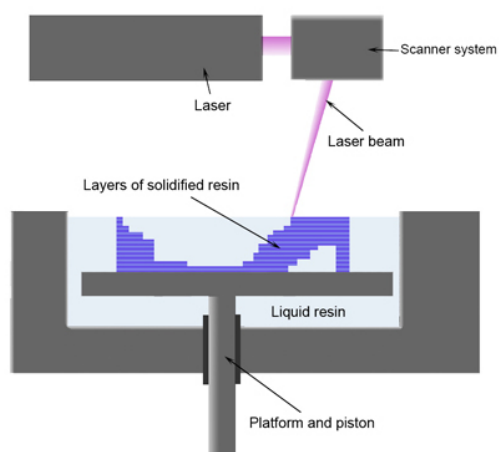
Stereolithography apparatus

Main article: Stereolithography

Stereolithography was patented in 1986 by Chuck Hull.[40] Photopolymerization is primarily used in stereolithography (SLA) to produce a solid part from a liquid. This process dramatically redefined previous efforts, from the "photosculpture" method of François Willème (1830–1905) in 1860 through the photopolymerization of Mitsubishi's Matsubara in 1974.[41] The "photosculpture" method consisted of photographing a subject from a variety of equidistant angles and projecting each photograph onto a screen, where a pantagraph was used to trace the outline onto modeling clay[42][43][44])

In photo-polymerization, a vat of liquid polymer is exposed to controlled lighting under safelight conditions. The exposed liquid polymer hardens. The build plate then moves down in small increments and the liquid polymer

is again exposed to light. The process repeats until the model has been built. The liquid polymer is then drained from the vat, leaving the solid model. The EnvisionTEC *Perfactory*[45] is an example of a DLP rapid prototyping system.

Inkjet printer systems like the *Objet PolyJet* system spray photopolymer materials onto a build tray in ultra-thin layers (between 16 and 30 μm) until the part is completed. Each photopolymer layer is cured with UV light after it is jetted, producing fully cured models that can be handled and used immediately, without post-curing. The gel- | Digital Light Processing (DLP) | photopolymerl-like support material, which is designed to support complicated geometries, is removed by hand and water jetting. It is also suitable for elastomers.

Ultra-small features can be made with the 3D microfabrication technique used in multiphoton photopolymerisation. This approach uses a focused laser to trace the desired 3D object into a block of gel. Due to the nonlinear nature of photo excitation, the gel is cured to a solid only in the places where the laser was focused while the remaining gel is then washed away. Feature sizes of under 100 nm are easily produced, as well as complex structures with moving and interlocked parts.[46]

Yet another approach uses a synthetic resin that is solidified using LEDs.[47]

In Mask-image-projection-based stereolithography a 3D digital model is sliced by a set of horizontal planes. Each slice is converted into a two-dimensional mask image. The mask image is then projected onto a photocurable liquid resin surface and light is projected onto the resin to cure it in the shape of the layer.[48] The technique has been used to create objects composed of multiple materials that cure at different rates.[48] In research systems, the light is projected from below, allowing the resin to be quickly spread into uniform thin layers, reducing production time from hours to minutes.[48] Commercially available devices such as Objet Connex apply the resin via small nozzles.[48]

7.3.5 Bioprinting

Main article: 3D bioprinting

3D bioprinting is the process of generating 3D structures and geometries utilizing cells and an encapsulation material. The medical applications of 3D bioprinting are numerous, and are thus the subject of intensive research at academic institutions such as Cornell University and companies such as Organovo. One major application area of bioprinting is in the tissue engineering field of regenerative medicine. In addition to the complexities associated with 3D printing in general, extra considerations must be taken regarding material, cell type, and growth factor selection.[49] Because of these extra considerations, bio-

printing research is truly a cross-disciplinary endeavor, involving researchers from the fields of materials science, cell biology, engineering of all kinds, and medicine.

3D bioprinting has seen much preliminary success in terms of generation of several different kinds of tissues. These include skin, bone, cartilage, trachea, and heart tissue.[49] While preliminary success has been attained in these noncritically functional tissue structures, significant research effort is directed towards the generation of fully functional replacement organs and tissues, such as aortic heart valves.

Researchers in the Jonathan Butcher Laboratory in the Cornell University College of Engineering have been developing methods to bioprint living aortic heart valves.[50] Poly(ethylene glycol)-diacrylate (PEGDA) is used as a base polymer, because of its biocompatibility and easily tunable mechanical properties.[51] Two different solutions of PEGDA were created with different mechanical stiffnesses when crosslinked, with the stiffer polymer to be used as the aortic root wall and the compliant polymer to be used as the valve leaflets. Using these solutions, a valve exhibiting mechanical heterogeneity and cytocompatibility was bioprinted, which will serve as a base for future development of the aortic valve printing process.[52]

The Lawrence Bonassar Laboratory at Cornell University has been working on 3D bioprinting cartilaginous geometries. One focus of their research involves the replacement of intervertebral disks with Tissue Engineered-Total Disk Replacement constructs.[53] Tissue engineered intervertebral disks were bioprinted with cell-seeded hydrogel constructs, and implanted into male rats.

Commercially, Printerinks, a UK company, and Organovo, a U.S. company, have worked together to develop human tissue through 3D printing. Printer cartridges are adapted to use stem cells obtained from biopsies and grown in cultures. The resulting substance is called Bioink.[54]

7.3.6   Nanoscale 3D printing

3D printing techniques can be employed to construct nanoscale-size objects. Such printed objects are typically grown on a solid substrate, e.g. silicon wafer, to which they adhere after printing as they're too small and fragile to be manipulated post-construction. While 2D nanostructures are usually created by depositing material through some sort of static stencil mask, 3D nanostructures can be printed by physically moving a stencil mask during the material deposition process. Programmable-height nanostructures with widths as small as 10 nm have been produced by metallic physical vapor deposition through a piezo-actuator controlled stencil mask having a milled nanopore in a silicon nitride membrane. This metal-vapor technique is also advantageous because it can be used on surfaces that are too sensitive to heat or chemicals for traditional lithography to be used on.[55]

7.4   Printers

7.4.1   Industry use

As of October 2012, Stratasys now sells additive manufacturing systems that range from $2,000 to $500,000 in price and are employed in several industries: aerospace, architecture, automotive, defense, and dental, among many others. For example, Ultimaker, its awarded as fastest and accurate 3d printer, General Electric uses the high-end model to build parts for turbines.[56]

7.4.2   Consumer use
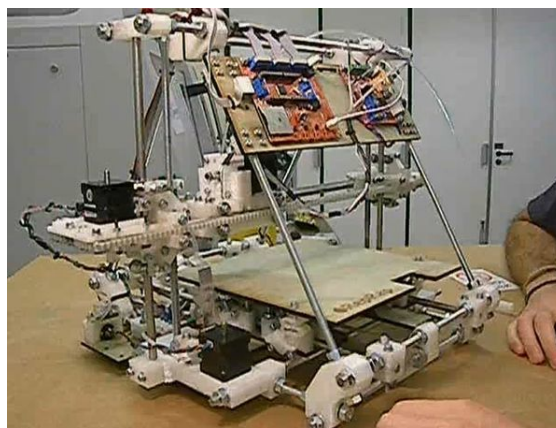
RepRap version 2.0 (Mendel)

Several projects and companies are making efforts to develop affordable 3D printers for home desktop use. Much of this work has been driven by and targeted at DIY/enthusiast/early adopter communities, with additional ties to the academic and hacker communities.[57]

RepRap is one of the longest running projects in the desktop category. The RepRap project aims to produce a free and open source hardware (FOSH) 3D printer, whose full specifications are released under the GNU General Public License, and which is capable of replicating itself by printing many of its own (plastic) parts to create more machines.[58][59] RepRaps have already been shown to be able to print circuit boards[60] and metal parts.[61][62]

Because of the FOSH aims of RepRap, many related projects have used their design for inspiration, creating an ecosystem of related or derivative 3D printers, most of which are also open source designs. The availability of these open source designs means that variants of 3D printers are easy to invent. The quality and complexity of printer designs, however, as well as the quality of kit or finished products, varies greatly from project to project. This rapid development of open source 3D printers is gaining interest in many spheres as it enables hyper-customization and the use of public domain designs to fabricate open source appropriate technology. This technology can also assist initiatives in
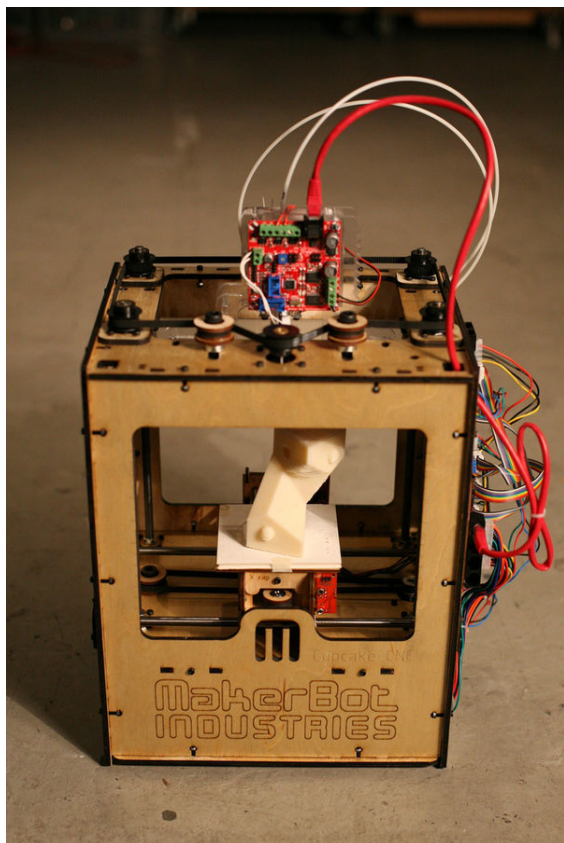
MakerBot Cupcake CNC
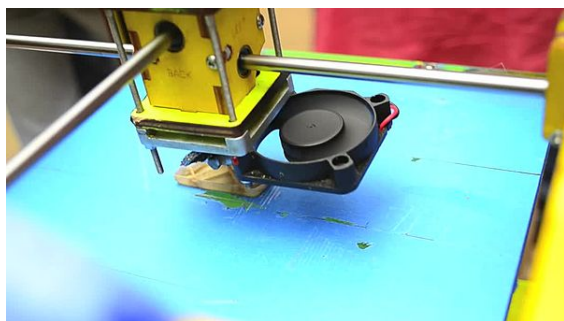
Printing in progress in a Ultimaker 3D printer during Mozilla Maker party, Bangalore

sustainable development since technologies are easily and economically made from resources available to local communities.[63][64]

The cost of 3D printers has decreased dramatically since about 2010, with machines that used to cost $20,000 now costing less than $1,000.[65] For instance, as of 2013, several companies and individuals are selling parts to build various RepRap designs, with prices starting at about €400 / US$500.[66] The open source Fab@Home project[67] has developed printers for general use with anything that can be squirted through a nozzle, from chocolate to silicone sealant and chemical reactants. Printers following the project's designs have been available from suppliers in kits or in pre-assembled form since
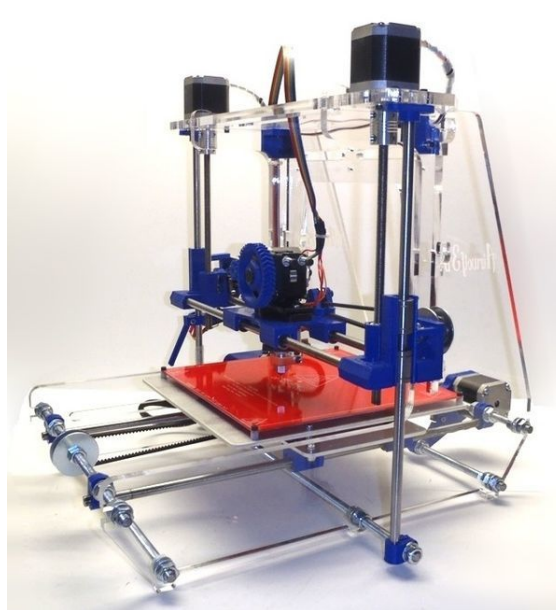
Airwolf 3D AW3D v.4 (Prusa)

2012 at prices in the US$2000 range.[66] The Kickstarter funded Peachy Printer is designed to cost $100[68] and several other new 3D printers are aimed at the small, inexpensive market including the mUVe3D and Lumi-fold. Rapide 3D has designed a professional grade crowd-sourced 3D-printer costing $1499 which has no fumes nor constant rattle during use.[69] The 3Doodler, "3D printing pen", raised $2.3 million on Kickstarter with the pens selling at $99,[70] though the 3D Doodler has been criticised for being more of a crafting pen than a 3D printer.[71]

As the costs of 3D printers have come down they are becoming more appealing financially to use for self-manufacturing of personal products.[21] In addition, 3D printing products at home may reduce the environmental impacts of manufacturing by reducing material use and distribution impacts.[72]

In addition, several RecycleBots such as the commercialised Filastruder have been designed and fabricated to convert waste plastic, such as shampoo containers and milk jugs, into inexpensive RepRap filament.[73] There is some evidence that using this approach of distributed recycling is better for the environment.[74]

The development and hyper-customization of the RepRap-based 3D printers has produced a new category of printers suitable for small business and consumer use. Manufacturers such as Solidoodle,[56] RoBo, RepRapPro and Pirx 3D have introduced models and kits priced at less than $1,000, thousands less than they were in September 2012.[56] Depending on the application, the print resolution and speed of manufacturing lies somewhere between a personal printer and an industrial printer. A list of printers with pricing and other information is maintained.[66] Most recently delta
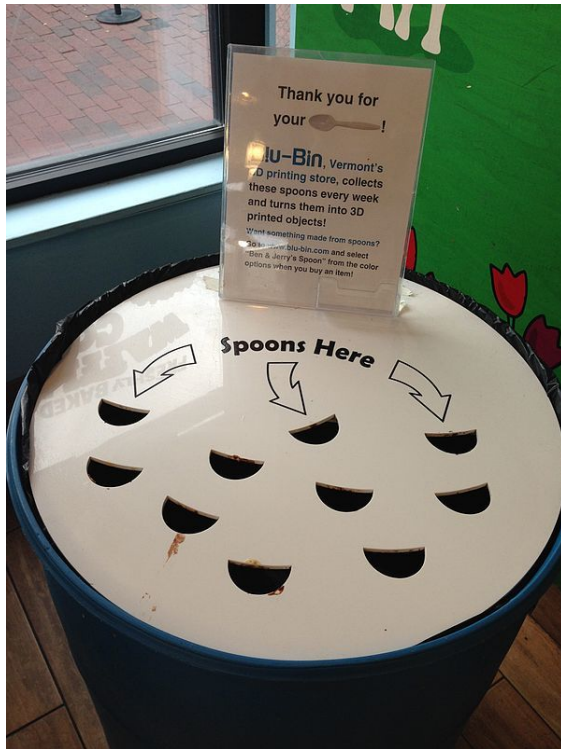
A container for recycling plastic spoons into material for 3-d printing
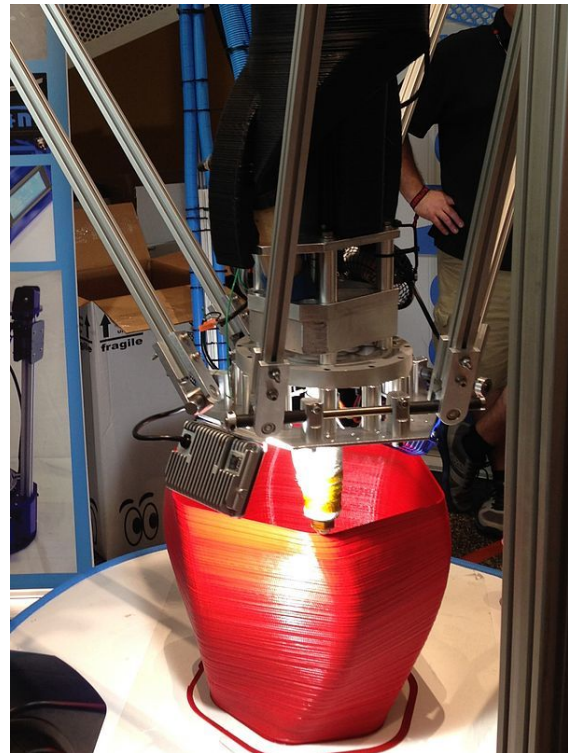
Large delta-style 3D printer

robots, like the TripodMaker, have been utilised for 3D printing to increase fabrication speed further.[75] For delta 3D printers, due to its geometry and differentiation movements, the accuracy of the print depends on the position of the printer head.[76]

Some companies are also offering software for 3D printing, as a support for hardware manufactured by other companies.[77]

7.4.3   Large 3D printers
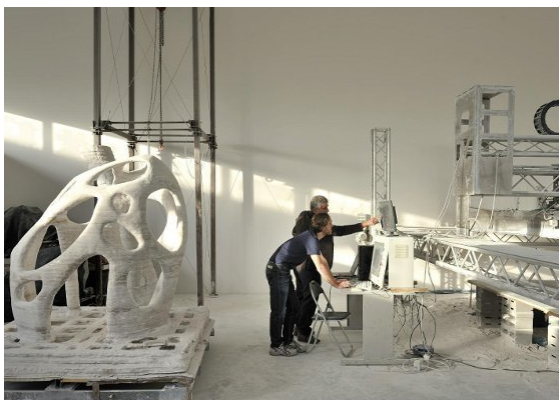
Large scale industrial 3D printing

Large 3D printers have been developed for industrial, education, and demonstrative uses. A large delta-style 3D

printer was built in 2014 by SeeMeCNC. The printer is capable of making an object with diameter of up to 4 feet (1.2 m) and up to 10 feet (3.0 m) in height. It also uses plastic pellets as the raw material instead of the typical plastic filaments used in other 3D printers.[78]

Another type of large printer is Big Area Additive Manufacturing (BAAM). The goal is to develop printers that can produce a large object in high speed. A BAAM machine of Cincinnati Incorporated can produce an object at the speeds 200-500 times faster than typical 3D printers available in 2014. Another BAAM machine is being developed by Lockheed Martin with an aim to print long objects of up to 100 feet (30 m) to be used in aerospace industries.[79]

7.5   Efficiency

The current slow print speed of 3D printers limits their use for mass production. To reduce this overhead, several fused filament machines now offer multiple extruder heads. These can be used to print in multiple colours, with different polymers, or to make multiple prints simultaneously. This increases their overall print speed during multiple instance production, while requiring less capital cost than duplicate machines since they can share a single controller.

Distinct from the use of multiple machines, multi-material machines are restricted to making identical copies of the same part, but can offer multi-color and
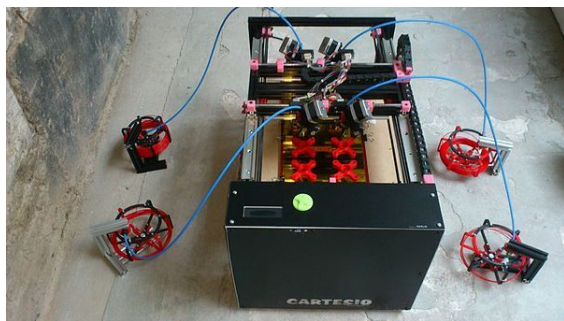
CartesioLDMP mass production 3Dprinter

multi-material features when needed. The print speed increases proportionately to the number of heads. Furthermore, the energy cost is reduced due to the fact that they share the same heated print volume. Together, these two features reduce overhead costs.

Printers are made with twin print heads, used to manufacture single (sets of) parts in multiple colours or materials.

As of 2014 few studies had been made in this field to see if conventional subtractive methods are comparable to additive methods.

7.6 Manufacturing applications
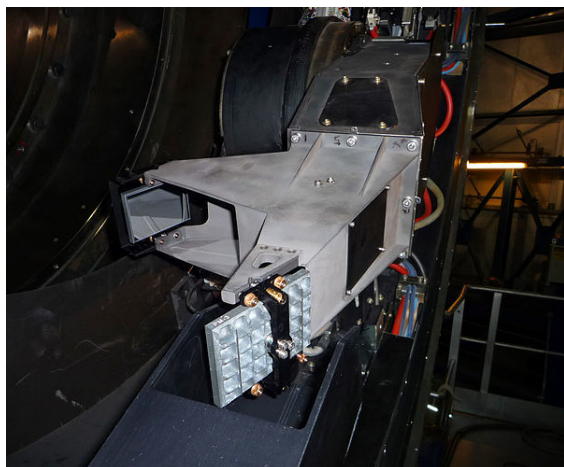
VLT component created using 3D printing[80]

Three-dimensional printing makes it as cheap to create single items as it is to produce thousands and thus undermines economies of scale. It may have as profound an impact on the world as the coming of the factory did....Just as nobody could have predicted the impact of the steam engine in 1750—or the printing press in 1450, or the transistor in 1950—it is impossible to foresee the long-term impact of 3D printing. But the technology is coming, and it is likely to disrupt every field it touches.

Printing 3D house project at Amsterdam

— *The Economist*, in a February 10, 2011 leader[81]

Additive manufacturing's earliest applications have been on the toolroom end of the manufacturing spectrum. For example, rapid prototyping was one of the earliest additive variants, and its mission was to reduce the lead time and cost of developing prototypes of new parts and devices, which was earlier only done with subtractive toolroom methods (typically slowly and expensively).[82] With technological advances in additive manufacturing, however, and the dissemination of those advances into the business world, additive methods are moving ever further into the production end of manufacturing in creative and sometimes unexpected ways.[82] Parts that were formerly the sole province of subtractive methods can now in some cases be made more profitably via additive ones.

Standard applications include design visualisation, prototyping/CAD, metal casting, architecture, education, geospatial, healthcare, and entertainment/retail.

7.6.1 Distributed manufacturing

Main article: 3D printing marketplace

Additive manufacturing in combination with cloud computing technologies allows decentralized and geographically independent distributed production.[83] Distributed manufacturing as such is carried out by some enterprises; there is also a service to put people needing 3D printing in contact with owners of printers.[84]

Some companies offer on-line 3D printing services to both commercial and private customers,[85] working from 3D designs uploaded to the company website. 3D-printed designs are either shipped to the customer or picked up from the service provider.[86]

7.6.2   Mass customization

Companies have created services where consumers can customise objects using simplified web based customisation software, and order the resulting items as 3D printed unique objects.[87][88] This now allows consumers to create custom cases for their mobile phones.[89] Nokia has released the 3D designs for its case so that owners can customise their own case and have it 3D printed.[90]

7.6.3   Rapid manufacturing

Advances in RP technology have introduced materials that are appropriate for final manufacture, which has in turn introduced the possibility of directly manufacturing finished components. One advantage of 3D printing for rapid manufacturing lies in the relatively inexpensive production of small numbers of parts.

Rapid manufacturing is a new method of manufacturing and many of its processes remain unproven. 3D printing is now entering the field of rapid manufacturing and was identified as a "next level" technology by many experts in a 2009 report.[91] One of the most promising processes looks to be the adaptation of selective laser sintering (SLS), or direct metal laser sintering (DMLS) some of the better-established rapid prototyping methods. As of 2006, however, these techniques were still very much in their infancy, with many obstacles to be overcome before RM could be considered a realistic manufacturing method.[92]

7.6.4   Rapid prototyping

Wearable 3D printed shoes

Main article: rapid prototyping

Industrial 3D printers have existed since the early 1980s and have been used extensively for rapid prototyping and research purposes. These are generally larger machines that use proprietary powdered metals, casting media (e.g. sand), plastics, paper or cartridges, and are used for rapid prototyping by universities and commercial companies.

Miniature face models (from FaceGen) produced using several colored plastics on a 3D Printer

A 3D printer at Maker's Party Bangalore 2013, Bangalore

7.6.5   Research

3D printing can be particularly useful in research labs due to its ability to make specialised, bespoke geometries. In 2012 a proof of principle project at the University of Glasgow, UK, showed that it is possible to use 3D printing techniques to assist in the production of chemical compounds. They first printed chemical reaction vessels, then used the printer to deposit reactants into them.[93] They have produced new compounds to verify the validity of the process, but have not pursued anything with a particular application.[93]

7.6.6   Food

Cornell Creative Machines Lab announced in 2012 that it was possible to produce customised food with 3D Hydrocolloid Printing.[94] Additative manufacturing of food is currently being developed by squeezing out food, layer by layer, into three-dimensional objects. A large variety of foods are appropriate candidates, such as chocolate

and candy, and flat foods such as crackers, pasta,[95] and pizza.[96]

Professor Leroy Cronin of Glasgow University proposed in a 2012 TED Talk that it was possible to use chemical inks to print medicine.[97]

7.7 Industrial applications

7.7.1 Apparel

3D printing has spread into the world of clothing with fashion designers experimenting with 3D-printed bikinis, shoes, and dresses.[98] In commercial production Nike is using 3D printing to prototype and manufacture the 2012 Vapor Laser Talon football shoe for players of American football, and New Balance is 3D manufacturing custom-fit shoes for athletes.[98][99]

3D printing has come to the point where companies are printing consumer grade eyewear with on demand custom fit and styling (although they cannot print the lenses). On demand customization of glasses is possible with rapid prototyping.[100]

7.7.2 Automobiles

In early 2014, the Swedish supercar manufacturer, Koenigsegg, announced the One:1, a supercar that utilises many components that were 3D printed. In the limited run of vehicles Koenigsegg produces, the One:1 has side-mirror internals, air ducts, titanium exhaust components, and even complete turbocharger assembles that have been 3D printed as part of the manufacturing process.[101]

An American company, Local Motors is working with Oak Ridge National Laboratory and Cincinnati Incorporated to develop large-scale additive manufacturing processes suitable for printing an entire car body.[102] The company plans to print the vehicle live in front of an audience in September 2014 at the International Manufacturing Technology Show. "Produced from a new fiber-reinforced thermoplastic strong enough for use in an automotive application, the chassis and body without drivetrain, wheels and brakes weighs a scant 450 pounds and the completed car is comprised of just 40 components, a number that gets smaller with every revision."[103]

Urbee is the name of the first car in the world car mounted using the technology 3D printing (his bodywork and his car windows were "printed"). Created in 2010 through the partnership between the US engineering group Kor Ecologic and the company Stratasys (manufacturer of printers Stratasys 3D), it is a hybrid vehicle with futuristic look.[104][105][106]

7.7.3 Construction

An additional use being developed is building printing, or using 3D printing to build buildings.[107][108][109][110] This could allow faster construction for lower costs, and has been investigated for construction of off-Earth habitats.[111][112] For example, the Sinterhab project is researching a lunar base constructed by 3D printing using lunar regolith as a base material. Instead of adding a binding agent to the regolith, researchers are experimenting with microwave sintering to create solid blocks from the raw material.[113]

7.7.4 Electric motors and generators

The magnetic cores of electric machines (motors and generators) require thin laminations of special preprocessed electrical steel that are insulated from each other to reduce core iron losses. 3D printing of any product that requires core materials with special properties or forms that must be preserved during the manufacturing process, such as the material density, non-crystalline or nano-crystalline atomic structures, etc. or material isolation, may only be compatible with a hybrid 3D printing method which does not use core material altering methods, such as sintering, fusing, deposition, etc. Preprocessing the raw material is not an extra manufacturing step because all 3D Printing methods require preprocessed material for compatibility with the 3D Printing method, such as preprocessed powdered metal for deposition or fusion 3D printing. To conveniently handle the very thin insulated laminations of amorphous or nano-crystalline metal ribbon, which can reduce electric machine core loss by up to 80%, the well-known Laminated Object Manufacturing (LOM) method of 3D Printing may show some compatibility for 3D-Printing of electric machines but only if the method mitigates at least the alteration of the non-crystalline structure of the amorphous material (for instance) during the forming of slot channels for holding the electric machine windings or during post manufacturing processes, such as grinding the air-gap surface to flat precision, all while enhancing the packing density of the material.

Under a contract from the US Dept. of Energy's Arpa-E (Advanced Research Project Agency-Energy) program, a team from the United Technologies Research Center as of 2014 was working toward producing a 30 kW induction motor using just additive manufacturing methods, trying to define an additively manufactured induction motor capable of delivering 50 kW peak and 30 kW continuous power over a speed range of zero to 12,000 rpm, using motor technology that does not involve rare-earth magnets.[114]

7.7.5   Firearms

Main article: 3D printed firearms

In 2012, the US-based group Defense Distributed disclosed plans to "[design] a working plastic gun that could be downloaded and reproduced by anybody with a 3D printer."[115][116] Defense Distributed has also designed a 3D printable AR-15 type rifle lower receiver (capable of lasting more than 650 rounds) and a 30 round M16 magazine The AR-15 has multiple receivers (both an upper and lower receiver), but the legally controlled part is the one that is serialised (the lower, in the AR-15's case). Soon after Defense Distributed succeeded in designing the first working blueprint to produce a plastic gun with a 3D printer in May 2013, the United States Department of State demanded that they remove the instructions from their website.[117] After Defense Distributed released their plans, questions were raised regarding the effects that 3D printing and widespread consumer-level CNC machining[118][119] may have on gun control effectiveness.[120][121][122][123]

In 2014, a man from Japan became the first person in the world to be imprisoned for making 3D printed firearms.[124] Yoshitomo Imura posted videos and blueprints of the gun online and was sentenced to jail for two years. Police found at least two guns in his household that were capable of firing bullets.[124]

7.7.6   Medical

3D printing has been used to print patient specific implant and device for medical use. Successful operations include a titanium pelvis implanted into a British patient, titanium lower jaw transplanted to a Belgian patient,[125] and a plastic tracheal splint for an American infant.[126] The hearing aid and dental industries are expected to be the biggest area of future development using the custom 3D printing technology.[127] In March 2014, surgeons in Swansea used 3D printed parts to rebuild the face of a motorcyclist who had been seriously injured in a road accident.[128] Research is also being conducted on methods to bio-print replacements for lost tissue due to arthritis and cancer.[129]

In October 24, 2014, a five-year-old girl born without fully formed fingers on her left hand became the first child in the UK to have a prosthetic hand made with 3D printing technology. Her hand was designed by US-based E-nable, an open source design organisation which uses a network of volunteers to design and make prosthetics mainly for children. The prosthetic hand was based on a plaster cast made by her parents.[130]

Printed prosthetics have been used in rehabilitation of crippled animals. In 2013, a 3D printed foot let a crippled duckling walk again.[131] In 2014 a chihuahua born without front legs was fitted with a harness and wheels created with a 3D printer.[132] 3D printed hermit crab shells let hermit crabs inhabit a new style home.[133]

As of 2012, 3D bio-printing technology has been studied by biotechnology firms and academia for possible use in tissue engineering applications in which organs and body parts are built using inkjet techniques. In this process, layers of living cells are deposited onto a gel medium or sugar matrix and slowly built up to form three-dimensional structures including vascular systems.[134] The first production system for 3D tissue printing was delivered in 2009, based on NovoGen bio-printing technology.[135] Several terms have been used to refer to this field of research: organ printing, bio-printing, body part printing,[136] and computer-aided tissue engineering, among others.[137] The possibility of using 3D tissue printing to create soft tissue architectures for reconstructive surgery is also being explored.[138]

China has committed almost $500 million towards the establishment of 10 national 3-D printing development institutes.[139] In 2013, Chinese scientists began printing ears, livers and kidneys, with living tissue. Researchers in China have been able to successfully print human organs using specialised 3D bio printers that use living cells instead of plastic. Researchers at Hangzhou Dianzi University actually went as far as inventing their own 3D printer for the complex task, dubbed the "Regenovo" which is a "3D bio printer." Xu Mingen, Regenovo's developer, said that it takes the printer under an hour to produce either a mini liver sample or a four to five inch ear cartilage sample. Xu also predicted that fully functional printed organs may be possible within the next ten to twenty years.[140][141] In the same year, researchers at the University of Hasselt, in Belgium had successfully printed a new jawbone for an 83-year-old Belgian woman.[142]

In January 2015, it was reported that doctors at London's St Thomas' Hospital had used images obtained from a Magnetic Resonance Imaging (MRI) scan to create a 3D printing replica of the heart of a two-year-old girl with a 'very complex' hole in it. They were then able to tailor a Gore-Tex patch to effect a cure. The lead surgeon of the operating team, Professor David Anderson, told *The Sunday Times*: "The 3D printing meant we could create a model of her heart and then see the inside of it with a replica of the hole as it looked when the heart was pumping. We could go into the operation with a much better idea of what we would find". The 3D printing technique used by the hospital was pioneered by Dr Gerald Greil.[143]

7.7.7   Computers and robots

See also: Modular design and Open-source robotics

3D printing can be used to make laptops and other computers, including cases, as Novena and VIA OpenBook standard laptop cases. I.e. a Novena motherboard can be

bought and be used in a printed VIA OpenBook case.[144]

Open-source robots are built using 3D printers. Double Robotics grant access to their technology (an open SDK).[145][146][147] On the other hand, 3&DBot is an Arduino 3D printer-robot with wheels[148] and ODOI is a 3D printed humanoid robot.[149]

7.7.8 Space

In September 2014, SpaceX delivered the first zero-gravity 3-D printer to the International Space Station (ISS). On December 19, 2014, NASA emailed CAD drawings for a socket wrench to astronauts aboard the ISS, who then printed the tool using its 3-D printer. Applications for space offer the ability to print broken parts or tools on-site, as opposed to using rockets to bring along pre-manufactured items for space missions to human colonies on the moon, Mars, or elsewhere.[150] The European Space Agency plans to deliver its new Portable On-Board 3D Printer (POP3D for short) to the International Space Station by June 2015, making it the second 3D printer in space.[151][152]

7.8 Sociocultural applications

An example of 3D printed limited edition jewellery. This necklace is made of glassfiber-filled dyed nylon. It has rotating linkages that were produced in the same manufacturing step as the other parts

7.8.1 Art

In 2005, academic journals had begun to report on the possible artistic applications of 3D printing technology.[153] By 2007 the mass media followed with an article in the Wall Street Journal[154] and Time Magazine, listing a 3D printed design among their 100 most influential designs of the year.[155] During the 2011 London Design Festival, an installation, curated by Murray Moss and focused on 3D Printing, was held in the Victoria and Albert Museum (the V&A). The installation was

Guardians of Time by Manfred Kielnhofer, 3D printing polished nickel steel by Shapeways 2014

3D printed ceramic pot

called *Industrial Revolution 2.0: How the Material World will Newly Materialize*.[156]

Some of the recent developments in 3D printing were revealed at the 3DPrintshow in London, which took place in November 2013 and 2014. The art section had in exposition artworks made with 3D printed plastic and metal. Several artists such as Joshua Harker, Davide Prete, Sophie Kahn, Helena Lukasova, Foteini Setaki showed how 3D printing can modify aesthetic and art processes. One part of the show focused on ways in which 3D printing can advance the medical field. The underlying theme of these advances was that these printers can be used to create parts that are printed with specifications to meet each individual. This makes the process safer and more effi-

flower model made with a 3D printer

cient. One of these advances is the use of 3D printers to produce casts that are created to mimic the bones that they are supporting. These custom-fitted casts are open, which allow the wearer to scratch any itches and also wash the damaged area. Being open also allows for open ventilation. One of the best features is that they can be recycled to create more casts.[157]

3D printing is becoming more popular in the customisable gifts industry, with products such as personalised mobile phone cases and dolls,[158] as well as 3D printed chocolate.[159]

The use of 3D scanning technologies allows the replication of real objects without the use of moulding techniques that in many cases can be more expensive, more difficult, or too invasive to be performed, particularly for precious or delicate cultural heritage artefacts[160] where direct contact with the moulding substances could harm the original object's surface.

Critical making refers to the hands on productive activities that link digital technologies to society. It is invented to bridge the gap between creative physical and conceptual exploration.[161] The term was popularized by Matt Ratto, an Assistant Professor and director of the Critical Making lab in the Faculty of Information at the University of Toronto. Ratto describes one of the main goals of critical as "to use material forms of engagement with technologies to supplement and extend critical reflection and,

in doing so, to reconnect our lived experiences with technologies to social and conceptual critique".[162] The main focus of critical making is open design,[163] which includes, in addition to 3D printing technologies, also other digital software and hardware. People usually reference spectacular design when explaining critical making.[164]

7.8.2 Communication

Employing additive layer technology offered by 3D printing, Terahertz devices which act as waveguides, couplers and bends have been created. The complex shape of these devices could not be achieved using conventional fabrication techniques. Commercially available professional grade printer EDEN 260V was used to create structures with minimum feature size of 100 μm. The printed structures were later DC sputter coated with gold (or any other metal) to create a Terahertz Plasmonic Device.[165]

7.8.3 Domestic use
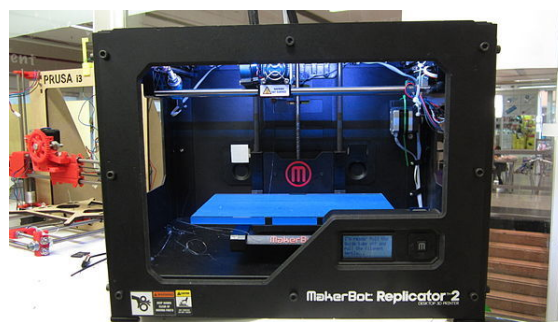
A MakerBot Replicator 2

As of 2012, domestic 3D printing was mainly practised by hobbyists and enthusiasts, and was little used for practical household applications. A working clock was made[166] and gears were printed for home woodworking machines among other purposes.[167] 3D printing was also used for ornamental objects. Web sites associated with home 3D printing tended to include backscratchers, coathooks, doorknobs etc.[168]

The open source Fab@Home project[67] has developed printers for general use. They have been used in research environments to produce chemical compounds with 3D printing technology, including new ones, initially without immediate application as proof of principle.[93] The printer can print with anything that can be dispensed from a syringe as liquid or paste. The developers of the chemical application envisage both industrial and domestic use for this technology, including enabling users in remote locations to be able to produce their own medicine or household chemicals.[169][170]

3D printing is now working its way into households and more and more children are being introduced to the concept of 3D printing at earlier ages. The prospects of

3D printing are growing and as more people have access to this new innovation, new uses in households will emerge.[171]

The OpenReflex SLR film camera was developed for 3D printing as an open-source student project.[172]

7.8.4 Education and research

3D printing, and open source RepRap 3D printers in particular, are the latest technology making inroads into the classroom.[173][174][175] 3D printing allows students to create prototypes of items without the use of expensive tooling required in subtractive methods. Students design and produce actual models they can hold. The classroom environment allows students to learn and employ new applications for 3D printing.[176] RepRaps, for example, have already been used for an educational mobile robotics platform.[177]

Some authors have claimed that RepRap 3D printers offer an unprecedented "revolution" in STEM education.[178] The evidence for such claims comes from both the low cost ability for rapid prototyping in the classroom by students, but also the fabrication of low-cost high-quality scientific equipment from open hardware designs forming open-source labs.[179] Engineering and design principles are explored as well as architectural planning. Students recreate duplicates of museum items such as fossils and historical artifacts for study in the classroom without possibly damaging sensitive collections. Other students interested in graphic designing can construct models with complex working parts. 3D printing gives students a new perspective with topographic maps. Science students can study cross-sections of internal organs of the human body and other biological specimens. And chemistry students can explore 3D models of molecules and the relationship within chemical compounds.[180]

According to a recent paper by Kostakis et al.,[181] 3D printing and design can electrify various literacies and creative capacities of children in accordance with the spirit of the interconnected, information-based world.

Future applications for 3D printing might include creating open-source scientific equipment.[179][182]

7.8.5 Environmental use

In Bahrain, large-scale 3D printing using a sandstone-like material has been used to create unique coral-shaped structures, which encourage coral polyps to colonise and regenerate damaged reefs. These structures have a much more natural shape than other structures used to create artificial reefs, and, unlike concrete, are neither acid nor alkaline with neutral pH.[183]

7.9 Intellectual property

See also: Free hardware

3D printing has existed for decades within certain manufacturing industries where many legal regimes, including patents, industrial design rights, copyright, and trademark may apply. However, there is not much jurisprudence to say how these laws will apply if 3D printers become mainstream and individuals and hobbyist communities begin manufacturing items for personal use, for non-profit distribution, or for sale.

Any of the mentioned legal regimes may prohibit the distribution of the designs used in 3D printing, or the distribution or sale of the printed item. To be allowed to do these things, where an active intellectual property was involved, a person would have to contact the owner and ask for a licence, which may come with conditions and a price. However, many patent, design and copyright laws contain a standard limitation or exception for 'private', 'non-commercial' use of inventions, designs or works of art protected under intellectual property (IP). That standard limitation or exception may leave such private, non-commercial uses outside the scope of IP rights.

Patents cover inventions including processes, machines, manufactures, and compositions of matter and have a finite duration which varies between countries, but generally 20 years from the date of application. Therefore, if a type of wheel is patented, printing, using, or selling such a wheel could be an infringement of the patent.[184]

Copyright covers an expression[185] in a tangible, fixed medium and often lasts for the life of the author plus 70 years thereafter.[186] If someone makes a statue, they may have copyright on the look of that statue, so if someone sees that statue, they cannot then distribute designs to print an identical or similar statue.

When a feature has both artistic (copyrightable) and functional (patentable) merits, when the question has appeared in US court, the courts have often held the feature is not copyrightable unless it can be separated from the functional aspects of the item.[186] In other countries the law and the courts may apply a different approach allowing, for example, the design of a useful device to be registered (as a whole) as an industrial design on the understanding that, in case of unauthorised copying, only the non-functional features may be claimed under design law whereas any technical features could only be claimed if covered by a valid patent.

7.9.1 Gun legislation and administration

The US Department of Homeland Security and the Joint Regional Intelligence Center released a memo stating that "significant advances in three-dimensional (3D) printing capabilities, availability of free digital 3D printable

files for firearms components, and difficulty regulating file sharing may present public safety risks from unqualified gun seekers who obtain or manufacture 3D printed guns," and that "proposed legislation to ban 3D printing of weapons may deter, but cannot completely prevent their production. Even if the practice is prohibited by new legislation, online distribution of these 3D printable files will be as difficult to control as any other illegally traded music, movie or software files."[187]

Internationally, where gun controls are generally tighter than in the United States, some commentators have said the impact may be more strongly felt, as alternative firearms are not as easily obtainable.[188] European officials have noted that producing a 3D printed gun would be illegal under their gun control laws,[189] and that criminals have access to other sources of weapons, but noted that as the technology improved the risks of an effect would increase.[190][191] Downloads of the plans from the UK, Germany, Spain, and Brazil were heavy.[192][193]

Attempting to restrict the distribution over the Internet of gun plans has been likened to the futility of preventing the widespread distribution of DeCSS which enabled DVD ripping.[194][195][196][197] After the US government had Defense Distributed take down the plans, they were still widely available via The Pirate Bay and other file sharing sites.[198] Some US legislators have proposed regulations on 3D printers, to prevent them being used for printing guns.[199][200] 3D printing advocates have suggested that such regulations would be futile, could cripple the 3D printing industry, and could infringe on free speech rights, with early pioneer of 3D printing Professor Hod Lipson suggesting that gunpowder could be controlled instead.[201][202][203][204][205][206][207]

7.10   Open-source 3D printers

See also: Free hardware

7.11   Impact

Additive manufacturing, starting with today's infancy period, requires manufacturing firms to be flexible, ever-improving users of all available technologies to remain competitive. Advocates of additive manufacturing also predict that this arc of technological development will counter globalisation, as end users will do much of their own manufacturing rather than engage in trade to buy products from other people and corporations.[3] The real integration of the newer additive technologies into commercial production, however, is more a matter of complementing traditional subtractive methods rather than displacing them entirely.[208]

7.11.1   Social change

Since the 1950s, a number of writers and social commentators have speculated in some depth about the social and cultural changes that might result from the advent of commercially affordable additive manufacturing technology.[209] Amongst the more notable ideas to have emerged from these inquiries has been the suggestion that, as more and more 3D printers start to enter people's homes, so the conventional relationship between the home and the workplace might get further eroded.[210] Likewise, it has also been suggested that, as it becomes easier for businesses to transmit designs for new objects around the globe, so the need for high-speed freight services might also become less.[211] Finally, given the ease with which certain objects can now be replicated, it remains to be seen whether changes will be made to current copyright legislation so as to protect intellectual property rights with the new technology widely available.

As 3D printers became more accessible to consumers, online social platforms have developed to support the community.[212] This includes websites that allow users to access information such as how to build a 3D printer, as well as social forums that discuss how to improve 3D print quality and discuss 3D printing news, as well as social media websites that are dedicated to share 3D models.[213][214][215] RepRap is a wiki based website that was created to hold all information on 3d printing, and has developed into a community that aims to bring 3D printing to everyone. Furthermore, there are other sites such as Thingiverse and MyMiniFactory, which was created initially to allow users to post 3D files for anyone to print, allowing for decreased transaction cost of sharing 3D files. These websites have allowed for greater social interaction between users, creating communities dedicated around 3D printing.

Some [216][217][218] call attention to the conjunction of Commons-based peer production with 3D printing and other low-cost manufacturing techniques. The self-reinforced fantasy of a system of eternal growth can be overcome with the development of economies of scope, and here, the civil society can play an important role contributing to the raising of the whole productive structure to a higher plateau of more sustainable and customised productivity.[216] Further, it is true that many issues, problems and threats rise due to the large democratisation of the means of production, and especially regarding the physical ones.[216] For instance, the recyclability of advanced nanomaterials is still questioned; weapons manufacturing could become easier; not to mention the implications on counterfeiting [219] and on IP.[220] It might be maintained that in contrast to the industrial paradigm whose competitive dynamics were about economies of scale, Commons-based peer production and 3D printing could develop economies of scope. While the advantages of scale rest on cheap global transportation, the economies of scope share infrastructure costs (intangible

and tangible productive resources), taking advantage of the capabilities of the fabrication tools.[216] And following Neil Gershenfeld [221] in that "some of the least developed parts of the world need some of the most advanced technologies", Commons-based peer production and 3D printing may offer the necessary tools for thinking globally but act locally in response to certain problems and needs.

Larry Summers wrote about the "devastating consequences" of 3-D printing and other technologies (robots, artificial intelligence, etc.) for those who perform routine tasks. In his view, "already there are more American men on disability insurance than doing production work in manufacturing. And the trends are all in the wrong direction, particularly for the less skilled, as the capacity of capital embodying artificial intelligence to replace white-collar as well as blue-collar work will increase rapidly in the years ahead." Summers recommends more vigorous cooperative efforts to address the "myriad devices" (e.g. tax havens, bank secrecy, money laundering, and regulatory arbitrage) enabling the holders of great wealth to "avoid paying" income and estate taxes, and to make it more difficult to accumulate great fortunes without requiring "great social contributions" in return, including: more vigorous enforcement of anti-monopoly laws, reductions in "excessive" protection for intellectual property, greater encouragement of profit-sharing schemes that may benefit workers and give them a stake in wealth accumulation, strengthening of collective bargaining arrangements, improvements in corporate governance, strengthening of financial regulation to eliminate subsidies to financial activity, easing of land-use restrictions that may cause the real estate of the rich to keep rising in value, better training for young people and retraining for displaced workers, and increased public and private investment in infrastructure development, e.g. in energy production and transportation.[222]

Michael Spence wrote that "Now comes a ... powerful, wave of digital technology that is replacing labor in increasingly complex tasks. This process of labor substitution and disintermediation has been underway for some time in service sectors – think of ATMs, online banking, enterprise resource planning, customer relationship management, mobile payment systems, and much more. This revolution is spreading to the production of goods, where robots and 3D printing are displacing labor." In his view, the vast majority of the cost of digital technologies comes at the start, in the design of hardware (e.g. 3D printers) and, more important, in creating the software that enables machines to carry out various tasks. "Once this is achieved, the marginal cost of the hardware is relatively low (and declines as scale rises), and the marginal cost of replicating the software is essentially zero. With a huge potential global market to amortize the upfront fixed costs of design and testing, the incentives to invest [in digital technologies] are compelling." Spence believes that, unlike prior digital technologies, which drove firms to deploy underutilized pools of valuable labor around the world, the motivating force in the current wave of digital technologies "is cost reduction via the replacement of labor." For example, as the cost of 3D printing technology declines, it is "easy to imagine" that production may become "extremely" local and customized. Moreover, production may occur in response to actual demand, not anticipated or forecast demand. Spence believes that labor, no matter how inexpensive, will become a less important asset for growth and employment expansion, with labor-intensive, process-oriented manufacturing becoming less effective, and that re-localization will appear in both developed and developing countries. In his view, production will not disappear, but it will be less labor-intensive, and all countries will eventually need to rebuild their growth models around digital technologies and the human capital supporting their deployment and expansion. Spence writes that "the world we are entering is one in which the most powerful global flows will be ideas and digital capital, not goods, services, and traditional capital. Adapting to this will require shifts in mindsets, policies, investments (especially in human capital), and quite possibly models of employment and distribution."[223]

Forbes investment pundits have predicted that 3D printing may lead to a resurgence of American Manufacturing, citing the small, creative companies that compromise the current industry landscape, and the lack of the necessary complex infrastructure in typical outsource markets.[224]

7.11.2 Specialty materials

Consumer grade 3D printing has resulted in new materials that have been developed specifically for 3D printers. For example, filament materials have been developed to imitate wood, in its appearance as well as its texture. Furthermore, new technologies, such as infusing carbon fiber[225] into printable plastics, allowing for a stronger, lighter material. In addition to new structural materials that have been developed due to 3D printing, new technologies have allowed for patterns to be applied directly to 3D printed parts. Iron oxide-free Portland cement powder has been used to create architectural structures up to 9 feet in height.[226][227][228]

7.12   See also

- List of notable 3D printed weapons and parts
- List of common 3D test models
- List of emerging technologies
- 3D Hubs
- 3D printing marketplace
- Additive Manufacturing File Format

- CGTrader
- Computer numeric control
- Digital modeling and fabrication
- Electron beam freeform fabrication
- Laser cutting
- MakerBot Industries
- Mass customization
- Milling center
- Modular design
- Molecular assembler
- MyMiniFactory
- Open design
- Open source hardware
- Organ-on-a-chip
- Self-replicating machine
- Shapeways
- Thingiverse
- Threeding
- Volumetric printing
- Youmagine

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7.15 Further reading

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7.16 External links

- 3D Printing Industry

- 3D Printer Testing Results, MAKE.

- 3D Printer Buyer's Guide, Tom's Guide.

- Introduction to 3d printing costs

- 3D printed gun breaches tight gov security in Israel

- Rapid prototyping websites at DMOZ

- 3D fabbers: don't let the DMCA stifle an innovative future // Arstechnica, 2010-11-10

- 3-D printing at MIT

- 3D Printing: The Printed World from *The Economist*

- All3DP - Inside Stories About 3D Printing

- Comparison chart of 3D printers

- How to Fabricate a Toy Model from Scratch

- Jay Leno's 3D Printer Replaces Rusty Old Parts

- Rapid Manufacturing for the production of Ceramic Components

- How does 3D printing work? (from physics.org)

- Will 3D Printing Change the World? Video produced by Off Book (web series)

- Comprehensive listing of consumer 3D printers

- Hub listing of example 3D printing projects

- Introduction to FDM technology

- New 3D printing algorithms speed production, reduce waste, Kurzweil Accelerating Intelligence.

Chapter 8

Direct numerical control

Direct numerical control (**DNC**), also known as **distributed numerical control** (also **DNC**), is a common manufacturing term for networking CNC machine tools. On some CNC machine controllers, the available memory is too small to contain the machining program (for example machining complex surfaces), so in this case the program is stored in a separate computer and sent *directly* to the machine, one block at a time. If the computer is connected to a number of machines it can *distribute* programs to different machines as required. Usually, the manufacturer of the control provides suitable DNC software. However, if this provision is not possible, some software companies provide DNC applications that fulfill the purpose. DNC networking or DNC communication is always required when CAM programs are to run on some CNC machine control.

Wireless DNC is also used in place of hard-wired versions. Controls of this type are very widely used in industries with significant sheet metal fabrication, such as the automotive, appliance, and aerospace industries.

8.1 History

8.1.1 1950s-1970s

Programs had to be walked to NC controls, generally on paper tape. NC controls had paper tape readers precisely for this purpose. Many companies were still punching programs on paper tape well into the 1980s, more than twenty-five years after its elimination in the computer industry.

8.1.2 1980s

The focus in the 1980s was mainly on reliably transferring NC programs between a host computer and the control. The Host computers would frequently be Sun Microsystems, HP, Prime, DEC or IBM type computers running a variety of CAD/CAM software. DNC companies offered machine tool links using rugged proprietary terminals and networks. For example, DLog offered an x86 based terminal, and NCPC had one based on the 6809.

The host software would be responsible for tracking and authorising NC program modifications. Depending on program size, for the first time operators had the opportunity to modify programs at the DNC terminal. No time was lost due to broken tapes, and if the software was correctly used, an operator running incorrect or out of date programs became a thing of the past.

Older controls frequently had no port capable of receiving programs such as an RS232 or RS422 connector. In these cases, a device known as a Behind The Reader or BTR card was used. The connection between the control's tape reader and the internal processor was interrupted by a microprocessor based device which emulated the paper tape reader's signals, but which had a serial port connected to the DNC system. As far as the control was concerned, it was receiving from the paper tape unit as it always had; in fact it was the BTR or Reader Emulation card which was transmitting. A switch was frequently added to permit the paper tape reader to be used as a backup.

8.1.3 1990s to present

The PC explosion in the late 1980s and early 1990s signalled the end of the road for proprietary DNC terminals. With some exceptions, CNC manufacturers began migrating to PC-based controls running DOS, Windows or OS/2 which could be linked in to existing networks using standard protocols. Customers began migrating away from expensive minicomputer and workstation based CAD/CAM toward more cost-effective PC-based solutions. Users began to demand more from their DNC systems than secure upload/download and editing. PC-based systems which could accomplish these tasks based on standard networks began to be available at minimal or no cost. In some cases, users no longer needed a DNC "expert" to implement shop floor networking, and could do it themselves. However, the task can still be a challenge based on the CNC Control wiring requirements, parameters and NC program format.

To remain competitive, therefore, DNC companies moved their offerings upmarket into DNC Networking, Shop Floor Control or SFC, Manufacturing Execution Systems or MES. These terms encompass concepts such as real-time Machine Monitoring, Graphics, Tool Man-

agement, Traveler Management and Scheduling. Instead of merely acting as a repository for programs, DNC systems aim to give operators at the machine an integrated view of all the information (both textual and graphical) they require in order to carry out a manufacturing operation, and give management timely information as to the progress of each step. DNC systems are frequently directly integrated with corporate CAD/CAM, ERP and Computer-aided Process Planning CAPP systems.

8.2 Special protocols

A challenge when interfacing into machine tools is that in some cases special protocols are used. Two well-known examples are Mazatrol and Heidenhain. Many DNC systems offer support for these protocols. Another protocol is DNC2 or LSV2 which is found on Fanuc controls. DNC2 allows advanced interchange of data with the control, such as tooling offsets, tool life information and machine status as well as automated transfer without operator intervention.

8.3 Machine monitoring

One of the issues involved in machine monitoring is whether or not it can be accomplished automatically in a practical way. In the 1980s monitoring was typically done by having a menu on the DNC terminal where the operator had to manually indicate what was being done by selecting from a menu, which has obvious drawbacks. There have been advances in passive monitoring systems where the machine condition can be determined by hardware attached in such a way as not to interfere with machine operations (and potentially void warranties). Many modern controls allow external applications to query their status using a special protocol. MTConnect is one prominent attempt to augment the existing world of proprietary systems with some open-source, industry-standard protocols and XML schemas and an ecosystem of massively multiplayer app development and mashups (analogous to that with smartphones) so that these long-sought higher levels of manufacturing business intelligence and workflow automation can be realized.

8.4 Alternatives

Smaller facilities will typically use a portable PC, palmtop or laptop to avoid the expense of a fully networked DNC system. In the past Facit Walk Disk and a similar device from Mazak were very popular.

8.5 Footnotes

Chapter 9

Design for manufacturability

Design for manufacturability (also sometimes known as **design for manufacturing** or DFM) is the general engineering art of designing products in such a way that they are easy to manufacture. The basic idea exists in almost all engineering disciplines, but of course the details differ widely depending on the manufacturing technology. This design practice not only focuses on the design aspect of a part but also on the producibility. In simple language it means relative ease to manufacture a product, part or assembly. DFM describes the process of designing or engineering a product in order to facilitate the manufacturing process in order to reduce its manufacturing costs. DFM will allow potential problems to be fixed in the design phase which is the least expensive place to address them. The design of the component can have an enormous effect on the cost of manufacturing. Other factors may affect the manufacturability such as the type of raw material, the form of the raw material, dimensional tolerances, and secondary processing such as finishing.

The design stage is very important in product design. Most of the product lifecycle costs are committed at design stage[Citation needed]. The product design is not just based on good design but it should be possible to produce by manufacturing as well. Often an otherwise good design is difficult or impossible to produce. Typically a design engineer will create a model or design and send it to manufacturing for review and invite feedback. This process is called a design review. If this process is not followed diligently, the product may fail at the manufacturing stage.

If these DFM guidelines are not followed, it will result in iterative design, loss of manufacturing time and overall resulting in longer time to market. Hence many organizations have adopted concept of Design for Manufacturing.

Depending on various types of manufacturing processes there are set guidelines for DFM practices. These DFM guidelines help to precisely define various tolerances, rules and common manufacturing checks related to DFM.

While DFM is applicable to the design process, a similar concept called DFSS (Design for Six Sigma) is also practiced in many organizations.

9.1 Design for manufacturability for printed circuit boards (PCB)

In the PCB design process, DFM leads to a set of design guidelines that attempt to ensure manufacturability. By doing so, probable production problems may be addressed during the design stage.

Ideally, DFM guidelines take into account the processes and capabilities of the manufacturing industry. Therefore, DFM is constantly evolving.

As manufacturing companies evolve and automate more and more stages of the processes, these processes tend to become cheaper. DFM is usually used to reduce these costs. For example, if a process may be done automatically by machines (i.e. SMT component placement and soldering), such process is likely to be cheaper than doing so by hand.

9.2 Design for manufacturability for integrated circuits (IC)

Achieving high-yielding designs in the state of the art VLSI technology has become an extremely challenging task due to the miniaturization as well as the complexity of leading-edge products. The design methodology called **design for manufacturability** (**DFM**) includes a set of techniques to modify the design of integrated circuits (IC) in order to make them more manufacturable, i.e., to improve their functional yield, parametric yield, or their reliability.

9.2.1 Background

Traditionally, in the prenanometer era, DFM consisted of a set of different methodologies trying to enforce some soft (recommended) design rules regarding the shapes and polygons of the physical layout of an integrated circuit. These DFM methodologies worked primarily at the full chip level. Additionally, worst-case simulations

at different levels of abstraction were applied to minimize the impact of process variations on performance and other types of parametric yield loss. All these different types of worst-case simulations were essentially based on a base set of worst-case (or corner) SPICE device parameter files that were intended to represent the variability of transistor performance over the full range of variation in a fabrication process.

9.2.2 Taxonomy of yield loss mechanisms

The most important yield loss models (YLMs) for VLSI ICs can be classified into several categories based on their nature.

- **Functional yield loss** is still the dominant factor and is caused by mechanisms such as misprocessing (e.g., equipment-related problems), systematic effects such as printability or planarization problems, and purely random defects.

- High-performance products may exhibit **parametric design marginalities** caused by either process fluctuations or environmental factors (such as supply voltage or temperature).

- The **test-related yield losses**, which are caused by incorrect testing, can also play a significant role.

9.2.3 Techniques

After understanding the causes of yield loss, the next step is to make the design as resistant as possible. Techniques used for this include:

- Substituting higher yield cells where permitted by timing, power, and routability.

- Changing the spacing and width of the interconnect wires, where possible

- Optimizing the amount of redundancy in internal memories.

- Substituting fault tolerant (redundant) vias in a design where possible

All of these require a detailed understanding of yield loss mechanisms, since these changes trade off against one another. For example, introducing redundant vias will reduce the chance of via problems, but increase the chance of unwanted shorts. Whether this is good idea, therefore, depends on the details of the yield loss models and the characteristics of the particular design.

9.3 Design for manufacturability for CNC machining

9.3.1 Material type

The most easily machined types of metals include aluminum, brass, and softer metals. As materials get harder, denser and stronger, such as steel, stainless steel, titanium, and exotic alloys, they become much harder to machine and take much longer, thus being less manufacturable. Most types of plastic are easy to machine, although additions of fiberglass or carbon fiber can reduce the machinability. Plastics that are particularly soft and gummy may have machinability problems of their own.

9.3.2 Material form

Metals come in all forms. In the case of aluminum as an example, bar stock and plate are the two most common forms from which machined parts are made. The size and shape of the component may determine which form of material must be used. It is common for engineering drawings to specify one form over the other. Bar stock is generally close to 1/2 of the cost of plate on a per pound basis. So although the material form isn't directly related to the geometry of the component, cost can be removed at the design stage by specifying the least expensive form of the material.

9.3.3 Tolerances

A significant contributing factor to the cost of a machined component is the geometric tolerance to which the features must be made. The tighter the tolerance required, the more expensive the component will be to machine. When designing, specify the loosest tolerance that will serve the function of the component. Tolerances must be specified on a feature by feature basis. There are creative ways to engineer components with lower tolerances that still perform as well as ones with higher tolerances.

9.3.4 Design and shape

As machining is a subtractive process, the time to remove the material is a major factor in determining the machining cost. The volume and shape of the material to be removed as well as how fast the tools can be fed will determine the machining time. When using milling cutters, the strength and stiffness of the tool which is determined in part by the length to diameter ratio of the tool will play the largest role in determining that speed. The shorter the tool is relative to its diameter the faster it can be fed through the material. A ratio of 3:1 (L:D) or under is optimum.[1] If that ratio cannot be achieved, a solution like this depicted here can be used.[2] For holes, the length

to diameter ratio of the tools are less critical, but should still be kept under 10:1.

There are many other types of features which are more or less expensive to machine. Generally chamfers cost less to machine than radii on outer horizontal edges. Undercuts are more expensive to machine. Features that require smaller tools, regardless of L:D ratio, are more expensive.

9.4   See also

- Electronic design automation

- Reliability engineering

- Six Sigma

- Statistical process control

- ISQED

- DFM in other areas

- Design for assembly

- Design for X

9.5   References

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[2] http://procnc.com/images/content/Design_Guide_Rev_C.pdf

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- Mentor Graphics - DFM: Magic Bullet or Marketing Hype (must fill request form).

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- *Design for Manufacturability And Statistical Design: A Constructive Approach*, by Michael Orshansky, Sani Nassif, Duane Boning ISBN 0-387-30928-4

- *Estimating Space ASICs Using SEER-IC/H*, by Robert Cisneros, Tecolote Research, Inc. (2008) Complete Presentation

9.7   External links

- Why DFM/DFMA is Business Critical

- Design for manufacturing checklist – DFM,DFA(Design for assembly checklist from Quick-teck PCB manufacturer

- Arc Design for Manufacturability Tips

- DFM Concept Explained

- Design for Manufacturing and Assembly

- Turning designs into reality: The Manufacturability paradigm

- List of DFM links

Chapter 10

Gerber format

For other uses, see Gerber.

The **Gerber format** is an open 2D bi-level vector image file format.[1] It is the de facto standard used by printed circuit board (PCB) industry software to describe the printed circuit board images: copper layers, solder mask, legend, etc.[2][3][4]

The standard file extension is *.GBR* or *.gbr*[1] though other extensions are also used.

There are two major generations of Gerber format:

- Extended Gerber, or RS-274X. This is the current Gerber format.

- Standard Gerber, or RS-274-D. This obsolete format is deprecated. It is superseded by Extended Gerber.[5][6][7]

10.1 Usage

Gerber is the standard input format for photoplotters in PCB fabrication and all other fabrication equipment that needs digital images, such as legend printers, direct imagers or automated optical inspection (AOI) machines or for viewing reference data in different departments.

Gerber files also contains a 'stencil' layer for solder paste and the central locations of components to allow the PCB assembler to create the stencil and place and bond the components.

10.1.1 PCB fabrication data

A third usage of Gerber is in PCB fabrication data.[8] PCBs are designed on a specialized electronic design automation (EDA) or a computer-aided design (CAD) system.[9] The CAD systems output a Gerber file for each image layer (copper layers, solder mask, legend or silk...). Drilled hole information is also transferred in Gerber but for historic reasons the Excellon Format is often used. (Using Excellon rather than Gerber usually leads to copper-drill registration problems.[8]) Typically, all these files are "zipped" into a single archive that is sent

to the PCB bare board fabrication shop. The fabricator loads them into a computer-aided manufacturing (CAM) system to prepare data for each step of the PCB production process. [10][11] [12]

Each layer in the PCB must be linked with a Gerber file in the fabrication data. In Gerber version 2 the .FileFunction attribute provides a standardized method to do this.[1] In legacy files only informal methods are available. A straightforward informal method is to express the file function clearly in the file name. Sometimes, however, cryptic file names are used and then documented in a free-format text file. Sometimes even the file extension is abused to indicate the file function - e.g. .BOT for the bottom layer rather than the standard extension .GBR ; very unpractical as the format of the file can no longer be deducted from the extension. [6][13][14]

PCB Fabrication Data must comply with a number of rules: all layers must be aligned, a profile layer must be included, etc.

A Gerber file cannot represent the netlist; the netlist is usually specified in the IPC-D-356 format.[15]

The material stack up, components and finishes are typically provided in informal text files or drawings.[16] Ucamco recommends using a subset of IPC-2581 for this non-image information.[6][17]

10.2 Extended Gerber

The Gerber format, also known as RS-274X, extended Gerber or X-Gerber, is a 2D bi-level vector image description format.[1]

It is a human readable ASCII format.[18] It consists of a stream of commands generating an ordered stream of graphics objects. The graphics objects can be positive or negative. Superimposed in the correct order they create the final image.

A Gerber file contains the complete description of a PCB layer image without requiring any external files. It has all the imaging operators needed for a PCB image. Any aperture shape can be defined. Planes and pads can be specified without the need to paint or vector-fill as in

Standard Gerber. (However painting is sometimes still used because implementations created for Standard Gerber and have not yet been upgraded to use the more powerful capabilities of Extended Gerber.)[19]

In February 2014 Ucamco extended the Gerber format with attributes (Gerber version 2). Attributes add meta-information to a Gerber file. These are akin to labels providing information associated with image files, or features within them. Examples of meta-information conveyed by attributes are:

- The function of the file. Is the file the top solder mask, or the bottom copper layer, etc?

- The part represented by the file. Does it represent a single PCB, an array, a coupon?

- The function of a pad. Is the flash is an SMD pad, or a via pad, or a fiducial, etc.

For more information see the version 2 FAQ or intro video in the external links. [20] [1] [21] [22] [23]

Gerber is a complete, powerful and unambiguous standard to describe a PCB layer. It can be input and processed fully automatically. This makes it well suited for fast and secure data transfer and for reliable and automated workflows.

An example of a Gerber file:

G04 Short version a file taken from the Example Job 1, created by Filip Vermeire, Ucamco*   %TF.FileFunction,Copper,Bot,L4*%
%TF.Part,Single*%   %FSLAX35Y35*%
%MOMM*% %TA.AperFunction,Conductor,NotC*%
%ADD10C,0.15000*% %TA.AperFunction,ViaPad*%
%ADD11C,0.75000*%
%TA.AperFunction,ComponentPad*%
%ADD12C,1.60000*%   %ADD13C,1.70000*%
%SRX1Y1I0.00000J0.00000*%   G01*   G75*
%LPD*%   D10*   X7664999Y3689998D02*
X8394995D01*   X8439999Y3734999D01*
X9369999D01*   D11*   X7664999Y3689998D03*
X8359999Y1874998D03*   X9882998Y3650498D03*
D12*   X4602988Y7841488D03*   D13*
X10729976Y2062988D03*   X10983976D03*
X11237976D03* M02*

The format specification is published.[1]

10.3 Standard Gerber

Standard Gerber was an NC format designed by Gerber Systems Corp to drive their vector photo plotters for the PCB industry in the 1960s and 1970s. As Gerber was the market leader its format became a de-facto standard.

Standard Gerber has been deprecated and declared obsolete. It no longer conforms to the Gerber format

specification.[6][7] Standard was designed for a manual workflow. It is not suitable for automated data transfer between PCB designers and manufacturers. Vector photo plotters are replaced by raster photoplotters. Standard Gerber is superseded by extended Gerber.

Standard Gerber was a subset of the Electronic Industries Association RS-274-D specification,[24] a format to drive mechanical NC machines in a wide range of industries. The term RS-274-D, without the qualifying "Gerber" postfix, is sometimes used informally for the standard Gerber subset rather than full RS-274-D.

RS-274-D standard Gerber was a simple ASCII format consisting of commands and XY coordinates.[25] An example:

D11*   X1785250Y2173980D02*
X1796650Y2177730D01*   X1785250Y2181480D01*
X1796650Y2184580D01*   D12*
X3421095Y1407208D03*   X1785250Y2173980D03*
M02*

A Standard Gerber file on its own is not an image description because it does not contain all information: the coordinate unit and the definitions of the *apertures* are not defined in the RS-274-D file. (Apertures are the basic shapes, similar to fonts in a PDF file.) The coordinate units set manually by the operator of the plotter. They were described in a free-format text file, called an *aperture file* or a *wheel file*, intended for human reading. It was called a wheel file because the apertures were mounted on a rotating wheel and the operator defined the apertures by selecting a wheel and mounting it on the plotter. There are no standards for wheel files. The designer and the plotter operator had to agree on these case-by-case. Therefore standard Gerber is an NC standard but not an image definition standard.[1][25]

Standard Gerber supports only imaging operators to draw tracks and flash aperture as vector plotters were only capable of these operations. The only way to create large copper pours is to *paint* (aka *stroke* or *vector-fill*) them with a vast number or tracks. This creates very large files that take long time to process. Because of the difficulty and cost of creating apertures with all but the simplest and most standard shapes *painting* was also used to create all but the simplest pads. Painting creates the desired image but the original shape of the copper pour or pad and must be laboriously recovered in CAM.[8][19][26][27]

10.4 History

The Gerber file format was originally developed by the Gerber Systems Corp., a division of Gerber Scientific, founded by Joseph Gerber.[28] The Gerber file format is now owned by Ucamco through its acquisition of Barco ETS, a company that previously acquired Gerber Systems Corp.[10][29] The specification can be freely downloaded.[1]

- In 1980, the first edition of the *Gerber Format: a subset of EIA RS-274-D; plot data format reference book*[30] was published by Gerber Systems Corporation. Gerber Scientific Corporation used a subset of EIA RS-274-D to drive their line of photoplotters. At this time the photoplotter had a limited set of fixed apertures of different shapes (typically round, rectangular and a few others) and in different sizes. An aperture could be exposed at a specific coordinate using a "flash" aperture, or the head could be moved from one coordinate to another with the shutter open to generate line or circular arc segments using a "draw" aperture. There was no uniform position for the apertures. Each was a small cut-out in a glass or film substrate. Before a design could be plotted the plotter operator needed a set of instructions from the designer (the aperture list) to tell him where to install each aperture before running the plot. The machine had a certain number of available aperture position numbers that were not consecutive, and usually not all were used for any given board plot. The person generating the plot file was responsible for ensuring that the aperture list used positions that were actually available and matched the plot file.

- In 1986, the Gerber format was extended to support apertures with variable sizes to produce rectangles of arbitrary sizes within a given range and tapered lines. This functionality is not in practical use any more.

- In the 1980s, the Gerber format was adopted by several other photoplotter vendors and also CAM systems for PCB manufacturing. It had by now become the de facto standard.

- In 1991 with the availability of raster scan capability the Gerber format was extended for polygon areas and Extended Mass Parameters. It becomes a superset of RS-274-D standard Gerber. These allow the user to dynamically define apertures of different shapes and sizes as well as defining polygon area fills without the need for "painting". The impetus to develop the Extended Mass Parameters was provided by AT&T.[31]

- In 1994, the last edition of the *Gerber Format Guide* was published by Gerber Systems Corporation.

- In April 1998, Gerber Systems Corporation was taken over by and integrated in Barco, Belgium. Barco's PCB division is now called Ucamco (former Barco ETS).

- In September 1998, the *RS-274X Format User's Guide* was published by Barco - Gerber Systems Corporation.

- In February 2010, the *Gerber Format Specification* was updated to revision F.

- In December 2010, the *Gerber Format Specification* was updated to revision G.[32]

- In January 2012, the *Gerber Format Specification* was updated to revision H.[33]

- In February 2013, the *Gerber Format Specification* was updated to revision I1.[5]

- In April 2013, the *Gerber Format Specification* was updated to revision I2.[34]

- In June 2013, the *Gerber Format Specification* was updated to revision I3.

- In June 2013, a proposal to extend the Gerber format with attributes is published.[21]

- In November 2013, the *Gerber Format Specification* was updated to revision I4.[35]

- In February 2014, the specification was updated to revision J1. It added attributes to convey PCB meta-information such as the layer the file represents.[21]

- In June 2014, the specification was updated to revision J2.

10.5 Related formats

Over the years there have been several attempts to replace Gerber by formats containing more information than just the layer image, e.g. netlist or component information.[10] None of these attempts have been widely accepted within the electronics manufacturing industry, probably because the formats are complex.[6] Gerber remains the most widely used data transfer format.[2][3][4]

- IPC-D-350 C *Printed Board Description in Digital Format*, 1989. This specification was standardized as IEC 61182-1 in 1992 and withdrawn in 2001. Rarely, if ever, used.

- DXF Sometimes used. These are typically constructed as drawings, PCB objects (tracks and pads) are lost, which makes them very difficult to use in CAM.

- PDF Rarely used. Very impractical to work with because PCB objects (tracks and pads) are lost.

- DPF Format, now at v7, a CAM format from Ucamco. Sometimes used.

- The *Electronic Design Interchange Format*, EDIF. Rarely, if ever, used.

- ODB++, a CAM format from Mentor Graphics. Sometimes used, the prevalent non-Gerber format.[36]

- GenCAM: IPC−2511A *Generic Requirements for Implementation of Product Manufacturing Description Data and Transfer Methodology*, 2000. Rarely, if ever, used.

- GenCAM: IPC−2511B *Generic Requirements for Implementation of Product Manufacturing Description Data and Transfer XML Schema Methodology*, 2002. Rarely, if ever, used.

- Offspring: IPC−2581 *Generic Requirements for Printed Board Assembly Products Manufacturing Description Data and Transfer Methodology*, 2004. Rarely, if ever, used, but receiving more attention recently.[37]

- STEP AP210: ISO 10303−210, *Electronic assembly interconnect and packaging design*, first edition 2001, second edition 2008 (to be published)

- Fujiko: JPCA-EB02,[38] based on work by Prof. Tomokage of Fukuoka University. A new standard in Japan. Rarely, if ever used.

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10.7 External links

- Gerber File Format Specification, sample files, technical notes

- Gerber version 2 intro movie

- Gerber version 2 FAQ

- PCB Fabrication Data - A Guide

Chapter 11

G-code

For other uses, see G-code (disambiguation) and G programming language (disambiguation).
"RS-274" redirects here. For the photoplotter format, see Gerber format.

G-code (also *RS-274*), which has many variants, is the common name for the most widely used numerical control (NC) programming language. It is used mainly in computer-aided manufacturing for controlling automated machine tools. G-code is sometimes called **G programming language**.

In fundamental terms, G-code is a language in which people tell computerized machine tools how to make something. The how is defined by instructions on where to move, how fast to move, and through what path to move. The most common situation is that, within a machine tool, a cutting tool is moved according to these instructions through a toolpath, cutting away excess material to leave only the finished workpiece. The same concept also extends to noncutting tools such as forming or burnishing tools, photoplotting, additive methods such as 3D printing, and measuring instruments.

11.1   Implementations

The first implementation of a numerical control programming language was developed at the MIT Servomechanisms Laboratory in the late 1950s. In the decades since, many implementations have been developed by many (commercial and noncommercial) organizations. G-code has often been used in these implementations. The main standardized version used in the United States was settled by the Electronic Industries Alliance in the early 1960s. A final revision was approved in February 1980 as *RS-274-D*.[1] In other countries, the standard *ISO 6983* is often used, but many European states use other standards. For example, *DIN 66025* is used in Germany, and PN-73M-55256 and PN-93/M-55251 are used in Poland.

Extensions and variations have been added independently by control manufacturers and machine tool manufacturers, and operators of a specific controller must be aware of differences of each manufacturer's product.

One standardized version of G-code, known as *BCL*, is used only on very few machines.

During the 1970s through 1990s, many CNC machine tool builders attempted to overcome compatibility difficulties by standardizing on machine tool controllers built by Fanuc. Siemens was another market dominator in CNC controls, especially in Europe. In the 2010s, controller differences and incompatibility are not as troublesome because machining operations are developed with CAD/CAM applications that can output the appropriate G-code for a specific machine tool.

Some CNC machines use "conversational" programming, which is a wizard-like programming mode that either hides G-code or completely bypasses the use of G-code. Some popular examples are Southwestern Industries' ProtoTRAK, Mazak's Mazatrol, Hurco's Ultimax, Haas' Intuitive Programming System (IPS), and Mori Seiki's CAPS conversational software.

G-code began as a limited type of language that lacked constructs such as loops, conditional operators, and programmer-declared variables with natural-word-including names (or the expressions in which to use them). It was thus unable to encode logic; it was essentially just a way to "connect the dots" where many of the dots' locations were figured out longhand by the programmer. The latest implementations of G-code include such constructs, creating a language somewhat closer to a high-level programming language. Additionally, all primary manufacturers (e.g. Fanuc, Siemens, Heidenhain) provide access to PLC data, such as axis positioning data and tool data,[2] via variables which can be used by NC programs. These constructs make it easier to develop automation applications.

11.2   Specific codes

G-codes are also called preparatory codes, and are any word in a CNC program that begins with the letter G. Generally it is a code telling the machine tool what type of action to perform, such as:

- Rapid move (transport the tool through space to the place where it is needed for cutting; do this as

quickly as possible)

- Controlled feed move in a straight line or arc

- Series of controlled feed moves that would result in a hole being bored, a workpiece cut (routed) to a specific dimension, or a profile (contour) shape added to the edge of a workpiece

- Set tool information such as offset

- Switch coordinate systems

There are other codes; the type codes can be thought of like registers in a computer.

Students and hobbyists have pointed out over the years that the term "G-code" referring to the language overall (using the mass sense of "code") is imprecise. It comes metonymically from the literal sense of the term, referring to one letter address among many in the language (G address, for preparatory commands) and to the specific codes (count sense) that can be formed with it (for example, G00, G01, G28). But every letter of the English alphabet is used somewhere in the language (although some letters' use is less common), so the name seems unfitting to people searching for strictly logical etymology. Nevertheless, "G-code" is indelibly established as the common name of the language.

11.2.1   Letter addresses

Some letter addresses are used only in milling or only in turning; most are used in both. **Bold** below are the letters seen most frequently throughout a program.

Sources: Smid 2008;[3] Smid 2010;[4] Green et al. 1996.[5]

11.2.2   List of G-codes commonly found on FANUC and similarly designed controls

Sources: Smid 2008;[3] Smid 2010;[4] Green et al. 1996.[5]

> **Note**: *Modal* means a code stays in effect until replaced, or cancelled, by another permitted code. *Non-Modal* means it executes only once. See, for example, codes G09, G61 & G64 below.

11.2.3   List of M-codes commonly found on FANUC and similarly designed controls

Sources: Smid 2008;[3] Smid 2010;[4] Green et al. 1996.[5]

11.3   Example program
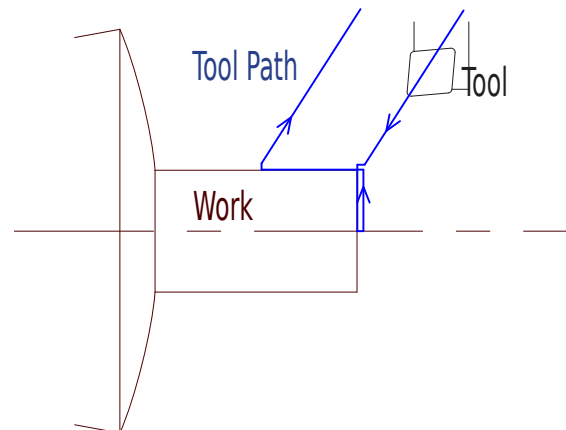
Tool Path for program

This is a generic program that demonstrates the use of G-Code to turn a 1" diameter X 1" long part. Assume that a bar of material is in the machine and that the bar is slightly oversized in length and diameter and that the bar protrudes by more than 1" from the face of the chuck. (Caution: This is generic, it might not work on any real machine! Pay particular attention to point 5 below.)

Several points to note:

1. There is room for some programming style, even in this short program. The grouping of codes in line N06 could have been put on multiple lines. Doing so may have made it easier to follow program execution.

2. Many codes are "modal", meaning that they stay in effect until they are cancelled or replaced by a contradictory code. For example, once variable speed cutting (CSS) had been selected (G96), it stayed in effect until the end of the program. In operation, the spindle speed would increase as the tool neared the center of the work in order to maintain a constant surface speed. Similarly, once rapid feed was selected (G00), all tool movements would be rapid until a feed rate code (G01, G02, G03) was selected.

3. It is common practice to use a load monitor with CNC machinery. The load monitor will stop the machine if the spindle or feed loads exceed a preset value that is set during the set-up operation. The jobs of the load monitor are various:

   (a) Prevent machine damage in the event of tool breakage or a programming mistake.

      i. This is especially important because it allows safe "lights-out machining", in which the operators set up the job and start it running during the day, then go home for the night, leaving the machines

running and cutting parts during the night. Because no human is around to hear, see, or smell a problem such as a broken tool, the load monitor serves an important sentry duty. When it senses overload condition, which semantically suggests a dull or broken tool, it commands a stop to the machining. Technology is available nowadays to send an alert to someone remotely (e.g., the sleeping owner, operator, or owner-operator) if desired, which can allow them to come intercede and get production going again, then leave once more. This can be the difference between profitability or loss on some jobs, because lights-out machining reduces labor hours per part.

   (b) Warn of a tool that is becoming dull and needs to be replaced or sharpened. Thus an operator who is busy tending multiple machines will be told by a machine, essentially, "Hey, pause what you're doing over there, and come attend to a need over here."

4. It is common practice to bring the tool in rapidly to a "safe" point that is close to the part—in this case 0.1" away—and then start feeding the tool. How close that "safe" distance is, depends on the preference of the programmer and/or operator and the maximum material condition for the raw stock.

5. If the program is wrong, there is a high probability that the machine will *crash*, or ram the tool into the part under high power. This can be costly, especially in newer machining centers. It is possible to intersperse the program with optional stops (M01 code) which allow the program to be run piecemeal for testing purposes. The optional stops remain in the program but they are skipped during the normal running of the machine. Fortunately, most CAD/CAM software ships with CNC simulators that will display the movement of the tool as the program executes. Many modern CNC machines also allow programmers to execute the program in a simulation mode and observe the operating parameters of the machine at a particular execution point. This enables programmers to discover semantic errors (as opposed to syntax errors) before losing material or tools to an incorrect program. Depending on the size of the part, wax blocks may be used for testing purposes as well.

6. For educational purposes, line numbers have been included in the program above. They are usually not necessary for operation of a machine, so they are seldom used in industry. However, if branching or looping statements are used in the code, then line numbers may well be included as the target of those statements (e.g. GOTO N99).

7. Some machines do not allow multiple M codes in the same line.

11.4   Programming environments

G-code's programming environments have evolved in parallel with those of general programming—from the earliest environments (e.g., writing a program with a pencil, typing it into a tape puncher) to the latest environments that combine CAD (computer-aided design), CAM (computer-aided manufacturing), and richly featured G-code editors. (G-code editors are analogous to XML editors, using colors and indents semantically [plus other features] to aid the user in ways that basic text editors can't. CAM packages are analogous to IDEs in general programming.)

Two high-level paradigm shifts have been (1) abandoning "manual programming" (with nothing but a pencil or text editor and a human mind) for CAM software systems that generate G-code automatically via postprocessors (analogous to the development of visual techniques in general programming), and (2) abandoning hardcoded constructs for parametric ones (analogous to the difference in general programming between hardcoding a constant into an equation versus declaring it a variable and assigning new values to it at will; and to the object-oriented approach in general). Macro (parametric) CNC programming uses human-friendly variable names, relational operators, and loop structures much as general programming does, to capture information and logic with machine-readable semantics. Whereas older manual CNC programming could only describe particular instances of parts in numeric form, macro programming describes abstractions which can be flowed with ease into a wide variety of instances. The difference has many analogues, both from before the computing era and from after its advent, such as (1) creating text as bitmaps versus using character encoding with glyphs; (2) the abstraction level of tabulated engineering drawings, with many part dash numbers parametrically defined by the one same drawing and a parameter table; or (3) the way that HTML passed through a phase of using content markup for presentation purposes, then matured toward the CSS model. In all of these cases, a higher layer of abstraction was introduced in order to pursue what was missing semantically.

STEP-NC reflects the same theme, which can be viewed as yet another step along a path that started with the development of machine tools, jigs and fixtures, and numerical control, which all sought to "build the skill into the tool". Recent developments of G-code and STEP-NC aim to build the information and semantics into the tool. The idea itself is not new; from the beginning of numerical control, the concept of an end-to-end CAD/CAM environment was the goal of such early technologies as DAC-1 and APT. Those efforts were fine for huge corporations like GM and Boeing. However, for small and

medium enterprises, there had to be an era in which the simpler implementations of NC, with relatively primitive "connect-the-dots" G-code and manual programming, ruled the day until CAD/CAM could improve and disseminate throughout the economy.

Any machine tool with a great number of axes, spindles, and tool stations is difficult to program well manually. It has been done over the years, but not easily. This challenge has existed for decades in CNC screw machine and rotary transfer programming, and it now also arises with today's newer machining centers called "turn-mills", "mill-turns", "multitasking machines", and "multifunction machines". Now that CAD/CAM systems are widely used, CNC programming (such as with G-code) requires CAD/CAM (as opposed to manual programming) to be practical and competitive in the market segments served by these classes of machines.[8] As Smid says, "Combine all these axes with some additional features, and the amount of knowledge required to succeed is quite overwhelming, to say the least."[9] At the same time, however, programmers still must thoroughly understand the principles of manual programming and must think critically and second-guess some aspects of the software's decisions.

Since about the mid-2000s, the era has finally arrived when "the death of manual programming" (that is, of writing lines of G-code without CAD/CAM assistance) sometimes seems to be approaching. However, it is currently only in *some* contexts that manual programming is obsolete. Although it is true that plenty of CAM programming can and does take place nowadays among people who are rusty on, or incapable of, manual programming, it is not true that *all* CNC programming can be done, or done *as well* or *as efficiently*, without being able to speak the language of G-code.[10][11] Tailoring and refining the CNC program at the machine is an area of practice where it can be easier or more efficient to edit the G-code directly rather than editing the CAM toolpaths and re-post-processing the program.

11.5 Abbreviations used by programmers and operators

This list is only a selection and, except for a few key terms, mostly avoids duplicating the many abbreviations listed at engineering drawing abbreviations and symbols (which see also).

11.6 See also

- 3D printing

- Canned cycle

11.6.1 Extended developments

- Direct Numerical Control (DNC)

- STEP-NC

- MTConnect

11.6.2 Similar concepts

- Gerber file

11.6.3 Concerns during application

- Cutter location, cutter compensation, offset parameters

- Coordinate systems

11.7 References

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11.9 External links

- CNC G-Code and M-Code Programming

- Tutorial for G-code

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Chapter 12

Part program

A **Part program** is a set of instructions given to a Computerized numerical control (CNC) machine.

CNC is an automation to machine tools such as A lathe controlled by program rather than manually i.e. by hand. Thus CNC has 3 main components such as

- A program (part program).

- Machine controller unit.

- processing unit.

Chapter 13

Wireless DNC

Wireless DNC is a form of wireless data transfer, known as Direct Numerical Control, performed between a Computer Numerical control (CNC) machine and the computer controlling it. These are very widely used in Automobile, Engineering, Sheet Metal, Aeronautic Industry. These machines are capable of producing different parts. For each type of part, a sequence of instructions is needed. This list of instructions is stored in a computer script, a computer file written in a programming language, such as G-code. This script is commonly referred to as a part program. When a part is to be produced this part program is uploaded to CNC machine by RS-232 link.

Now this RS-232 link between a PC & CNC machine with a Software is called a DNC System. In a typical Machine shop floor, it is difficult to maintain the data cable. Hence wireless data transfer has come into existence. There are mainly two types of wireless hardware units available in the market. One is using wireless Bluetooth Technology, while the other uses wireless Wi-Fi technology.

In case of Bluetooth, generally one pair of Bluetooth device is used. One gets plugged on COM port of a PC or Laptop & the other is connected to RS-232 port of a CNC machine. The wireless link is established with the required driver software. Once this is established, the user can run his DNC Software for data transfer. In most of the cases, the file is sent from a remote PC to a selected CNC machine.

In Wi-Fi technology, a wireless link is established between a device called Wireless access point (Generally near PC) & a device called as wireless node, which is interfaced near CNC. There is one Access Point & multiple nodes. Each wireless access point, wireless node has one IP address. This IP address must be of the same domain name of a PC. Thus a wireless Ethernet link is created. The wireless node has RS-232 port, which is connected to a RS-232 port of a CNC. There is a driver software on PC which maps the RS-232 port of wireless node as a virtual COM Port of a PC. Once this is done, a DNC Software takes care of two way data transfer.

Chapter 14

Coordinate system

In geometry, a **coordinate system** is a system which uses
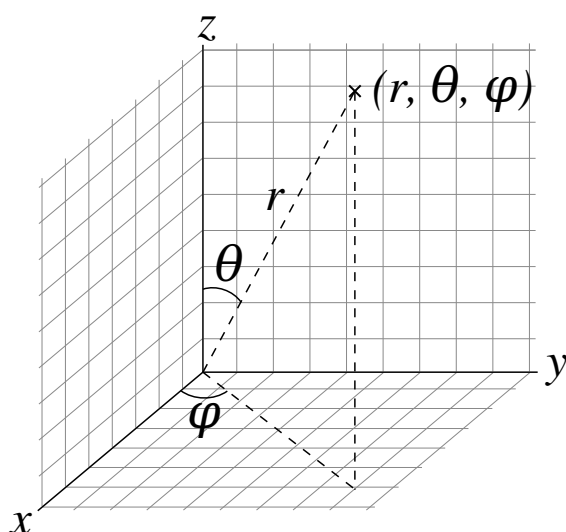
The spherical coordinate system is commonly used in physics. It assigns three numbers (known as coordinates) to every point in Euclidean space: radial distance r, polar angle θ (theta), and azimuthal angle φ (phi). The symbol ρ (rho) is often used instead of r.

one or more numbers, or **coordinates**, to uniquely determine the position of a point or other geometric element on a manifold such as Euclidean space.[1][2] The order of the coordinates is significant and they are sometimes identified by their position in an ordered tuple and sometimes by a letter, as in "the *x*-coordinate". The coordinates are taken to be real numbers in elementary mathematics, but may be complex numbers or elements of a more abstract system such as a commutative ring. The use of a coordinate system allows problems in geometry to be translated into problems about numbers and *vice versa*; this is the basis of analytic geometry.[3]

14.1 Common coordinate systems

14.1.1 Number line

Main article: Number line

The simplest example of a coordinate system is the identification of points on a line with real numbers using the *number line*. In this system, an arbitrary point O (the *origin*) is chosen on a given line. The coordinate of a point P is defined as the signed distance from O to P, where the signed distance is the distance taken as positive or negative depending on which side of the line P lies. Each point is given a unique coordinate and each real number is the coordinate of a unique point.[4]
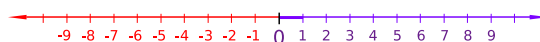
The number line

14.1.2 Cartesian coordinate system

Main article: Cartesian coordinate system

The prototypical example of a coordinate system is
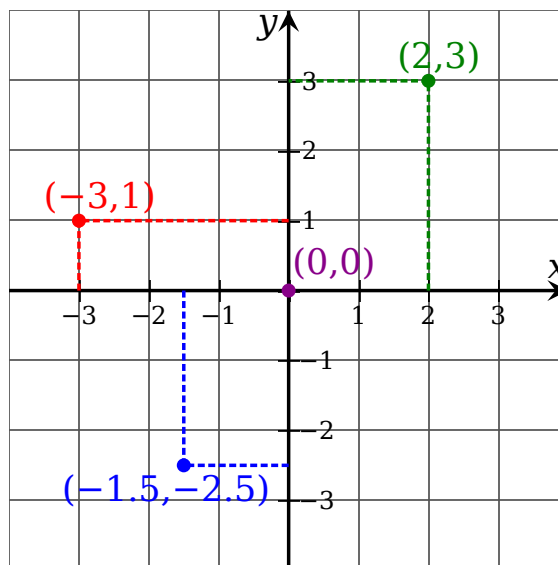
The Cartesian coordinate system in the plane.

the Cartesian coordinate system.   In the plane, two perpendicular lines are chosen and the coordinates of a point are taken to be the signed distances to the lines.
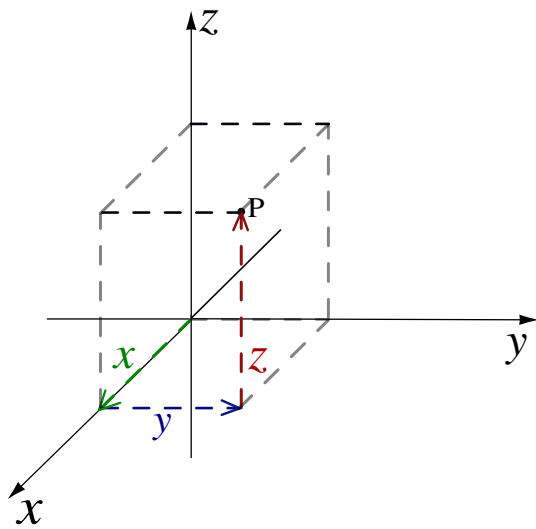
In three dimensions, three perpendicular planes are chosen and the three coordinates of a point are the signed distances to each of the planes.[5] This can be generalized to create n coordinates for any point in n-dimensional Euclidean space.

Depending on the direction and order of the coordinate axis the system may be a right-hand or a left-hand system.

14.1.3   Polar coordinate system

Main article: Polar coordinate system

Another common coordinate system for the plane is the *polar coordinate system*.[6] A point is chosen as the *pole* and a ray from this point is taken as the *polar axis*. For a given angle θ, there is a single line through the pole whose angle with the polar axis is θ (measured counterclockwise from the axis to the line).   Then there is a unique point on this line whose signed distance from the origin is r for given number r. For a given pair of coordinates (r, θ) there is a single point, but any point is represented by many pairs of coordinates. For example (r, θ), (r, θ+2π) and (−r, θ+π) are all polar coordinates for the same point. The pole is represented by (0, θ) for any value of θ.

14.1.4   Cylindrical and spherical coordinate systems

Main articles: Cylindrical coordinate system and Spherical coordinate system

There are two common methods for extending the polar coordinate system to three dimensions. In the **cylindrical coordinate system**, a z-coordinate with the same meaning as in Cartesian coordinates is added to the r and θ polar coordinates.[7] Spherical coordinates take this a step further by converting the pair of cylindrical coordinates (r, z) to polar coordinates (ρ, φ) giving a triple (ϱ, θ, φ).[8] Cylindrical coordinates system have the following coordinates, ρ,φ,z

14.1.5   Homogeneous coordinate system

Main article: Homogeneous coordinates

A point in the plane may be represented in *homogeneous coordinates* by a triple (x, y, z) where x/z and y/z are the Cartesian coordinates of the point.[9] This introduces an "extra" coordinate since only two are needed to specify a point on the plane, but this system is useful in that it represents any point on the projective plane without the use of infinity. In general, a homogeneous coordinate system is one where only the ratios of the coordinates are significant and not the actual values.

14.1.6   Other commonly used systems

Some other common coordinate systems are the following:

- Curvilinear coordinates are a generalization of coordinate systems generally; the system is based on the intersection of curves.

  - Orthogonal coordinates: coordinate surfaces meet at right angles

  - Skew coordinates: coordinate surfaces are not orthogonal

orthogonal coordinates

- The log-polar coordinate system represents a point in the plane by the logarithm of the distance from the origin and an angle measured from a reference line intersecting the origin.

- Plücker coordinates are a way of representing lines in 3D Euclidean space using a six-tuple of numbers as homogeneous coordinates.

- Generalized coordinates are used in the Lagrangian treatment of mechanics.

- Canonical coordinates are used in the Hamiltonian treatment of mechanics.

- Parallel coordinates visualise a point in n-dimensional space as a polyline connecting points on n vertical lines.

- Barycentric coordinates as used for ternary plots and more generally in the analysis of triangles.

- Trilinear coordinates are used in the context of triangles.

There are ways of describing curves without coordinates, using intrinsic equations that use invariant quantities such as curvature and arc length. These include:

- The Whewell equation relates arc length and the tangential angle.

- The Cesàro equation relates arc length and curvature.

14.2 Coordinates of geometric objects

Coordinates systems are often used to specify the position of a point, but they may also be used to specify the position of more complex figures such as lines, planes, circles or spheres. For example Plücker coordinates are used to determine the position of a line in space.[10] When there is a need, the type of figure being described is used to distinguish the type of coordinate system, for example the term *line coordinates* is used for any coordinate system that specifies the position of a line.

It may occur that systems of coordinates for two different sets of geometric figures are equivalent in terms of their analysis. An example of this is the systems of homogeneous coordinates for points and lines in the projective plane. The two systems in a case like this are said to be *dualistic*. Dualistic systems have the property that results from one system can be carried over to the other since these results are only different interpretations of the same analytical result; this is known as the *principle of duality*.[11]

14.3 Transformations

See also: Active and passive transformation
Main article: List of common coordinate transformations

Because there are often many different possible coordinate systems for describing geometrical figures, it is important to understand how they are related. Such relations are described by *coordinate transformations* which give formulas for the coordinates in one system in terms of the coordinates in another system. For example, in the plane, if Cartesian coordinates (x, y) and polar coordinates (r, θ) have the same origin, and the polar axis is the positive x axis, then the coordinate transformation from polar to Cartesian coordinates is given by $x = r \cos\theta$ and $y = r \sin\theta$.

With every bijection from the space to itself two coordinate transformations can be associated:

- such that the new coordinates of the image of each point are the same as the old coordinates of the original point (the formulas for the mapping are the inverse of those for the coordinate transformation)

- such that the old coordinates of the image of each point are the same as the new coordinates of the original point (the formulas for the mapping are the same as those for the coordinate transformation)

For example, in 1D, if the mapping is a translation of 3 to the right, the first moves the origin from 0 to 3, so that the coordinate of each point becomes 3 less, while the second moves the origin from 0 to −3, so that the coordinate of each point becomes 3 more.

14.4 Coordinate curves and surfaces

Coordinate surfaces in the Spherical coordinate system

In two dimensions if all but one coordinate in a point coordinate system is held constant and the remaining coordinate is allowed to vary, then the resulting curve is called a **coordinate curve** (some authors use the phrase "coordinate line"). This procedure does not always make sense, for example there are no coordinate curves in a homogeneous coordinate system. In the Cartesian coordinate system the coordinate curves are, in fact, straight lines. Specifically, they are the lines parallel to one of the coordinate axes. For other coordinate systems the coordinates curves may be general curves. For example the coordinate curves in polar coordinates obtained by holding r constant are the circles with center at the origin. Coordinates systems for Euclidean space other than the

Cartesian coordinate system are called curvilinear coordinate systems.[12]

In three-dimensional space, if one coordinate is held constant and the remaining coordinates are allowed to vary, then the resulting surface is called a **coordinate surface**. For example the coordinate surfaces obtained by holding ρ constant in the spherical coordinate system are the spheres with center at the origin. In three-dimensional space the intersection of two coordinate surfaces is a coordinate curve. **Coordinate hypersurfaces** are defined similarly in higher dimensions.[13]

14.5   Coordinate maps

Main article: Manifold

The concept of a *coordinate map*, or *chart* is central to the theory of manifolds. A coordinate map is essentially a coordinate system for a subset of a given space with the property that each point has exactly one set of coordinates. More precisely, a coordinate map is a homeomorphism from an open subset of a space *X* to an open subset of $\mathbf{R}^n$.[14] It is often not possible to provide one consistent coordinate system for an entire space. In this case, a collection of coordinate maps are put together to form an atlas covering the space. A space equipped with such an atlas is called a *manifold* and additional structure can be defined on a manifold if the structure is consistent where the coordinate maps overlap. For example a differentiable manifold is a manifold where the change of coordinates from one coordinate map to another is always a differentiable function.

14.6   Orientation-based coordinates

In geometry and kinematics, coordinate systems are used not only to describe the (linear) position of points, but also to describe the angular position of axes, planes, and rigid bodies.[15] In the latter case, the orientation of a second (typically referred to as "local") coordinate system, fixed to the node, is defined based on the first (typically referred to as "global" or "world" coordinate system). For instance, the orientation of a rigid body can be represented by an orientation matrix, which includes, in its three columns, the Cartesian coordinates of three points. These points are used to define the orientation of the axes of the local system; they are the tips of three unit vectors aligned with those axes.

14.7   See also

- Absolute angular momentum

- Alpha-numeric grid
- Analytic geometry
- Astronomical coordinate systems
- Axes conventions in engineering
- Coordinate-free
- Fractional coordinates
- Frame of reference
- Galilean transformation
- Geographic coordinate system
- Nomogram, graphical representations of different coordinate systems

14.7.1   Relativistic Coordinate Systems

- Eddington–Finkelstein coordinates
- Gaussian polar coordinates
- Gullstrand–Painlevé coordinates
- Isotropic coordinates
- Kruskal–Szekeres coordinates
- Schwarzschild coordinates

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14.9 External links

- Hexagonal Coordinate System

14.10 Text and image sources, contributors, and licenses

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- **Direct numerical control** *Source:* http://en.wikipedia.org/wiki/Direct%20numerical%20control?oldid=636236426 *Contributors:* Deb, Pnm, Darkwind, Zoicon5, Jrp, Espoo, Redvers, Kelly Martin, RHaworth, BD2412, Bill37212, Rsrikanth05, Dv82matt, JLaTondre, Rwwww, Stifle, Commander Keane bot, Addshore, Shafique 9643, Wizard191, OS2Warp, Cydebot, Electron9, Cutterman, C.moulin, R'n'B, RJASE1, DimiTalen, Jamelan, Ffcarpy, Djd sd, The Sunshine Man, ClueBot, Hutcher, Three-quarter-ten, XLinkBot, Addbot, Yobot, Fraggle81, AnomieBOT, Omnipaedista, Kierkkadon, Bryancpark, Trojan65, Alister 77, Cgt, Vacation9, MerlIwBot, My name is not dave, Crackerlex, Jeremymcniel and Anonymous: 34

- **Design for manufacturability** *Source:* http://en.wikipedia.org/wiki/Design%20for%20manufacturability?oldid=653323260 *Contribu-tors:* Michael Hardy, Kku, Ronz, Hectorthebat, Dave6, Graeme Bartlett, BD2412, Rjwilmsi, Veinor, Sarah, SmackBot, Villarinho, LouScheffer, Wizard191, Amalas, Goldenrowley, Davewho2, Mariolina, Mausy5043, We the blight, Inwind, Hanwufu, Vpdvpd, Denis-arona, Prashant chan, Christian.fritz, XLinkBot, Dgtsyb, Addbot, Damiens.rf, DFMPro123, Yobot, Fraggle81, AnomieBOT, Dfmcnc, Louperibot, PigFlu Oink, FoxBot, MichelCharette, Makki98, EmausBot, WikitanvirBot, Wilhkar, Mjbmrbot, ClueBot NG, Jack Green-maven, Johnmills2010, Mediran, 14GTR, Poeggi, Ginsuloft, Gpanos123, Rambolino2005 and Anonymous: 29

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