CHAPTER 14

NEW DIRECTIONS IN MACHINE DESIGN

SOFTWARE IMPROVEMENTS EXPAND CAD CAPABILITIES

Computer Aided Design (CAD) is a computer-based technology that allows a designer to draw and label the engineering details of a product or project electronically on a computer screen while relegating drawing reproduction to a printer or X-Y plotter. It also permits designers in different locations to collaborate in the design process via a computer network and permits the drawing to be stored digitally in computer memory for ready reference. CAD has done for engineering graphics what the word processor did for writing. The introduction of CAD in the late 1960s changed the traditional method of drafting forever by relieving the designer of the tedious and time-consuming tasks of manual drawing from scratch, inking, and dimensioning on a conventional drawing board.

While CAD offers many benefits to designers or engineers never before possible, it does not relieve them of the requirement for extensive technical training and wide background knowledge of drawing standards and practice if professional work is to be accomplished. Moreover, in making the transition from the drawing board to the CAD workstation, the designer must spend the time and make the effort to master the complexities of the specific CAD software systems in use, particularly how to make the most effective use of the icons that appear on the screen.

The discovery of the principles of 3D isometric and perspective drawing in the Middle Ages resulted in a more realistic and accurate portrayal of objects than 2D drawings, and they conveyed at a glance more information about that object, but making a 3D drawing manually was then and is still more difficult and time-consuming, calling for a higher level of drawing skill. Another transition is required for the designer moving up from 2D to 3D drawing, contouring, and shading.

The D in CAD stands for design, but CAD in its present state is still essentially "computer-aided drawing" because the user, not the computer, must do the designing. Most commercial CAD programs permit lettering, callouts, and the entry of notes and parts lists, and some even offer the capability for calculating such physical properties as volume, weight, and center of gravity if the drawing meets certain baseline criteria. Meanwhile, CAD software developers are busy adding more automated features to their systems to move them closer to being true design programs and more user-friendly. For example, CAD techniques now available can perform analysis and simulation of the design as well as generate manufacturing instructions. These features are being integrated with the code for modeling the form and structure of the design.

In its early days, CAD required at least the computing power of a minicomputer and the available CAD software was largely application specific and limited in capability. CAD systems were neither practical nor affordable for most design offices and independent consultants. As custom software became more sophisticated and costly, even more powerful workstations were required to support them, raising the cost of entry into CAD even higher. Fortunately, with the rapid increases in the speed and power of microprocessors and memories, desktop personal computers rapidly began to close the gap with workstations even as their prices fell. Before long, high-end PCs become acceptable low-cost CAD platforms. When commercial CAD software producers addressed that market sector with lower-cost but highly effective software packages, their sales surged.

PCs that include high-speed microprocessors, Windows operating systems, and sufficient RAM and hard-drive capacity can now run software that rivals the most advanced custom Unix-based products of a few years ago. Now both 2D and 3D CAD software packages provide professional results when run on off-the-shelf personal computers. The many options available in commercial CAD software include

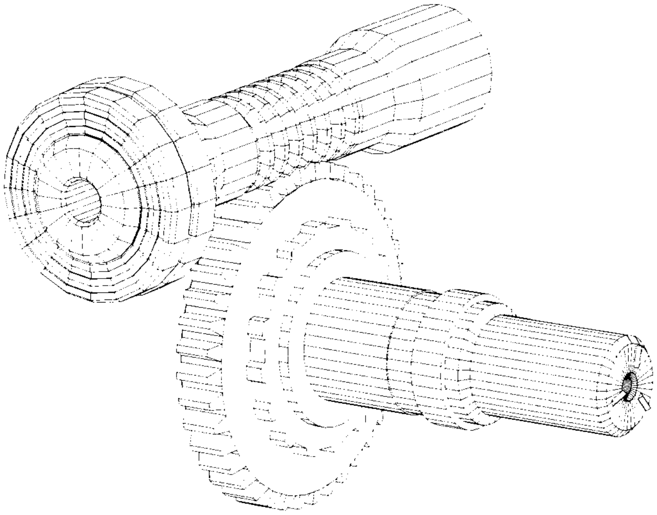
- 2D drafting
- 3D wireframe and surface modeling
- 3D solid modeling
- 3D feature-based solid modeling
- 3D hybrid surface and solid modeling

Two-Dimensional Drafting

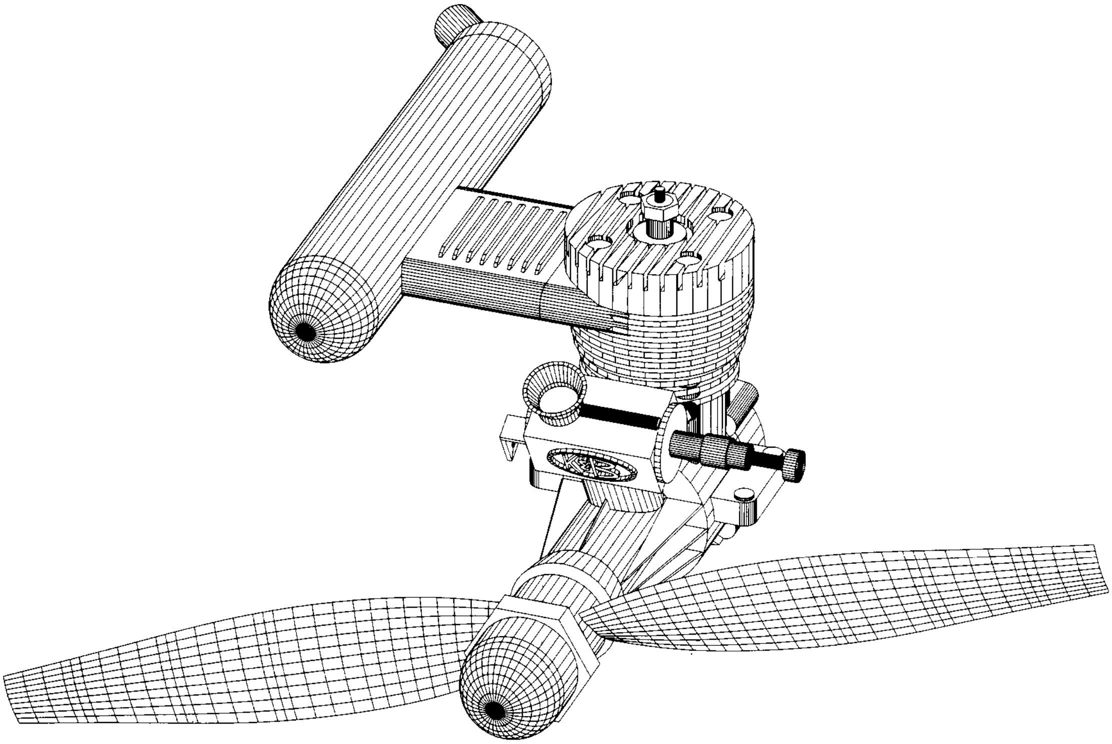
Two-dimensional drafting software for mechanical design is focused on drawing and dimensioning traditional engineering drawings. This CAD software was readily accepted by engineers, designers, and draftspersons with many years of experience. They felt comfortable with it because it automated their customary design changes, provided a way to make design changes quickly, and also permitted them to reuse their CAD data for new layouts.

A typical 2D CAD software package includes a complete library of geometric entities. It can also support curves, splines, and polylines as well as define hatching patterns and place hatching within complex boundaries. Other features include the ability to perform associative hatching and provide complete dimensioning. Some 2D packages can also generate bills of materials. 2D drawing and detailing software packages are based on ANSI, ISO, DIN, and JIS drafting standards.

In a 2D CAD drawing, an object must be described by multiple 2D views, generally three or more, to reveal profile and internal geometry from specific viewpoints. Each view of the object is created independently from other views. However, 2D views typically contain many visible and hidden lines, dimensions, and other detailing features. Unless careful checks of the finished drawing are made, mistakes in drawing or dimensioning intricate details can be overlooked. These can lead to costly problems downstream in the product design cycle. Also, when a change is



A three-dimensional "wireframe" drawing of two meshed gears made on a personal computer using software that cost less than $500. (*Courtesy of American Small Business Computers, Inc.*)



A three-dimensional "wireframe" drawing of a single-drawing model airplane engine showing the principal contours of both propeller and engine. This also was drawn on a personal computer using software that cost less than $500. (*Courtesy of American Small Business Computers, Inc.*)

made, each view must be individually updated. One way to avoid this problem (or lessen the probability that errors will go undetected) is to migrate upward to a 3D CAD system

Three-Dimensional Wireframe and Surface Modeling

A 3D drawing provides more visual impact than a 2D drawing because it portrays the subject more realistically and its value does not depend on the viewer's ability to read and interpret the multiple drawings in a 2D layout. Of more importance to the designer or engineer, the 3D presentation consolidates important information about a design, making it easier and faster to detect design flaws. Typically a 3D CAD model can be created with fewer steps than are required to produce a 2D CAD layout. Moreover, the data generated in producing a 3D model can be used to generate a 2D CAD layout, and this information can be preserved throughout the product design cycle. In addition, 3D models can be created in the orthographic or perspective modes and rotated to any position in 3D space.

The wireframe model, the simplest of the 3D presentations, is useful for most mechanical design work and might be all that is needed for many applications where 3D solid modeling is not required. It is the easiest 3D system to migrate to when making the transition from 2D to 3D drawing. A wireframe model is adequate for illustrating new concepts, and it can also be used to build on existing wireframe designs to create models of working assemblies.

Wireframe models can be quickly edited during the concept phase of the design without having to maintain complex solid-face relationships or parametric constraints. In wireframe modeling only edge information is stored, so data files can be significantly smaller than for other 3D modeling techniques. This can increase productivity and conserve available computer memory.

The unification of multiple 2D views into a single 3D view for modeling a complex machine design with many components permits the data for the entire machine to be stored and managed in a single wireframe file rather than many separate files. Also, model properties such as color, line style, and line width can be controlled independently to make component parts more visually distinctive.

The construction of a wireframe structure is the first step in the preparation of a 3D surface model. Many commercial CAD software packages include surface modeling with wireframe capability. The designer can then use available surface-modeling tools to apply a "skin" over the wire framework to convert it to a surface model whose exterior shape depends on the geometry of the wireframe.

One major advantage of surface modeling is its ability to provide the user with visual feedback. A wireframe model does not readily show any gaps, protrusions, and other defects. By making use of dynamic rotation features as well as shading, the designer is better able to evaluate the model. Accurate 2D views can also be generated from the surface model data for detailing purposes. Surface models can also be used to generate tool paths for numerically controlled (NC) machining. Computer-aided manufacturing (CAM) applications require accurate surface geometry for the manufacture of mechanical products.

Yet another application for surface modeling is its use in the preparation of photorealistic graphics of the end product. This capability is especially valued in consumer product design, where graphics stress the aesthetics of the model rather than its precision.

Some wireframe software also includes data translators, libraries of machine design elements and icons, and 2D drafting and detailing capability, which support design collaboration and compatibility among CAD, CAM, and computer-aided engineering (CAE) applications. Designers and engineers can store and use data accumulated during the design process. This data permits product manufacturers with compatible software to receive 2D and 3D wireframe data from other CAD systems.

Among the features being offered in commercial wireframe software are:

- Basic dimensioning, dual dimensioning, balloon notes, datums, and section lines.
- Automated geometric dimensioning and tolerancing (GD&T).
- Symbol creation, including those for weld and surface finish, with real-time edit or move capability and leaders.
- A library of symbols for sheet metal, welding, electrical piping, fluid power, and flow chart applications.

Data translators provide an effective and efficient means for transferring information from the source CAD design station to outside contract design offices, manufacturing plants, or engineering analysis consultants, job shops, and product development services. These include IGES, DXF, DWG, STL, CADL, and VRML.

Three-Dimensional Solid Modeling

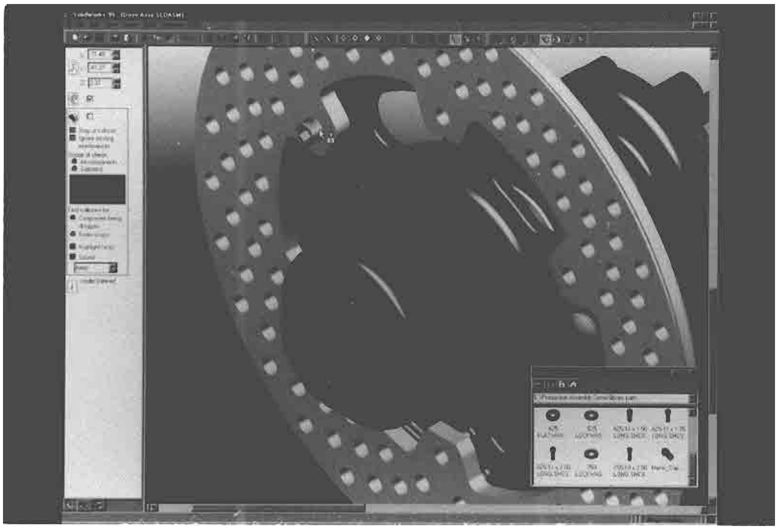
CAD solid-modeling programs can perform many more functions than simple 3D wireframe modelers. These programs are used to form models that are solid objects rather than simple 3D line drawings. Because these models are represented as solids, they are the source of data that permits the physical properties of the parts to be calculated.

Some solid-modeling software packages provide fundamental analysis features. With the assignment of density values for a variety of materials to the solid model, such vital statistics as strength and weight can be determined. Mass properties such as area, volume, moment of inertia, and center of gravity can be calculated for regularly and irregularly shaped parts. Finite element analysis software permits the designer to investigate stress, kinematics, and other factors useful in optimizing a part or component in an assembly. Also, solid models can provide the basic data needed for rapid prototyping using stereolithography, and can be useful in CAM software programs.

Most CAD solid-model software includes a library of primitive 3D shapes such as rectangular prisms, spheres, cylinders, and cones. Using Boolean operations for forming unions, subtractions, and intersections, these components can be added, subtracted, intersected, and sectioned to form complex 3D assemblies. Shading can be used to make the solid model easier for the viewers to comprehend. Precise 2D standard, isometric, and auxiliary views as well as cross sections can be extracted from the solid modeling data, and the cross sections can be cross-hatched.

Three-Dimensional Feature-Based Solid Modeling

3D feature-based solid modeling starts with one or more wireframe profiles. It creates a solid model by extruding, sweeping, revolving, or skinning these profiles. Boolean operations can



3D illustration of an indexing wheel drawn with 3D solid modeling software. *Courtesy of SolidWorks Corporation*

3D illustration of the ski suspension mechanism of a bobsled drawn with 3D modeling software. *Courtesy of SolidWorks Corporation* also be used on the profiles as well as the solids generated from these profiles. Solids can also be created by combining surfaces, including those with complex shapes. For example, this technique can be used to model streamlined shapes such as those of a ship's hull, racing-car's body, or aircraft.

3D feature-based solid modeling allows the designer to create such features as holes, fillets, chamfers, bosses, and pockets, and combine them with specific edges and faces of the model. If a design change causes the edges or faces to move, the features can be regenerated so that they move with the changes to keep their original relationships.

However, to use this system effectively, the designer must make the right dimensioning choices when developing these models, because if the features are not correctly referenced, they could end up the wrong location when the model is regenerated. For example, a feature that is positioned from the edge of an object rather than from its center might no longer be centered when the model is regenerated. The way to avoid this is to add constraints to the model that will keep the feature at the center of the face.

The key benefit of the parametric feature of solid modeling is that it provides a method for facilitating change. It imposes dimensional constraints on the model that permit the design to meet specific requirements for size and shape. This software permits the use of constraint equations that govern relationships between parameters. If some parameters remain constant or a specific parameter depends on the values of others, these relationships will be maintained throughout the design process. This form of modeling is useful if the design is restricted by space allowed for the end product or if its parts such as pipes or wiring must mate precisely with existing pipes or conduits.

Thus, in a parametric model, each entity, such as a line or arc in a wireframe, or fillet, is constrained by dimensional parameters. For example, in the model of a rectangular object, these parameters can control its geometric properties such as the length, width, and height. The parametric feature allows the designer to make changes as required to create the desired model. This software uses stored historical records that have recorded the steps in producing the model so that if the parameters of the model are changed, the software refers to the stored history and repeats the sequence of operations to create a new model for regeneration. Parametric modeling can also be used in trial-and-error operations to determine the optimum size of a component best suited for an application, either from an engineering or aesthetic viewpoint, simply by adjusting the parameters and regenerating a new model.

Parametric modeling features will also allow other methods of relating entities. Design features can, for example, be located at the origin of curves, at the end of lines or arcs, at vertices, or at the midpoints of lines and faces, and they can also be located at a specified distance or at the end of a vector from these points. When the model is regenerated, these relationships will be maintained. Some software systems also allow geometric constraints between features. These can mandate that the features be parallel, tangent, or perpendicular.

Some parametric modeling features of software combine freeform solid modeling, parametric solid modeling, surface modeling, and wireframe modeling to produce true hybrid models. Its features typically include hidden line removal, associative layouts, photorealistic rendering, attribute masking, and level management.

Three-Dimensional Hybrid Surface and Solid Modeling

Some modeling techniques are more efficient that others. For example, some are better for surfacing the more complex shapes as well as organic and freeform shapes. Consequently, commercial software producers offer 3D hybrid surface and solid-modeling suites that integrate 2D drafting and 3D wireframe with 3D surface and 3D solid modeling into a single CAD package. Included in these packages might also be software for photorealistic rendering and data translators to transport all types of data from the component parts of the package to other CAD or CAM software.

Glossary of Commonly Used CAD Terms

absolute coordinates: Distances measured from a fixed reference point, such as the origin, on the computer screen.

ANSI: An abbreviation for the American National Standards Institute.

associative dimensions: A method of dimensioning in CAD software that automatically updates dimension values when dimension size is changed.

Boolean modeling: A CAD 3D modeling technique that permits the user to add or subtract 3D shapes from one model to another.

Cartesian coordinates: A rectangular system for locating points in a drawing area in which the origin point is the 0,0 location and *X* represents length, *Y* width, and *Z* height. The surfaces between them can be designated as the *X–Z*, *X–Y*, and *Y–Z* planes.

composite drawing: A drawing containing multiple drawings in the form of CAD layers.

DXF: An abbreviation for Data Exchange Format, a standard format or translator for transferring data describing CAD drawings between different CAD programs.

FEM: An acronym for Finite Element Method for CAD structural design.

FTD: An abbreviation for File Transfer Protocol for upload and download of files to the Internet.

function: A task in a CAD program that can be completed by issuing a set of commands.

GD&T: An automated geometric, dimensioning, and tolerancing feature of CAD software.

GIS: An abbreviation for Geographic Information System.

IGES: An abbreviation for International Graphics Exchange Specification, a standard format or translator for transferring CAD data between different programs.

ISO: An abbreviation for International Standards Organization.

linear extrusion: A 3D technique that projects 2D into 3D shapes along a linear path.

MCAD: An abbreviation for mechanical CAD.

menu: A set of modeling functions or commands that are displayed on the computer screen. Options can be selected from the menu by a pointing device such as a mouse.

object snaps: A method for indicating point locations on existing drawings as references.

origin point: The 0,0 location in the coordinate system.

parametric modeling: CAD software that links the 3D drawing on the computer screen with data that sets dimensional and positional constraints.

polar coordinates: A coordinate system that locates points with an angle and radial distance from the origin, considered to be the center of a sphere.

polyline: A string of lines that can contain many connected line segments.

primitives: The basic elements of a graphics display such as points, lines, curves, polygons, and alphanumeric characters.

prototype drawing: A master drawing or template that includes preset computer defaults so that it can be reused in other applications.

radial extrusion: A 3D technique for projecting 2D into 3D shapes along a circular path.

spline: A flexible curve that can be drawn to connect a series of points in a smooth shape.

STL: An abbreviation for Solid Transfer Language, files created by a CAD system for use in rapid prototyping (RP).

tangent: A line in contact with the circumference of a circle that is at right angles to a line drawn between the contact point and the center of the circle.

NEW PROCESSES EXPAND CHOICES FOR RAPID PROTOTYPING

New concepts in rapid prototyping (RP) have made it possible to build many different kinds of 3D prototype models faster and cheaper than by traditional methods. The 3D models are fashioned automatically from such materials as plastic or paper, and they can be full size or scaled-down versions of larger objects. Rapid-prototyping techniques make use of computer programs derived from computer-aided design (CAD) drawings of the object. The completed models, like those made by machines and manual wood carving, make it easier for people to visualize a new or redesigned product. They can be passed around a conference table and will be especially valuable during discussions among product design team members, manufacturing managers, prospective suppliers, and customers.

At least nine different RP techniques are now available commercially, and others are still in the development stage. Rapid prototyping models can be made by the owners of proprietary equipment, or the work can be contracted out to various RP centers, some of which are owned by the RP equipment manufacturers. The selection of the most appropriate RP method for any given modeling application usually depends on the urgency of the design project, the relative costs of each RP process, and the anticipated time and cost savings RP will offer over conventional model-making practice. New and improved RP methods are being introduced regularly, so the RP field is in a state of change, expanding the range of designer choices.

Three-dimensional models can be made accurately enough by RP methods to evaluate the design process and eliminate interference fits or dimensioning errors before production tooling is ordered. If design flaws or omissions are discovered, changes can be made in the source CAD program and a replacement model can be produced quickly to verify that the corrections or improvements have been made. Finished models are useful in evaluations of the form, fit, and function of the product design and for organizing the necessary tooling, manufacturing, or even casting processes.

Most of the RP technologies are additive; that is, the model is made automatically by building up contoured laminations sequentially from materials such as photopolymers, extruded or beaded plastic, and even paper until they reach the desired height. These processes can be used to form internal cavities, overhangs, and complex convoluted geometries as well as simple planar or curved shapes. By contrast, a subtractive RP process involves milling the model from a block of soft material, typically plastic or aluminum, on a computer-controlled milling machine with commands from a CAD-derived program.

In the additive RP processes, photopolymer systems are based on successively depositing thin layers of a liquid resin, which are then solidified by exposure to a specific wavelengths of light. Thermoplastic systems are based on procedures for successively melting and fusing solid filaments or beads of wax or plastic in layers, which harden in the air to form the finished object. Some systems form layers by applying adhesives or binders to materials such as paper, plastic powder, or coated ceramic beads to bond them.

The first commercial RP process introduced was *stereolithography* in 1987, followed by a succession of others. Most of the commercial RP processes are now available in Europe and Japan as well as the United States. They have become multinational businesses through branch offices, affiliates, and franchises.

Each of the RP processes focuses on specific market segments, taking into account their requirements for model size, durability, fabrication speed, and finish in the light of anticipated economic benefits and cost. Some processes are not effective in making large models, and each process results in a model with a different finish. This introduces an economic tradeoff of higher price for smoother surfaces versus additional cost and labor of manual or machine finishing by sanding or polishing.

Rapid prototyping is now also seen as an integral part of the even larger but not well defined rapid tooling (RT) market. Concept modeling addresses the early stages of the design process, whereas RT concentrates on production tooling or mold making.

Some concept modeling equipment, also called 3D or office printers, are self-contained desktop or benchtop manufacturing units small enough and inexpensive enough to permit prototype fabrication to be done in an office environment. These units include provision for the containment or venting of any smoke or noxious chemical vapors that will be released during the model's fabrication.

Computer-Aided Design Preparation

The RP process begins when the object is drawn on the screen of a CAD workstation or personal computer to provide the digital data base. Then, in a post-design data processing step, computer software slices the object mathematically into a finite number of horizontal layers in generating an STL (Solid Transfer Language) file. The thickness of the "slices" can range from 0.0025 to 0.5 in. (0.06 to 13 mm) depending on the RP process selected. The STL file is then converted to a file that is compatible with the specific 3D "printer" or processor that will construct the model.

The digitized data then guides a laser, X-Y table, optics, or other apparatus that actually builds the model in a process comparable to building a high-rise building one story at a time. Slice thickness might have to be modified in some RP processes during model building to compensate for material shrinkage.

Prototyping Choices

All of the commercial RP methods depend on computers, but four of them depend on laser beams to cut or fuse each lamination, or provide enough heat to sinter or melt certain kinds of materials. The four processes that make use of lasers are Directed-Light Fabrication (DLF), Laminated-Object Manufacturing (LOM), Selective Laser Sintering (SLS), and Stereolithography (SL); the five processes that do not require lasers are Ballistic Particle Manufacturing (BPM), Direct-Shell Production Casting (DSPC), Fused-Deposition Modeling (FDM), Solid-Ground Curing (SGC), and 3D Printing (3DP).

Stereolithography (SL)

The stereolithographic (SL) process is performed on the equipment shown in Fig. 1. The movable platform on which the 3D model is formed is initially immersed in a vat of liquid photopolymer resin to a level just below its surface so that a thin layer of the resin covers it. The SL equipment is located in a sealed chamber to prevent the escape of fumes from the resin vat.

The resin changes from a liquid to a solid when exposed to the ultraviolet (UV) light from a low-power, highly focused laser. The UV laser beam is focused on an X-Y mirror in a computer-controlled beam-shaping and scanning system so that it draws the outline of the lowest cross-section layer of the object being built on the film of photopolymer resin.

After the first layer is completely traced, the laser is then directed to scan the traced areas of resin to solidify the model's first cross section. The laser beam can harden the layer down to a depth of 0.0025 to 0.0300 in. (0.06 to 0.8 mm). The laser beam scans at speeds up to 350 in./s (890 cm/s). The photopolymer not scanned by the laser beam remains a liquid. In general, the thinner the resin film (slice thickness), the higher the resolution or more refined the finish of the completed model. When model surface finish is important, layer thicknesses are set for 0.0050 in. (0.13 mm) or less.

The table is then submerged under computer control to the specified depth so that the next layer of liquid polymer flows over the first hardened layer. The tracing, hardening, and recoating steps are repeated, layer-by-layer, until the complete 3D model is built on the platform within the resin vat.

Because the photopolymer used in the SL process tends to curl or sag as it cures, models with overhangs or unsupported horizontal sections must be reinforced with supporting structures: walls, gussets, or columns. Without support, parts of the model can sag or break off before the polymer has fully set. Provision for forming these supports is included in the digitized fabrication data. Each scan of the laser forms support layers where necessary while forming the layers of the model.

When model fabrication is complete, it is raised from the polymer vat and resin is allowed to drain off; any excess can be removed manually from the model's surfaces. The SL process leaves the model only partially polymerized, with only about half of its fully cured strength. The model is then finally cured by exposing it to intense UV light in the enclosed chamber of post-curing apparatus (PCA). The UV completes the hardening or curing of the liquid polymer by linking its molecules in chainlike formations. As a final step, any supports that were required are removed, and the model's surfaces are sanded or polished. Polymers such as urethane acrylate resins can be milled, drilled, bored, and tapped, and their outer surfaces can be polished, painted, or coated with sprayed-on metal.

The liquid SL photopolymers are similar to the photosensitive UV-curable polymers used to form masks on semiconductor wafers for etching and plating features on integrated circuits. Resins can be formulated to solidify under either UV or visible light.

The SL process was the first to gain commercial acceptance, and it still accounts for the largest base of installed RP systems. 3D Systems of Valencia, California, is a company that manufactures stereolithography equipment for its proprietary SLA process. It offers the *ThermoJet Solid Object Printer*. The SLA process can build a model within a volume measuring 10 × 7.5 × 8 in. (25 × 19 × 20 cm). It also offers the SLA 7000 system, which can form objects within a volume of 20 × 20 × 23.62 in. (51 × 51 × 60 cm). Aaroflex, Inc. of Fairfax, Virginia, manufactures the Aacura 22 solid-state SL system and operates AIM, an RP manufacturing service.

Solid Ground Curing (SGC)

Solid ground curing (SGC) (or the "solider process") is a multistep in-line process that is diagrammed in Fig. 2. It begins when a photomask for the first layer of the 3D model is generated by the equipment shown at the far left. An electron gun writes a charge pattern of the photomask on a clear glass plate, and opaque toner is transferred electrostatically to the plate to form the photolithographic pattern in a xerographic process. The photomask is then moved to the exposure station, where it is aligned over a work platform and under a collimated UV lamp.

Model building begins when the work platform is moved to the right to a resin application station where a thin layer of photopolymer resin is applied to the top surface of the work platform and wiped to the desired thickness. The platform is then moved left to the exposure station, where the UV lamp is then turned on and a shutter is opened for a few seconds to expose the resin layer to the mask pattern. Because the UV light is so intense,

Fig. 1 Stereolithography (SL): A computer-controlled neon–helium ultraviolet light (UV)–emitting laser outlines each layer of a 3D model in a thin liquid film of UV-curable photopolymer on a platform submerged a vat of the resin. The laser then scans the outlined area to solidify the layer, or "slice." The platform is then lowered into the liquid to a depth equal to layer thickness, and the process is repeated for each layer until the 3D model is complete. Photopolymer not exposed to UV remains liquid. The model is them removed for finishing.

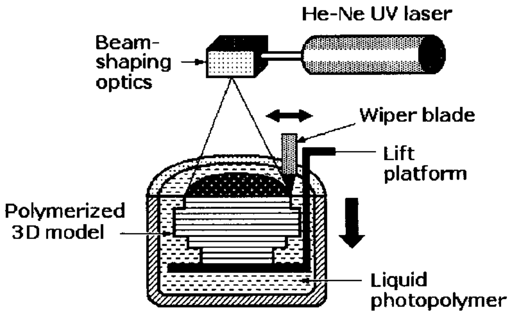
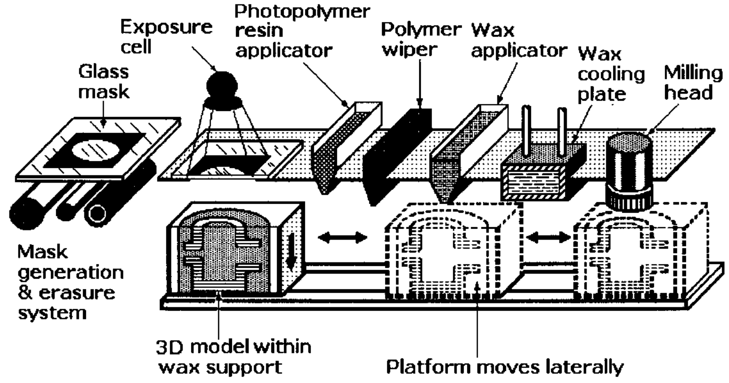


Fig. 2 Solid Ground Curing (SGC): First, a photomask is generated on a glass plate by a xerographic process. Liquid photopolymer is applied to the work platform to form a layer, and the platform is moved under the photomask and a strong UV source that defines and hardens the layer. The platform then moves to a station for excess polymer removal before wax is applied over the hardened layer to fill in margins and spaces. After the wax is cooled, excess polymer and wax are milled off to form the first "slice." The first photomask is erased, and a second mask is formed on the same glass plate. Masking and layer formation are repeated with the platform being lowered and moved back and forth under the stations until the 3D model is complete. The wax is then removed by heating or immersion in a hot water bath to release the prototype.



the layer is fully cured and no secondary curing is needed.

The platform is then moved back to the right to the wiper station, where all of resin that was not exposed to UV is removed and discarded. The platform then moves right again to the wax application station, where melted wax is applied and spread into the cavities left by the removal of the uncured resin. The wax is hardened at the next station by pressing it against a cooling plate. After that, the platform is moved right again to the milling station, where the resin and wax layer are milled to a precise thickness. The platform piece is then returned to the resin application station, where it is lowered a depth equal to the thickness of the next layer and more resin is applied.

Meanwhile, the opaque toner has been removed from the glass mask and a new mask for the next layer is generated on the same plate. The complete cycle is repeated, and this will continue until the 3D model encased in the wax matrix is completed. This matrix supports any overhangs or undercuts, so extra support structures are not needed.

After the prototype is removed from the process equipment, the wax is either melted away or dissolved in a washing chamber similar to a dishwasher. The surface of the 3D model is then sanded or polished by other methods.

The SGC process is similar to *drop on demand inkjet plotting*, a method that relies on a dual inkjet subsystem that travels on a precision X-Y drive carriage and deposits both thermoplastic and wax materials onto the build platform under CAD program control. The drive carriage also energizes a flatbed milling subsystem for obtaining the precise vertical height of each layer and the overall object by milling off the excess material.

Cubital America Inc., Troy, Michigan, offers the *Solider 4600/5600* equipment for building prototypes with the SGC process.

Selective Laser Sintering (SLS)

Selective laser sintering (SLS) is another RP process similar to stereolithography (SL). It creates 3D models from plastic, metal, or ceramic powders with heat generated by a carbon dioxide infrared (IR)–emitting laser, as shown in Fig. 3. The prototype is fabricated in a cylinder with a piston, which acts as a moving platform, and it is positioned next to a cylinder filled with preheated powder. A piston within the powder delivery system rises to eject powder, which is spread by a roller over the top of the build cylinder. Just before it is applied, the powder is heated further until its temperature is just below its melting point

When the laser beam scans the thin layer of powder under the control of the optical scanner system, it raises the temperature of the powder even further until it melts or sinters and flows together to form a solid layer in a pattern obtained from the CAD data.

As in other RP processes, the piston or supporting platform is lowered upon completion of each layer and the roller spreads the next layer of powder over the previously deposited layer. The process is repeated, with each layer being fused to the underlying layer, until the 3D prototype is completed.

The unsintered powder is brushed away and the part removed. No final curing is required, but because the objects are sintered they are porous. Wax, for example, can be applied to the inner and outer porous surfaces, and it can be smoothed by various manual or machine grinding or melting processes. No supports are required in SLS because overhangs and undercuts are supported by the compressed unfused powder within the build cylinder.

Many different powdered materials have been used in the SLS process, including polycarbonate, nylon, and investment casting wax. Polymer-coated metal powder is also being studied as an alternative. One advantage of the SLS process is that materials such as polycarbonate and nylon are strong and stable enough to permit the model to be used in limited functional and environmental testing. The prototypes can also serve as molds or patterns for casting parts.

SLS process equipment is enclosed in a nitrogen-filled chamber that is sealed and maintained at a temperature just below the melting point of the powder. The nitrogen prevents an explosion that could be caused by the rapid oxidation of the powder.

The SLS process was developed at the University of Texas at Austin, and it has been licensed by the DTM Corporation of Austin, Texas. The company makes a *Sinterstation 2500plus*. Another company participating in SLS is EOS GmbH of Germany.

Laminated-Object Manufacturing (LOM)

The Laminated-Object Manufacturing (LOM) process, diagrammed in Fig. 4, forms 3D models by cutting, stacking, and bonding successive layers of paper coated with heat-activated adhesive. The carbon-dioxide laser beam, directed by an optical system under CAD data control, cuts cross-sectional outlines of the prototype in the layers of paper, which are bonded to previous layers to become the prototype.

The paper that forms the bottom layer is unwound from a supply roll and pulled across the movable platform. The laser beam cuts the outline of each lamination and cross-hatches the waste material within and around the lamination to make it easier to remove after the prototype is completed. The outer waste material web from each lamination is continuously removed by a take-up roll. Finally, a heated roller applies pressure to bond the adhesive coating on each layer cut from the paper to the previous layer.

A new layer of paper is then pulled from a roll into position over the previous layer, and the cutting, cross hatching, web removal, and bonding procedure is repeated until the model is completed.

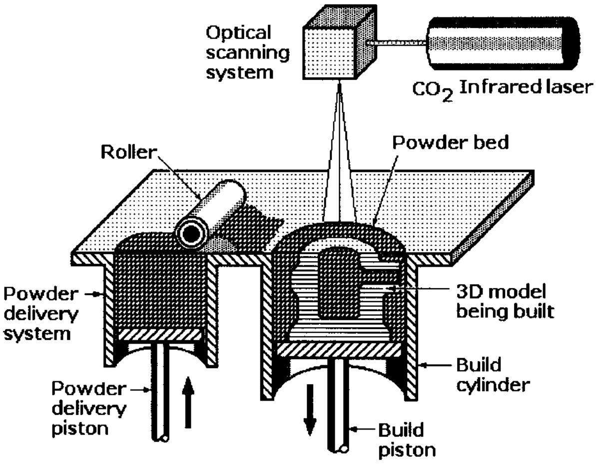


Fig. 3 Selective Laser Sintering (SLS): Loose plastic powder from a reservoir is distributed by roller over the surface of piston in a build cylinder positioned at a depth below the table equal to the thickness of a single layer. The powder layer is then scanned by a computer-controlled carbon dioxide infrared laser that defines the layer and melts the powder to solidify it. The cylinder is again lowered, more powder is added, and the process is repeated so that each new layer bonds to the previous one until the 3D model is completed. It is then removed and finished. All unbonded plastic powder can be reused.

When all the layers have been cut and bonded, the excess cross-hatched material in the form of stacked segments is removed to reveal the finished 3D model. The models made by the LOM have woodlike finishes that can be sanded or polished before being sealed and painted.

Using inexpensive, solid-sheet materials makes the 3D LOM models more resistant to deformity and less expensive to produce than models made by other processes, its developers say. These models can be used directly as patterns for investment and sand casting, and as forms for silicone molds. The objects made by LOM can be larger than those made by most other RP processes—up to 30 × 20 × 20 in. (75 × 50 × 50 cm).

The LOM process is limited by the ability of the laser to cut through the generally thicker lamination materials and the additional work that must be done to seal and finish the model's inner and outer surfaces. Moreover, the laser cutting process burns the paper, forming smoke that must be removed from the equipment and room where the LOM process is performed.

Helysys Corporation, Torrance, California, manufactures the LOM-2030H LOM equipment. Alternatives to paper including sheet plastic and ceramic and metal-powder-coated tapes have been developed.

Other companies offering equipment for building prototypes from paper laminations are the Schroff Development Corporation, Mission, Kansas, and CAM-LEM, Inc. Schroff manufactures the *JP System 5* to permit desktop rapid prototyping.

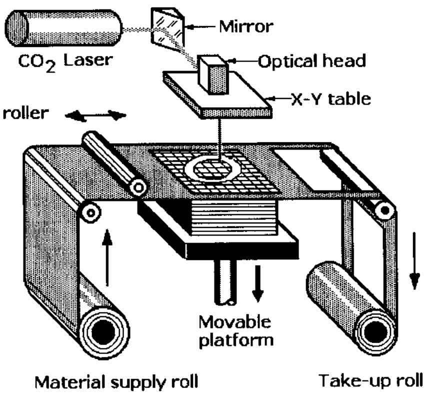


Fig. 4 Laminated Object Manufacturing (LOM): Adhesive-backed paper is fed across an elevator platform and a computer-controlled carbon dioxide infrared-emitting laser cuts the outline of a layer of the 3D model and cross-hatches the unused paper. As more paper is fed across the first layer, the laser cuts the outline and a heated roller bonds the adhesive of the second layer to the first layer. When all the layers have been cut and bonded, the cross-hatched material is removed to expose the finished model. The complete model can then be sealed and finished.

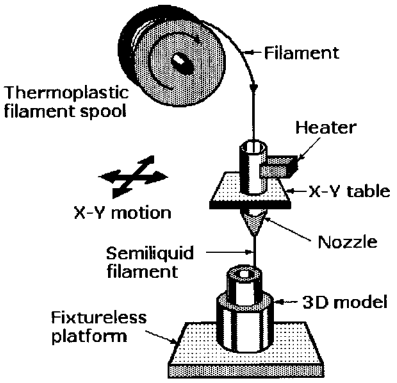


Fig. 5 Fused Deposition Modeling (FDM): Filaments of thermoplastic are unwound from a spool, passed through a heated extrusion nozzle mounted on a computer-controlled X-Y table, and deposited on the fixtureless platform. The 3D model is formed as the nozzle extruding the heated filament is moved over the platform. The hot filament bonds to the layer below it and hardens. This laserless process can be used to form thin-walled, contoured objects for use as concept models or molds for investment casting. The completed object is removed and smoothed to improve its finish.

Fused Deposition Modeling (FDM)

The Fused Deposition Modeling (FDM) process, diagrammed in Fig. 5, forms prototypes from melted thermoplastic filament. This filament, with a diameter of 0.070 in. (1.78 mm), is fed into a temperature-controlled FDM extrusion head where it is heated to a semi-liquid state. It is then extruded and deposited in ultrathin, precise layers on a fixtureless platform under X-Y computer control. Successive laminations ranging in thickness from 0.002 to 0.030 in. (0.05 to 0.76 mm) with wall thicknesses of 0.010 to 0.125 in. (0.25 to 3.1 mm) adhere to each by thermal fusion to form the 3D model.

Structures needed to support overhanging or fragile structures in FDM modeling must be designed into the CAD data file and fabricated as part of the model. These supports can easily be removed in a later secondary operation.

All components of FDM systems are contained within temperature-controlled enclosures. Four different kinds of inert, nontoxic filament materials are being used in FDM: ABS polymer (acrylonitrile butadiene styrene), high-impact-strength ABS (ABSi), investment casting wax, and elastomer. These materials melt at temperatures between 180 and 220°F (82 and 104°C).

FDM is a proprietary process developed by Stratasys, Eden Prairie, Minnesota. The company offers four different systems. Its *Genisys* benchtop 3D printer has a build volume as large as 8 × 8 × 8 in. (20 × 20 × 20 cm), and it prints models from square polyester wafers that are stacked in cassettes. The material is heated and extruded through a 0.01-in. (0.25-mm)–diameter hole at a controlled rate. The models are built on a metallic substrate that rests on a table. Stratasys also offers four systems that use spooled material. The *FDM2000*, another benchtop system, builds parts up to 10 in^3 (164 cm^3) while the *FDM3000*, a floor-standing system, builds parts up to 10 × 10 × 16 in. (26 × 26 × 41 cm).

Two other floor-standing systems are the *FDM 8000*, which builds models up to 18 × 18 × 24 in. (46 × 46 × 61 cm), and the *FDM Quantum* system, which builds models up to 24 × 20 × 24 in. (61 × 51 × 61 cm). All of these systems can be used in an office environment.

Stratasys offers two options for forming and removing supports: a breakaway support system and a water-soluble support system. The water-soluble supports are formed by a separate extrusion head, and they can be washed away after the model is complete.

Three-Dimensional Printing (3DP)

The Three-Dimensional Printing (3DP) or inkjet printing process, diagrammed in Fig. 6, is similar to Selective Laser Sintering (SLS) except that a multichannel inkjet head and liquid adhesive supply replaces the laser. The powder supply cylinder is filled with starch and cellulose powder, which is delivered to the work platform by elevating a delivery piston. A roller rolls a single layer of powder from the powder cylinder to the upper surface of a piston within a build cylinder. A multichannel inkjet head sprays a water-based liquid adhesive onto the surface of the powder to bond it in the shape of a horizontal layer of the model.

In successive steps, the build piston is lowered a distance equal to the thickness of one layer while the powder delivery piston pushes up fresh powder, which the roller spreads over the previous layer on the build piston. This process is repeated until the 3D model is complete. Any loose excess powder is brushed away, and wax is coated on the inner and outer surfaces of the model to improve its strength.

The 3DP process was developed at the Three-Dimensional Printing Laboratory at the Massachusetts Institute of Technology, and it has been licensed to several companies. One of those firms, the Z Corporation of Somerville, Massachusetts, uses the original MIT process to form 3D models. It also offers the *Z402* 3D modeler. Soligen Technologies has modified the 3DP process to make ceramic molds for investment casting. Other companies are using the process to manufacture implantable drugs, make metal tools, and manufacture ceramic filters.

Direct-Shell Production Casting (DSPC)

The Direct Shell Production Casting (DSPC) process, diagrammed in Fig. 7, is similar to the 3DP process except that it is focused on forming molds or shells rather than 3D models. Consequently, the actual 3D model or prototype must be produced by a later casting process. As in the 3DP process, DSPC begins with a CAD file of the desired prototype.

Two specialized kinds of equipment are needed for DSPC: a dedicated computer called a shell-design unit (SDU) and a shell- or mold-processing unit (SPU). The CAD file is loaded into the SDU to generate the data needed to define the mold. SDU software also modifies the original design dimensions in the CAD file to compensate for ceramic shrinkage. This software can also add fillets and delete such features as holes or keyways that must be machined after the prototype is cast.

The movable platform in DSPC is the piston within the build cylinder. It is lowered to a depth below the rim of the build cylinder equal to the thickness of each layer. Then a thin layer of fine aluminum oxide (alumina) powder is spread by roller over the platform, and a fine jet of colloidal silica is sprayed precisely onto the powder surface to bond it in the shape of a single mold layer. The piston is then lowered for the next layer and the complete process is repeated until all layers have been formed, completing the entire 3D shell. The excess powder is then removed, and the mold is fired to convert the bonded powder to monolithic ceramic.

After the mold has cooled, it is strong enough to withstand molten metal and can function like a conventional investment-casting mold. After the molten metal has cooled, the ceramic shell and any cores or gating are broken away from the prototype. The casting can then be finished by any of the methods usually used on metal castings.

DSPC is a proprietary process of Soligen Technologies, Northridge, California. The company also offers a custom mold manufacturing service.

Ballistic Particle Manufacturing (BPM)

There are several different names for the Ballistic Particle Manufacturing (BPM) process, diagrammed in Fig. 8.

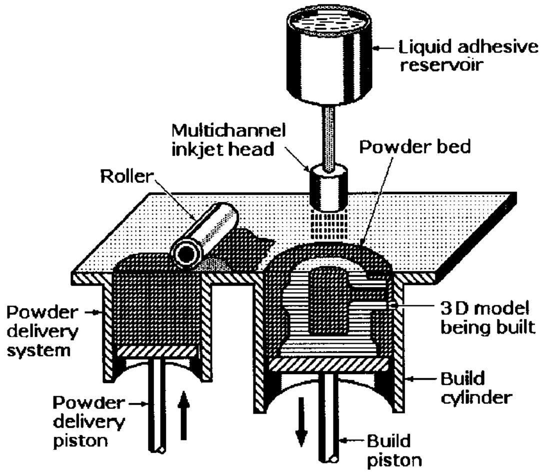


Fig. 6 Three-Dimensional Printing (3DP): Plastic powder from a reservoir is spread across a work surface by roller onto a piston of the build cylinder recessed below a table to a depth equal to one layer thickness in the 3DP process. Liquid adhesive is then sprayed on the powder to form the contours of the layer. The piston is lowered again, another layer of powder is applied, and more adhesive is sprayed, bonding that layer to the previous one. This procedure is repeated until the 3D model is complete. It is then removed and finished.

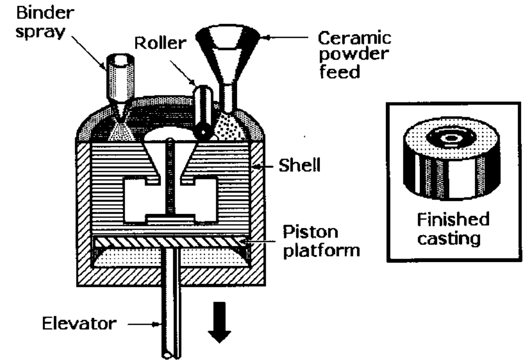


Fig. 7 Direct Shell Production Casting (DSPC): Ceramic molds rather than 3D models are made by DSPC in a layering process similar to other RP methods. Ceramic powder is spread by roller over the surface of a movable piston that is recessed to the depth of a single layer. Then a binder is sprayed on the ceramic powder under computer control. The next layer is bonded to the first by the binder. When all of the layers are complete, the bonded ceramic shell is removed and fired to form a durable mold suitable for use in metal casting. The mold can be used to cast a prototype. The DSPC process is considered to be an RP method because it can make molds faster and cheaper than conventional methods.

Variations of it are also called *inkjet methods*. The molten plastic used to form the model and the hot wax for supporting overhangs or indentations are kept in heated tanks above the build station and delivered to computer-controlled jet heads through thermally insulated tubing. The jet heads squirt tiny droplets of the materials on the work platform as it is moved by an X-Y table in the pattern needed to form each layer of the 3D object. The droplets are deposited only where directed, and they harden rapidly as they leave the jet heads. A milling cutter is passed over the layer to mill it to a uniform thickness. Particles that are removed by the cutter are vacuumed away and deposited in a collector.

Nozzle operation is monitored carefully by a separate fault-detection system. After each layer has been deposited, a stripe of each material is deposited on a narrow strip of paper for thickness measurement by optical detectors. If the layer meets specifications, the work platform is lowered a distance equal to the required layer thickness and the next layer is deposited. However, if a clot is detected in either nozzle, a jet cleaning cycle is initiated to clear it. Then the faulty layer is milled off and that layer is redeposited. After the 3D model is completed, the wax material is either melted from the object by radiant heat or dissolved away in a hot water wash.

The BPM system is capable of producing objects with fine finishes, but the process is slow. With this RP method, a slower process that yields a 3D model with a superior finish is traded off against faster processes that require later manual finishing.

The version of the BPM system shown in Fig. 8 is called *Drop on Demand Inkjet Plotting* by Sanders Prototype Inc, Merrimac, New Hampshire. It offers the *ModelMaker II* processing equipment, which produces 3D models with this method. AeroMet Corporation builds titanium parts directly from CAD renderings by fusing titanium powder with an 18-kW carbon dioxide laser, and 3D Systems of Valencia, California, produces a line of inkjet printers that feature multiple jets to speed up the modeling process.

Directed Light Fabrication (DLF)

The Directed Light Fabrication (DLF) process, diagrammed in Fig. 9, uses a neodymium YAG (Nd:YAG) laser to fuse powdered metals to build 3D models that are more durable than models made from paper or plastics. The metal powders can be finely milled 300 and 400 series stainless steel, tungsten, nickel aluminides, molybdenum disilicide, copper, and aluminum. The technique is also called *Direct-Metal Fusing*, *Laser Sintering,* and *Laser Engineered Net Shaping (LENS).*

The laser beam under X-Y computer control fuses the metal powder fed from a nozzle to form dense 3D objects whose dimensions are said to be within a few thousandths of an inch of the desired design tolerance.

DLF is an outgrowth of nuclear weapons research at the Los Alamos National Laboratory (LANL), Los Alamos, New Mexico, and it is still in the development stage. The laboratory has been experimenting with the laser fusing of ceramic powders to fabricate parts as an alternative to the use of metal powders. A system that would regulate and mix metal powder to modify the properties of the prototype is also being investigated.

Optomec Design Company, Albuquerque, New Mexico, has announced that direct fusing of metal powder by laser in its LENS process is being performed commercially. Protypes made by this method have proven to be durable and they have shown close dimensional tolerances.

Research and Development in RP

Many different RP techniques are still in the experimental stage and have not yet achieved commercial status. At the same time, practical commercial processes have been improved. Information about this research has been announced by the laboratories doing the work, and some of the research is described in patents. This discussion is limited to two techniques, SDM and Mold SDM, that have shown commercial promise.

Shape Deposition Manufacturing (SDM)

The Shape Deposition Manufacturing (SDM) process, developed at the SDM Laboratory of Carnegie Mellon University, Pittsburgh, Pennsylvania, produces functional metal prototypes directly from CAD data. This process, diagrammed in Fig. 10, forms successive layers of metal on a platform without masking, and is also called *solid free-form* (SFF) fabrication. It uses hard met-

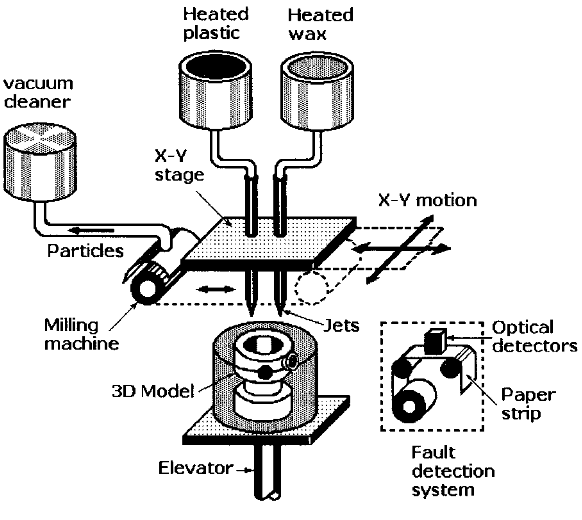


Fig. 8 Ballistic Particle Manufacturing (BPM): Heated plastic and wax are deposited on a movable work platform by a computer-controlled X-Y table to form each layer. After each layer is deposited, it is milled to a precise thickness. The platform is lowered and the next layer is applied. This procedure is repeated until the 3D model is completed. A fault detection system determines the quality and thickness of the wax and plastic layers and directs rework if a fault is found. The supporting wax is removed from the 3D model by heating or immersion in a hot liquid bath.

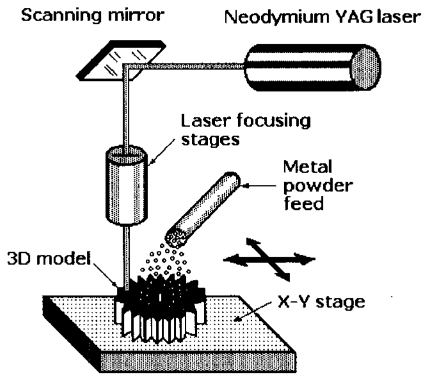


Fig. 9 Directed Light Fabrication (DLF): Fine metal powder is distributed on an X-Y work platform that is rotated under computer control beneath the beam of a neodymium YAG laser. The heat from the laser beam melts the metal powder to form thin layers of a 3D model or prototype. By repeating this process, the layers are built up and bonded to the previous layers to form more durable 3D objects than can be made from plastic. Powdered aluminum, copper, stainless steel, and other metals have been fused to make prototypes as well as practical tools or parts that are furnace-fired to increase their bond strength.

als to form more rugged prototypes that are then accurately machined under computer control during the process.

The first steps in manufacturing a part by SDM are to reorganize or destructure the CAD data into slices or layers of optimum thickness that will maintain the correct 3D contours of the outer surfaces of the part and then decide on the sequence for depositing the primary and supporting materials to build the object.

The primary metal for the first layer is deposited by a process called *microcasting* at the deposition station, Fig. 10(a). The work is then moved to a machining station (b), where a computer-controlled milling machine or grinder removes deposited metal to shape the first layer of the part. Next, the work is moved to a stress-relief station (c), where it is shot-peened to relieve stresses that have built up in the layer. The work is then transferred back to the deposition station (a) for simultaneous deposition of primary metal for the next layer and sacrificial support metal. The support material protects the part layers from the deposition steps that follow, stabilizes the layer for further machining operations, and provides a flat surface for milling the next layer. This SDM cycle is repeated until the part is finished, and then the sacrificial metal is etched away with acid. One combination of metals that has been successful in SDM is stainless steel for forming the prototype and copper for forming the support structure

The SDM Laboratory investigated many thermal techniques for depositing high-quality metals, including thermal spraying and plasma or laser welding, before it decided on microcasting, a compromise between these two techniques that provided better results than either technique by itself. The metal droplets in microcasting are large enough (1 to 3 mm in diameter) to retain their heat longer than the 50-µm droplets formed by conventional thermal spraying. The larger droplets remain molten and retain their heat long enough so that when they impact the metal surfaces they remelt them to form a strong metallurgical interlayer bond. This process overcame the low adhesion and low mechanical strength problems encountered with conventional thermal metal spraying. Weld-based deposition easily remelted the substrate material to form metallurgical bonds, but the larger amount of heat transferred tended to warp the substrate or delaminate it.

The SDM laboratory has produced custom-made functional mechanical parts and has embedded prefabricated mechanical parts, electronic components, electronic circuits, and sensors in the metal layers during the SDM process. It has also made custom tools such as injection molds with internal cooling pipes and metal heat sinks with embedded copper pipes for heat redistribution.

Mold SDM

The Rapid Prototyping Laboratory at Stanford University, Palo Alto, California, has developed its own version of SDM, called Mold SDM, for building layered molds for casting ceramics and polymers. Mold SDM, as diagrammed in Fig. 11, uses wax to form the molds. The wax occupies the same position as the sacrificial support metal in SDM, and water-soluble photopolymer sacrificial support material occupies and supports the mold cavity. The photopolymer corresponds to the primary metal deposited to form the finished part in SDM. No machining is performed in this process.

The first step in the Mold SDM process begins with the decomposition of CAD mold data into layers of optimum thickness, which depends on the complexity and contours of the mold. The actual processing begins at Fig. 11(a), which shows the results of repetitive cycles of the deposition of wax for the mold and sacrificial photopolymer in each layer to occupy the mold cavity and support it. The polymer is hardened by an ultraviolet (UV) source. After the mold and support structures are built up, the work is moved to a station (b) where the photopolymer is removed by dissolving it in water. This exposes the wax mold cavity into which the final part material is cast. It can be any compatible castable material. For example, ceramic parts can be formed by pouring a gelcasting ceramic slurry into the wax mold (c) and then curing the slurry. The wax mold is then removed (d) by melting it, releasing the "green" ceramic part for furnace firing. In step (e), after firing, the vents and sprues are removed as the final step.

Mold SDM has been expanded into making parts from a variety of polymer materials, and it has also been used to make preassembled mechanisms, both in polymer and ceramic materials.

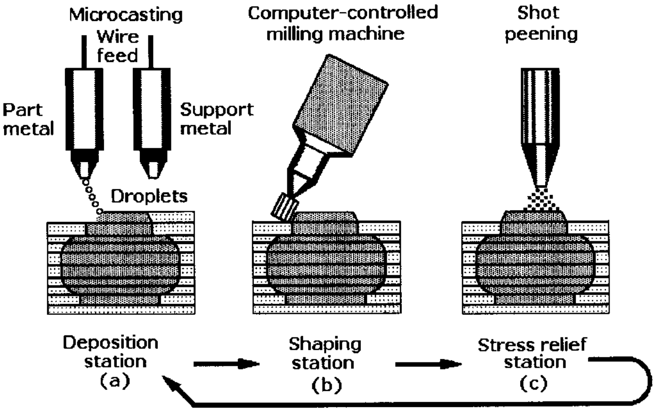


Fig. 10 Shape Deposition Manufacturing (SDM): Functional metal parts or tools can be formed in layers by repeating three basic steps repetitively until the part is completed. Hot metal droplets of both primary and sacrificial support material form layers by a thermal metal spraying technique (a). They retain their heat long enough to remelt the underlying metal on impact to form strong metallurgical interlayer bonds. Each layer is machined under computer control (b) and shot-peened (c) to relieve stress buildup before the work is returned for deposition of the next layer. The sacrificial metal supports any undercut features. When deposition of all layers is complete, the sacrificial metal is removed by acid etching to release the completed part.

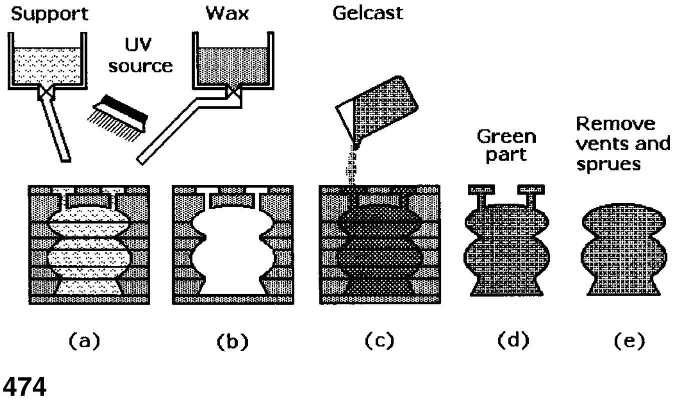


Fig. 11 Mold Shape Deposition Manufacturing (MSDM): Casting molds can be formed in successive layers: Wax for the mold and water-soluble photopolymer to support the cavity are deposited in a repetitive cycle to build the mold in layers whose thickness and number depend on the mold's shape (a). UV energy solidifies the photopolymer. The photopolymer support material is removed by soaking it in hot water (b). Materials such as polymers and ceramics can be cast in the wax mold. For ceramic parts, a gelcasting ceramic slurry is poured into the mold to form green ceramic parts, which are then cured (c). The wax mold is then removed by heat or a hot liquid bath and the green ceramic part released (d). After furnace firing (e) any vents and sprues are removed.

MICROMACHINES OPEN A NEW FRONTIER FOR MACHINE DESIGN

A new technology for fabricating microminiature motors, valves, and transducers is a spinoff of the microcircuit fabrication technology that made microprocessors and semiconductor memories possible. This technology has opened the new field of microelectromechanical systems (MEMS) in machine design. These microscopic-scale machines require their own unique design rules, tools, processes, and materials.

These microminiature machines might not be familiar to traditional machine designers because their manufacture calls for photolithographic and chemical-etching processes rather than better-known casting, welding, milling, drilling, and lathe turning.

Nevertheless, even when made at a scale so small that they are best seen under an electronic microscope, the laws of physics, mechanics, electricity, and chemistry still apply to these micromachines. MEMS are moving machine and mechanism design down to dimensions measurable in atomic units. Until a few years ago, those dimensions were strictly the province of microbiologists, atomic physicists, and microcircuit designers.

Among the more remarkable examples of MEMS are a miniscule electric vehicle that can be parked on a pinhead, electric motors so small that they can easily fit inside the eye of a needle, and pumps and gear trains the size of grains of salt. Far from novelties that only demonstrate the feasibility of a technology, many are now being produced for automotive applications, and many more are being used in science and medicine.

The products now being routinely micromachined in quantity for the automotive industry are limited to microminiature pressures sensors, accelerometers, and fuel injectors. Nevertheless, research and development of microminiature actuators and motors for insertion into human arteries in order to perform certain kinds of delicate surgical procedures is now underway. In addition, other potential uses for them in biomedicine and electronics are now being tested.

The Microactuators

The rotary electrostatic motor shown in Fig. 1 is an outstanding example of a microactuator. The cutaway drawing shows a section view of a typical micromotor that is driven by static electricity. The experimental motors produced so far have diameters of 0.1 to 0.2 mm and they are about 4 to 6 μm high.

The rotor of a well-designed micromotor, driven with an excitation voltage of 30 to 40 V, can achieve speeds that exceed 10,000 rpm. Some of the tiny motors have operated continuously for 150 h. Motors of this kind have been made at the University of California at Berkeley and at the Massachusetts Institute of Technology (MIT).

The rotor shown in Fig. 1 has a “rising sun” geometry. It rests on bushings that minimize frictional contact with the base substrate, and it is free to rotate around a central hub. Slots separate individual commutator sections. Electrostatic forces are introduced by the inner surfaces of the stator and outer surfaces of the rotor, which form a rotating capacitor.

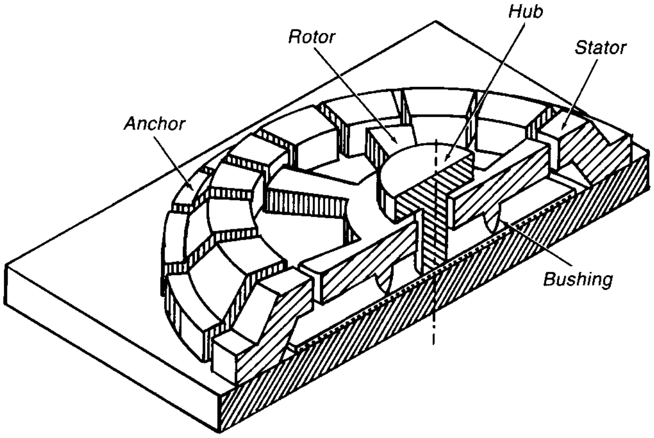


Fig. 1 A cross-section view of a typical micromotor that is driven electrostatically rather than electromagnetically.

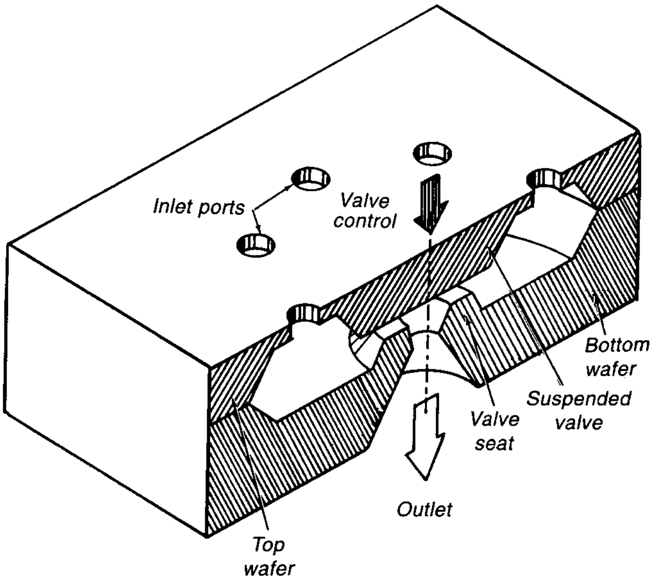


Fig. 2 A cutaway view of a typical microvalve. The diaphragm moves perpendicular to its base substrate. The diaphragms can be moved by an embedded piezoelectric film, by electrostatic forces, or by thermal expansion.

Micropumps and microvalves with deformable diaphragms are other forms of microactuator. Figure 2 is a cutaway view of a typical microvalve. The diaphragms of these devices flex in a direction that is perpendicular to their base substrates. The diaphragms can be moved by an embedded piezoelectric film, electrostatic forces, or thermal expansion. Applications are seen for the microminiature pumps and valves in biomedicine because they are orders of magnitude smaller than conventional biomedical pumps and valves.

Actuators have also been made in the form of vibrating microstructures with flexible suspensions. Figure 3 is a drawing of a linear resonator consisting of two identical folded beams of an interdigital electrostatic "comb" drive. The folded beams are supported by anchors grown on the semiconductor substrate, and the comb drive is supported by a pedestal grown on the same silicon substrate.

The folded beams are dimensioned to have a specific resonant frequency, and they are driven by electrostatic charges placed on the comb-drive digits, which act as capacitors. Both beam structures vibrate simultaneously but only in the X direction because lateral or Y-direction motion is constrained by the geometrics of the folded beams.

Materials

Currently, the most popular material for fabricating all of these micromachines is silicon, the material from which most microcircuit chips and discrete transistors are made. The silicon can be in either of several different forms. However, micromachines have also included parts made of aluminum and diamonds. The successful design and manufacture of billions of integrated circuits over the past 35 years have left an extensive database and body of knowledge about silicon—how to grow it, alter its structure chemically, mill it chemically, and bond slices of it together permanently.

Silicon is a very strong material with a modulus of elasticity that closely matches steel. Its lack of mechanical hysteresis makes it an almost perfect material for fabricating sensors and transducers. Silicon exceeds stainless steel in yield strength and aluminum in strength-to-weight ratio. It also exhibits high thermal conductivity and a low thermal expansion coefficient. Because silicon is sensitive to stress, strain, and temperature, silicon sensors can easily communicate with electronic circuitry for the transmission of electrical signals.

In the fabrication of micromachines, silicon is chemically etched into a wide variety of shapes rather than being machined with traditional cutting tools. Silicon, as well as such associated materials as polysilicon, silicon nitride, and aluminum, can be micromachined in batches into many different shapes and contours. In micromachining, mechanical structures are sculpted from a silicon wafer by selectively etching away sacrificial supporting layers or structures.

The etching process is complemented by such standard integrated circuit processes as photolithography for producing the required masks at the various stages of the process. Diffusion can alter the chemical makeup of the material by introducing "dopants." Epitaxy is a process for growing new material on the basic substrate, and deposition is a process for the "plating" of one type of material on another.

The bulk micromachining process is widely used for fabricating silicon accelerometers, but has also been applied to the fabrication of flow sensors, inkjet nozzles, microvalves, and motors. The etching process can be controlled by dispersing different doping materials within the silicon or by concentrating electrical current in specific regions.

Powering Micromachines

Micromachines can be actuated by the piezoelectric effect, thermal expansion, electrostatic force, or magnetic force. The choice of actuation method is influenced by the nature of the device and its specific application requirements. However, the microscopic dimensions of the devices generally rule out current-induced magnetic forces such as those that drive conventional electric motors and solenoids because those forces are too weak when scaled to the small sizes required to power the devices.

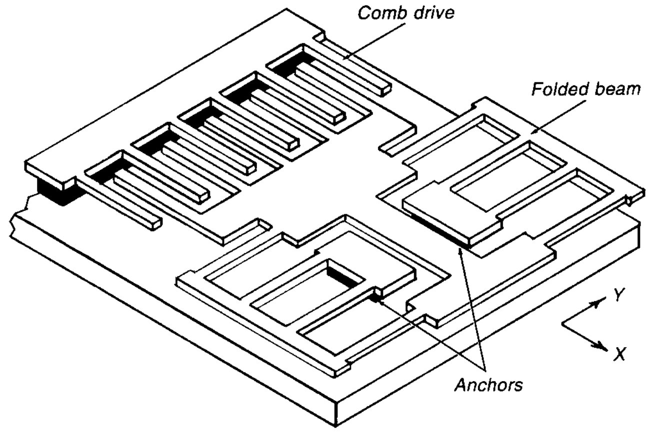


Fig. 3 **This linear resonator** consists of a pair of folded beams that are set in vibrational motion in the X direction by an electrostatically driven comb structure. Lateral or Y-direction motion is restrained by the geometry of the folded beams.

The high power consumption required to concentrate enough heat in a small local area to move parts by the thermal expansion of unlike materials is unacceptable for many applications. Therefore, the two most commonly used microactuation drive methods are the piezoelectric effect and electrostatic force.

Electrostatic Forces

Electrostatic forces are used to drive micromachines because, unlike magnetic forces, induced electrostatic forces can be scaled down favorably with size. Electrostatic force is induced by setting up equivalent parallel-plate capacitors between adjacent mechanical elements. There must be two conductive surfaces that act as opposing capacitor plates. The electrostatic force is directly proportional to the product of the square of the voltage across the plates and plate area, and it is inversely proportional to the square of the distance between the plates.

A surface-micromachined motor is shown in Fig. 1. The end surfaces of the rotor spokes and segmented inner walls of the insulated stator electrodes effectively form capacitors, which are separated by a small air gap. The rotor is the spoked wheel free to rotate around a central post. To drive the motor, the opposing insulated stator segments are energized in a rotating pattern and rotor spokes are attracted to the stator segments as they move into position near the stators to keep the rotor turning, making one revolution for many polarity changes in the stator elements. It can be seen that the spacing between the spokes and stator segments change with respect to time as the rotor turns. As a result, the electrostatic force varies with time or is a nonlinear function of the applied voltage.

Problems can arise if the rotor spokes are not uniform in radius dimensions, the bearing surfaces are not smooth, or the rotor does not rotate concentrically. Any of these mechanical defects could cause the rotor to stick in one position.

The handicap for surface micromachined motors is their small vertical dimensions, making it difficult for them to obtain large enough changes in capacitance when the rotor is in motion. Somewhat larger motors with thicker, taller stators and rotor segments have been made by LIGA techniques to overcome this drawback. (The abbreviation LIGA stands for the German words for lithography, electroplating, and molding-—Lithographie, Galvanoformung, Abformung.)

Another kind of electrostatic actuator, the electrostatic-comb drive shown in Fig. 3, was developed to maximize the capacitance effects in electrostatic micromachines by taking advantage of the classical parallel plate capacitor formula because only attractive forces can be generated.

$$E = \frac{CV^2}{2}$$

Where E is the energy stored,

C is the capacitance, and

V is the voltage across the capacitor.

Surface micromachined comb drives consist of many interdigitated fingers, as shown in Fig. 3. When a voltage is applied, an attractive force is developed between the fingers, which move together. The increase in capacitance is proportional to the number of fingers.

This means that large numbers of fingers are required to generate large forces. Because the direction of motion of the electrostatic comb drive is parallel with the length of the comb-finger electrodes, the effective plate area with respect to spacing between the plates remains constant.

Consequently, capacitance with respect to the direction of motion is linear, and the induced force in the X direction is directly proportional to the square of the voltage applied across the plates. Comb-drive structures have been driven to deflect by as much as one quarter of the comb finger length with DC voltages of 20 to 40 V.

A disadvantage of the comb drive is that if the lateral gaps between the fingers are not equal on the sides or if the fingers are not parallel, it is possible for the fingers to move at right angles to the intended direction of motion and adhere together until the voltage is turned off. They could remain stuck permanently.

Piezoelectric Films

Microminiature transducers have been made in the form of rigid beams and diaphragms with a core of polycrystalline zinc-oxide piezoelectric film. Figure 4 is a diagram of a beam with a central piezoelectric layer of insulated polycrystalline zinc oxide (ZnO) up to several micrometers thick. The layer is then insulated on both sides and sandwiched between two conductive electrodes to form the rigid structure.

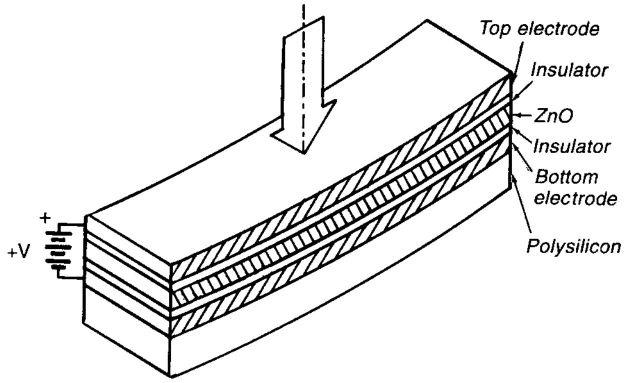


Fig. 4 A microminiature piezoelectric transducer is made as an insulated layer of polycrystalline zinc oxide (ZnO) sandwiched between two conductive electrodes to form a rigid bimetallic structure.

When voltage is applied to the two electrodes, the piezoelectrically induced stress in the ZnO film causes the structure to deflect. The converse of the piezoelectric effect can be obtained in applications where it is desirable to convert the strain on the beam or diaphragm into electrical signals that are proportional to strain.

Bulk Micromachining

The development of micromachines, sensors, and actuators over the past decade has been driven by advancements in silicon microcircuits. Micromachining by the chemical etching of crystalline silicon wafers has been an important fabrication technique. Strong alkalines etch single-crystal silicon at a rate that depends on the crystal orientation, its dopant concentration, and an externally applied electric field.

The etching is controlled by photolithographic etch masks that are applied over silicon which has been coated with a photoresist. The photoresist can be chemically removed from those areas of the silicon that have been exposed to ultraviolet light through the transparent parts of the mask. When the silicon is exposed, it can be etched, plated, or diffused with dopants.

This bulk micromachining process has been combined with methods for fusion-bonding silicon substrates to form precise three-dimensional structures such as micropumps and microvalves. Two or more etched wafers can be bonded by pressing them together and annealing the structure, making the three-dimensional microstructure permanent. This approach permits internal or re-entrant cavities to be formed.

Surface Micromachining

Deposited thin films of such materials as polysilicon, silicon oxide (SiO_2), silicon nitride (Si_3N_4), and phosphosilicate glass (PSG) have been surface micromachined by both dry ionic and wet chemical etching to define those films. Freestanding structures have been formed by the removal of underlying sacrificial layers (typically of SiO_2 or PSG). The film is removed by a highly selective chemical etchant such as hydrofluoric acid after the structure layer, usually polysilicon, is deposited and patterned.

The electrostatic motor shown in Fig. 1 is made by a succession of deposition and masking steps in which alternate layers of permanent silicon material and sacrificial material are deposited until the structure of the motor—stator, rotor, and central hub—is completed. Then the sacrificial material is chemically removed, effectively sculpting the permanent silicon structure so that the rotor is free to move on the hub. At the same time, an electrostatic shield and interconnections are formed.

MULTILEVEL FABRICATION PERMITS MORE COMPLEX AND FUNCTIONAL MEMS

Researchers at Sandia National Laboratories, Albuquerque, New Mexico, have developed two surface micromachining processes for fabricating multilevel MEMS (microelectromechanical systems) from polysilicon that are more complex and functional than those made from two- and three-level processes. The processes are SUMMiT Technology, a four-level process in which one ground or electrical interconnect plane and three mechanical layers can be micromachined, and SUMMiT V Technology, a similar five-level process except that four mechanical layers can be micromachined. Sandia offers this technology under license agreement to qualified commercial IC producers.

According to Sandia researchers, polycrystalline silicon (also called polysilicon or poly) is an ideal material for making the microscopic mechanical systems. It is stronger than steel, with a strength of 2 to 3 GPa (assuming no surface flaws), whereas steel has a strength of 200 MPa to 1 GPa (depending on how it is processed). Also, polysilicon is extremely flexible, with a maximum strain before fracture of approximately 0.5%, and it does not readily fatigue.

Years of experience in working with polysilicon have been gained by commercial manufacturers of large-scale CMOS integrated circuits chips because it is used to form the gate structures of most CMOS transistors. Consequently, MEMS can be produced in large volumes at low cost in IC manufacturing facilities with standard production equipment and tools. The Sandia researchers report that because of these advantages, polysilicon surface micromachining is being pursued by many MEMS fabrication facilities.

The complexity of MEMS devices made from polysilicon is limited by the number of mechanical layers that can be deposited. For example, the simplest actuating comb drives can be made with one ground or electrical plane and one mechanical layer in a two-level process, but a three-level process with two mechanical layers permits micromachining mechanisms such as gears that rotate on hubs or movable optical mirror arrays. A four-level process such as SUMMiT permits mechanical linkages to be formed that connect actuator drives to gear trains. As a result, it is expected that entirely new kinds of complex and sophisticated micromachines will be fabricated with the five-level process.

According to the Sandia scientists, the primary difficulties encountered in forming the extra polysilicon layers for surface micromachining the more complex devices are residual film stress and device topography. The film stress can cause the mechanical layers to bow from the required flatness. This can cause the mechanism to function poorly or even prevent it from working. The scientists report that this has even been a problem in the fabrication of MEMS with only two mechanical layers.

To surmount the bowing problem, Sandia has developed a proprietary process for holding stress levels to values typically less than 5 MPa, thus permitting the successful fabrication and operation of two meshing gears, whose diameters are as large as 2000 μm.

The intricacies of device topography that make it difficult to pattern and etch successive polysilicon layers restrict the complexities of the devices that can be built successfully. Sandia has minimized that problem by developing a proprietary chemical-mechanical polishing (CMP) process called “planarizing” for forming truly flat top layers on the polysilicon. Because CMP is now so widely used in integrated circuit chip manufacture, it will allow MEMS to be batch fabricated by the SUMMiT processes using standard commercial IC fabrication equipment.

GALLERY OF MEMS ELECTRON-MICROSCOPE IMAGES

The Sandia National Laboratories, Albuquerque, New Mexico, have developed a wide range of microelectromechanical systems (MEMS). The scanning electron microscope (SEM) micrographs presented here show the range of these devices, and the captions describe their applications.

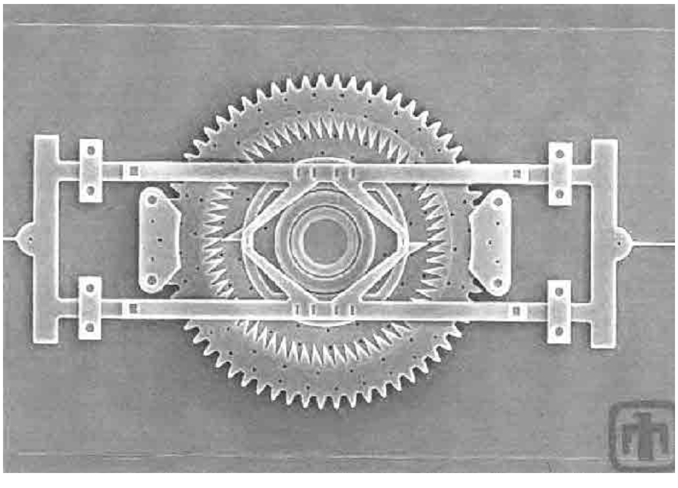


Fig. 1 Wedge Stepping Motor: This indexing motor can precisely index other MEMS components such as microgear trains. It can also position gears and index one gear tooth at a time at speeds of more than 200 teeth/s or less than 5 ms/step. An input of two simple input pulse signals will operate it. This motor can index gears in MEMS such as locking devices, counters, and odometers. It was built with Sandia’s four-layer SUMMiT technology. Torque and indexing precision increase as the device is scaled up in size.

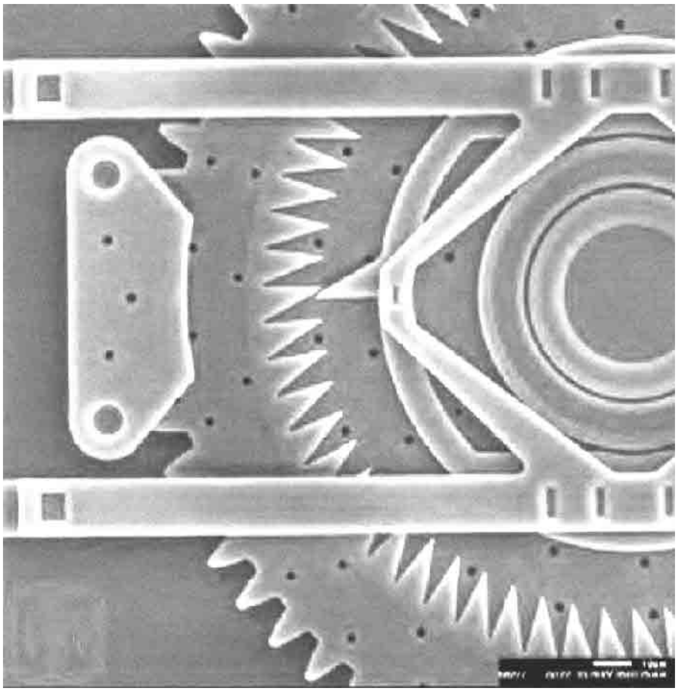


Fig. 2 Wedge Stepping Motor: A close-up view of one of the teeth of the indexing motor shown in Fig. 1.

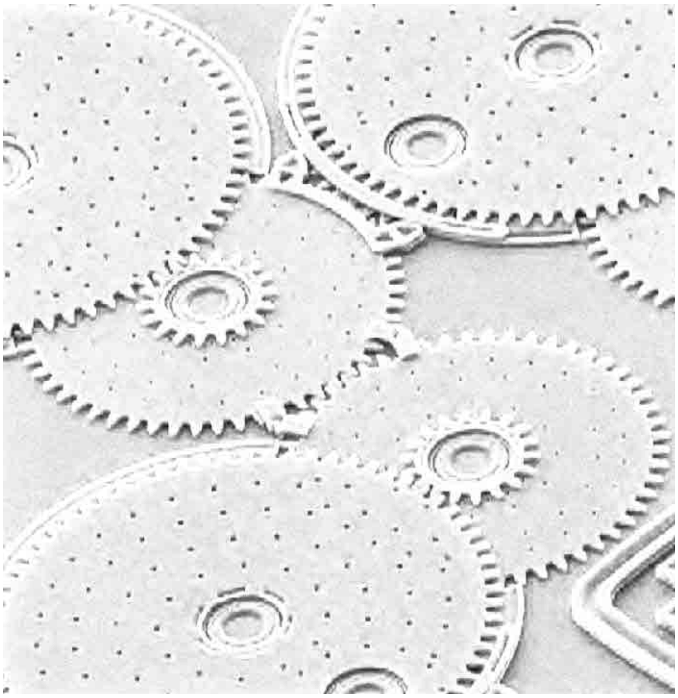


Fig. 4 Torque Converter: By cascading six stages of the modular 12-to-1 transmission units shown in Fig. 3, a 2,985,894-to-1 gear reduction ratio is obtained in a die area of less than 1 mm^2. The converter can step up or step down.

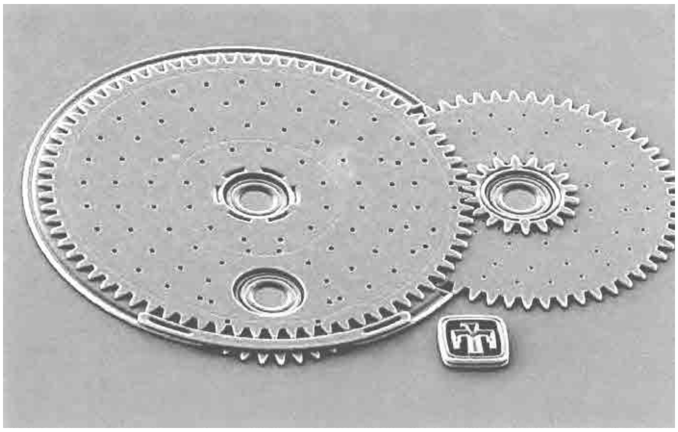


Fig. 3 Torque Converter: This modular transmission unit has an overall gear reduction ratio of 12 to 1. It consists of two multilevel gears, one with a gear reduction ratio of 3 to 1 and the other with a ratio of 4 to 1. A coupling gear within the unit permits cascading.

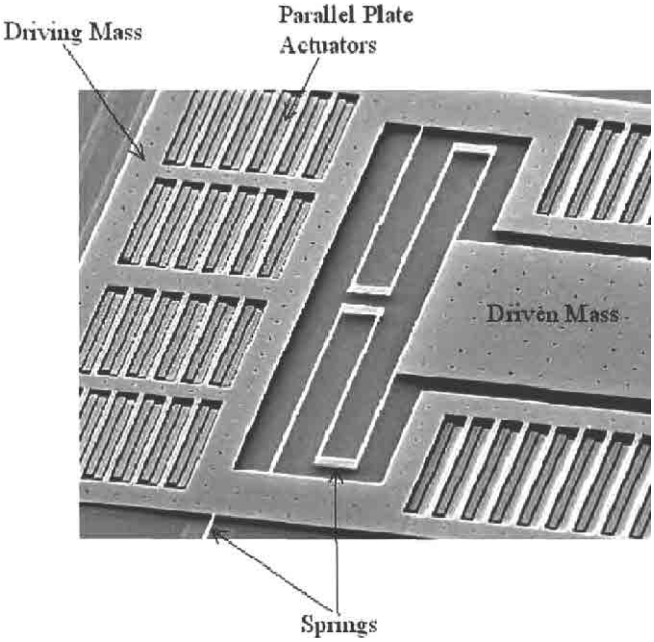


Fig. 5 Dual-Mass Oscillator: This oscillator uses parallel plate actuation and system dynamics to amplify motion. The 10-mm-long parallel plate actuators on the driving mass produce an amplified motion on the second mass when it is driven by a signal. The actuated mass remains nearly motionless, while the moving mass has an amplitude of approximately 4 μm when driven by a 4-V signal. It was designed to be part of a vibrating gyroscope.

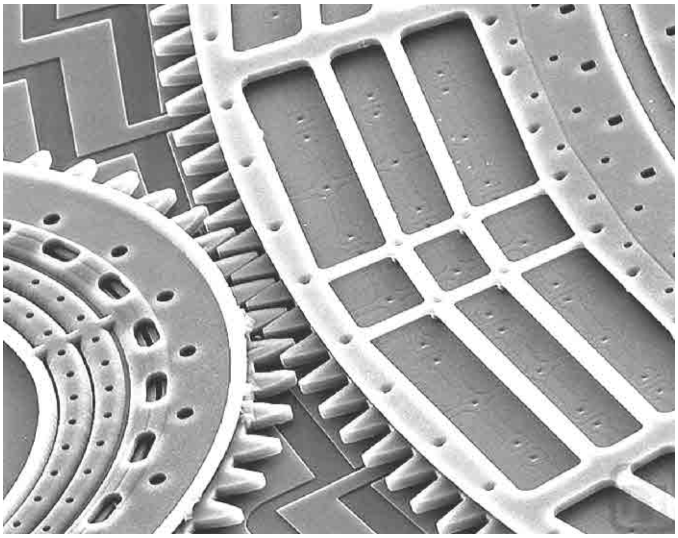


Fig. 6 Rotary Motor: This close-up shows part of a rotary motor that offers advantages over other MEMS actuators. Its operates on linear-comb drive principles, but the combs are bent in a circle to permit unlimited travel. The combs are embedded inside the rotor so that other micromachines can be powered directly from the rotor's perimeter. Built by Sandia's four-level SUMMiT technology, the motor is powered by a lower voltage and produces higher output torque than other MEMS actuators, but it still occupies a very small footprint. It can also operate as a stepper motor for precise positioning applications.

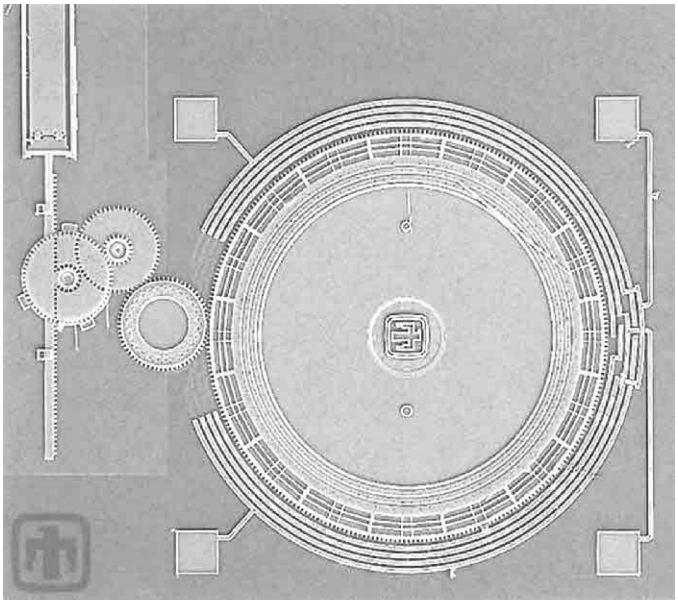


Fig. 7 Comb Drive Actuation: Two sets of comb-drive actuators (not shown) drive a set of linkages (upper right) to a set of rotary gears. The comb-drive actuators drive the linkages 90° out of phase with each other to rotate the small 19-tooth gear at rotational speeds in excess of 300,000 rpm. The operational lifetime of these small devices can exceed 8×10^9 revolutions. The smaller gear drives a larger 57-tooth (1.6-mm-diameter) gear that has been driven as fast as 4800 rpm.

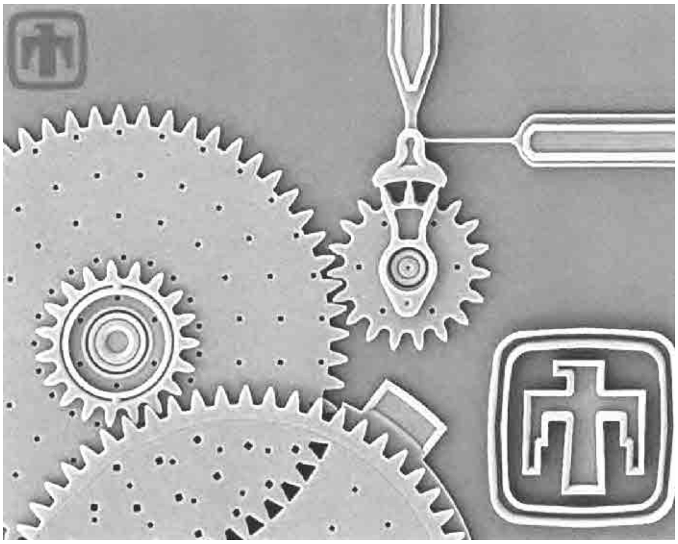


Fig. 8 Micro Transmission: This transmission has sets of small and large gears mounted on the same shaft so that they interlock with other sets of gears to transfer power while providing torque multiplication and speed reduction. Its output gear is coupled to a double-level gear train.

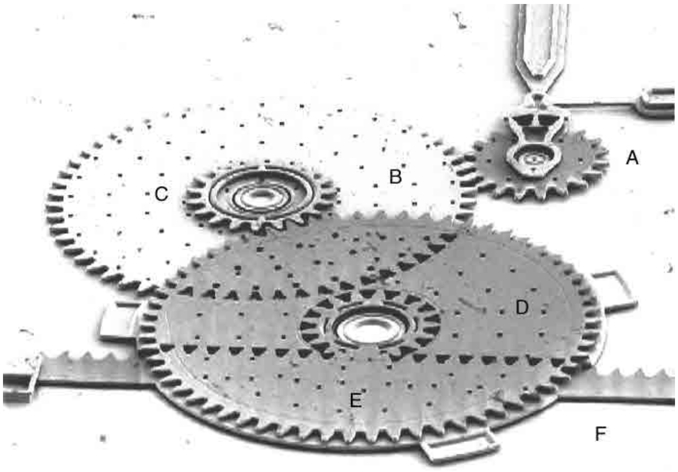


Fig. 9 Microtransmission and Gear Reduction Unit: This mechanism is the same as that in Fig. 8 except that it performs a gear-reduction function. The microengine pinion gear, labeled A in the figure, meshes directly with the large 57-tooth gear, labeled B. A smaller 19-tooth gear, C, is positioned on top of gear B and is linked to B's hub. Because the gears are joined, both make the same number of turns per minute. The small gear essentially transmits the power of the larger gear over a shorter distance to turn the larger 61-tooth gear D. Two of the gear pairs (B and C, D and E) provide 12 times the torque of the engine. A linear rack F, capable of driving an external load, has been added to the final 17-tooth output gear E to provide a speed reduction/torque multiplication ratio of 9.6 to 1.

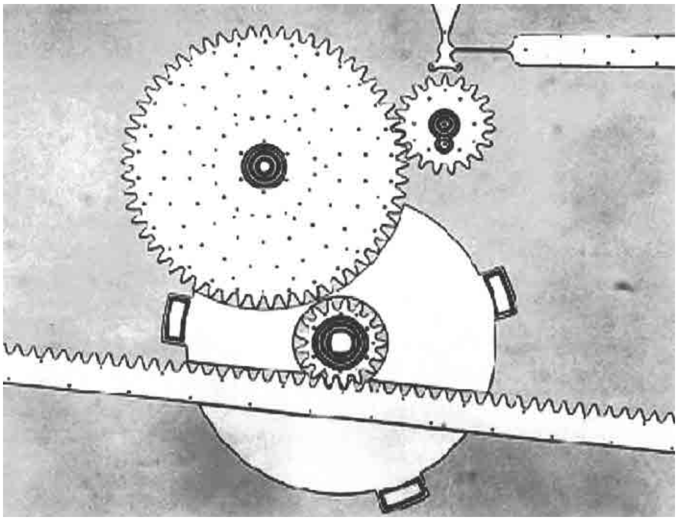


Fig. 10 Gear-Reduction Units: This micrograph shows the three lower-level gears (A, B, and E) as well as the rack (F) of the system shown in Fig. 9. The large flat area on the lower gear provides a planar surface for the fabrication of the large, upper-level 61-tooth gear (D).

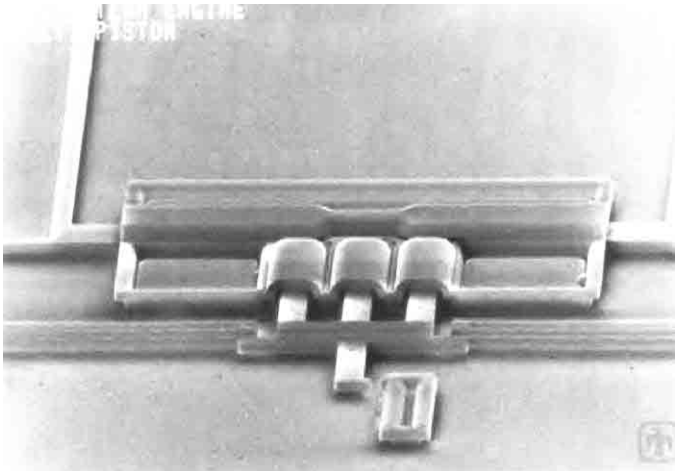


Fig. 11 Microsteam Engine: This is the world's smallest multipiston microsteam engine. Water inside the three compression cylinders is heated by electric current, and when it vaporizes, it pushes the pistons out. Capillary forces then retract the piston once current is removed.

MINIATURE MULTISPEED TRANSMISSIONS FOR SMALL MOTORS

Transmissions would be batch-fabricated using micromachining technologies.
NASA's Jet Propulsion Laboratory, Pasadena, California

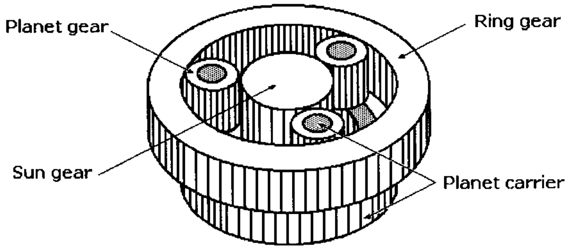


Fig. 1 Simple epicyclic gear train. Compound epicyclic gears in traditional automatic transmissions usually consist of simple epicyclics which are stacked one on top of the other along a radial axis.

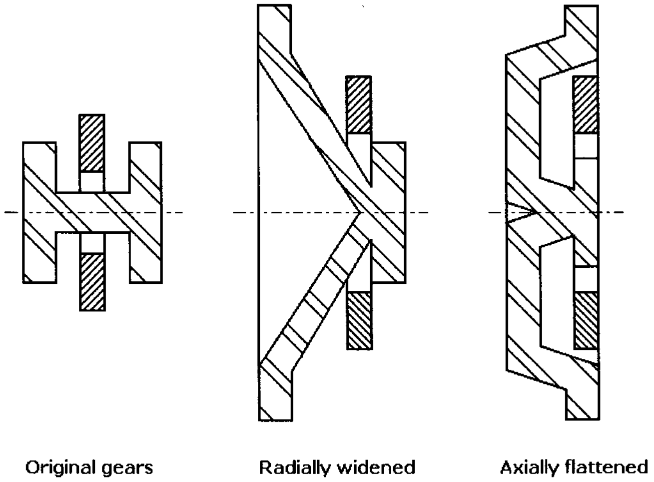


Fig. 2 Evolutionary stages in converting conventional gears to axially flattened gears.

A design has been developed for manufacturing multispeed transmissions that are small enough to be used with minimotors—electromagnetic motors with power ratings of less than 1 W. Like similar, larger systems, such as those in automobiles, the proposed mechanism could be used to satisfy a wider dynamic range than could be achieved with fixed-ratio gearing. However, whereas typical transmission components are machined individually and then assembled, this device would be made using silicon batch-fabrication techniques, similar to those used to manufacture integrated circuits and sensors.

Until now, only fixed-ratio gear trains have been available for minimotors, affording no opportunity to change gears in operation to optimize for varying external conditions, or varying speed, torque, and power requirements. This is because conventional multispeed gear-train geometries and actuation techniques do not lend themselves to cost-effective miniaturization. In recent years, the advent of microelectromechanical systems (MEMS) and of micromachining techniques for making small actuators and gears has created the potential for economical mass production of multispeed transmissions for minimotors. In addition, it should be possible to integrate these mechanisms with sensors, such as tachometers and load cells, as well as circuits, to create integrated silicon systems, which could perform closed-loop speed or torque control under a variety of conditions. In comparison with a conventional motor/transmission assembly, such a package would be smaller and lighter, contain fewer parts,

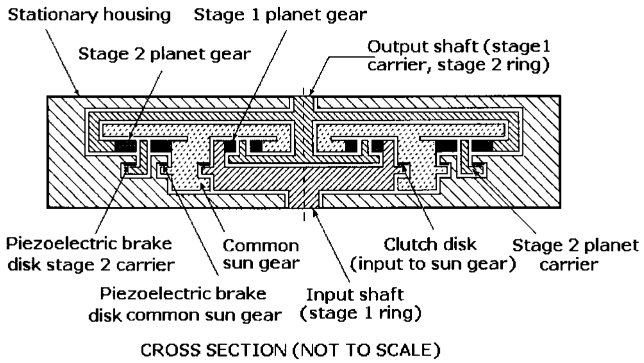


Fig. 3 This Miniature Transmission could be regarded as a flattened version of a conventional three-speed automatic transmission. The components would be fabricated by micromachining.

consume less power, and impose less of a computational burden on an external central processing unit (CPU).

Like conventional multispeed transmissions for larger motors, miniature multispeed transmissions would contain gears, clutches, and brakes. However, the designs would be more amenable to micromachining and batch fabrication. Gear stages would be nestled one inside the other (see figures 1, 2, and 3), rather than stacked one over the other, creating a more planar device. Actuators and the housing would be fabricated on separate layers. The complex mechanical linkages and bearings used to shift gears in conventional transmissions would not be practical at the small scales of interest here. Promising alternatives might include electrostatic-friction locks or piezoelectric actuators. For example, in the transmission depicted in the figure, piezoelectric clamps would serve as actuators in clutches and brakes.

The structures would be aligned and bonded, followed by a final etch to release the moving parts. The entire fabrication process can be automated, making it both precise and relatively inexpensive. The end product is a "gearbox on a chip," which can be "dropped" onto a compatible motor to make an integrated drive system.

This work was done by Indrani Chakraborty and Linda Miller of Caltech for **NASA's Jet Propulsion Laboratory**.

MEMS CHIPS BECOME INTEGRATED MICROCONTROL SYSTEMS

The successful integration of MEMS (microelectromechanical systems) on CMOS integrated circuit chips has made it possible to produce "smart" control systems whose size, weight, and power requirements are significantly lower than those for other control systems. MEMS development has previously produced microminiature motors, sensors, gear trains, valves, and other devices that easily fit on a silicon microchip, but difficulties in powering these devices has inhibited their practical applications.

MEMS surface micromachining technology is a spin-off of conventional silicon IC fabrication technology, but fundamental differences in processing steps prevented their successful integration. The objective was to put both the control circuitry and mechanical device on the same substrate. However, the results of recent development work showed that they could be successfully merged.

It has been possible for many years to integrate the transistors, resistors, capacitors, and other electronic components needed for drive, control, and signal processing circuits on a single CMOS silicon chip, and many different MEMS have been formed on separate silicon chips. However, the MEMS required external control and signal-processing circuitry. It was clear that the best way to upgrade MEMS from laboratory curiosities to practical mechanical devices was to integrate them with their control circuitry. The batch fabrication of the electrical and mechanical sections on the same chip would offer the same benefits as other large-scale ICs—increased reliability and performance. Component count could be reduced, wire-bonded connections between the sections could be eliminated, minimizing power-wasting parasitics, and standard IC packaging could replace multichip hybrid packages to reduce product cost.

MEMS sections are fabricated by multilevel polysilicon surface micromachining that permits the formation of such intricate mechanisms as linear comb-drive actuators coupled to gear trains. This technology has produced micromotors, microactuators, microlocks, microsensors, microtransmissions, and micromirrors.

Early attempts to integrate CMOS circuitry with MEMS by forming the electronic circuitry on the silicon wafer before the MEMS devices met with only limited success. The aluminum electrical interconnects required in the CMOS process could not withstand the long, high-temperature annealing cycles needed to relieve stresses built up in the polysilicon mechanical layers of the MEMS. Tungsten interconnects that could withstand those high temperatures were tried, but the performance of the CMOS circuitry was degraded when the heat altered the doping profiles in the transistor junctions.

When the MEMS were formed before the CMOS sections, the thermal problems were eliminated, but the annealing procedure tended to warp the previously flat silicon wafers. Irregularities in the flatness or planarity of the wafer distorted the many photolithographic images needed in the masking steps required in CMOS processing. Any errors in registration can lower attainable resolution and cause circuit malfunction or failure.

Experiments showed that interleaving CMOS and MEMS process steps in a compromise improved yield but limited both the complexity and performance of the resulting system. In other experiments materials such as stacked aluminum and silicon dioxide layers were substituted for polysilicon as the mechanical layers, but the results turned out to be disappointing.

Each of these approaches had some merit for specific applications, but they all resulted in low yields. The researchers persevered in their efforts until they developed a method for embedding the MEMS in a trench below the surface of the silicon wafer before fabricating the CMOS. This is the procedure that now permits the sections to be built reliably on a single silicon chip.

Sandia's IMEMS Technology

Sandia National Laboratories, Albuquerque, New Mexico, working with the University of California's Berkeley Sensor and Actuator Center (BSAC), developed the unique method for forming the micromechanical section first in a 12-μm-deep "trench"

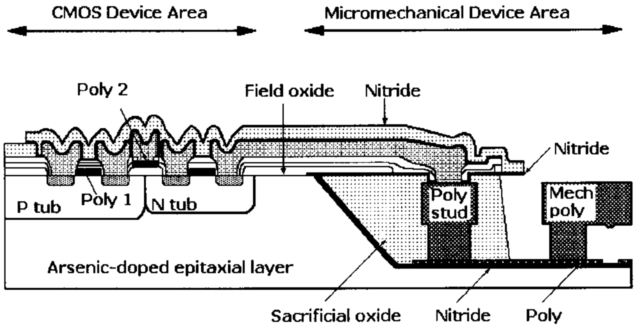


Fig. 1 A cross-section view of CMOS drive circuitry integrated on the same silicon chip with a microelectromechanical system.

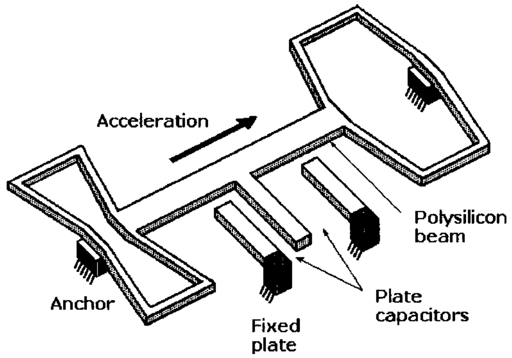


Fig. 2 A simplified view of the movement of a polysilicon beam in a surface-micromachined accelerometer moving in response to acceleration. The two fixed plates and one moving plate form a unit cell.

and backfilling that trench with sacrificial silicon dioxide before forming the electronic section. This technique, called Integrated MicroElectroMechanical Systems (IMEMS), overcame the wafer-warping problem. Figure 1 is cross-section view of both sections combined on a single chip.

The mechanical polysilicon devices are surface micromachined by methods similar to Sandia's SUMMiT process in the trench, using special photolithography methods. After the trench is filled with the silicon dioxide, the silicon wafer is annealed and that section is "planarized," or etched flat and flush with the rest of the wafer surface, by a process called chemical-mechanical polishing (CMP). After the CMOS section is complete, the sacrificial silicon dioxide in the trench is etched away, leaving the MEMS devices electrically interconnected with the adjacent CMOS circuitry.

Advantages of IMEMS

Sandia spokespersons say the IMEMS process is completely modular, meaning that the planarized wafers can be processed in any facility capable of processing CMOS, bipolar, and combinations of these processes. They add that modularity permits the mechanical devices and electronic circuitry to be optimized independently, making possible the development of high-performance microsystems.

Early Research and Development

Analog Devices Inc. (ADI) was one of the first companies to develop commercial surface-micromachined integrated-circuit accelerometers. ADI developed and marketed these accelerometer chips, demonstrating its capability and verifying commercial demand. Initially ADI built these devices by interleaving, combining, and customizing its internal manufacturing processes to produce the micromechanical devices with the same processes it used to produce monolithic electronic circuitry.

At the same time, researchers at BSAC developed the alternative process for replacing conventional aluminum interconnect layers with tungsten layers to enable the CMOS device to withstand the higher thermal stresses associated with subsequent micromechanical device processing. This process was later superseded by the joint BSAC–Sandia development of IMEMS.

Accelerometers

ADI offered the single-axis ADXL150 and dual-axis ADXL250, and Motorola Inc. offered the XMMAS40GWB. Both of ADI's integrated accelerometers are rated for ±5 *g* to ±50 *g*. They have been in high-volume production since 1993. The company is now licensed to use Sandia's integrated MEMS/CMOS technology. Motorola is now offering the MMA1201P and MMA2200W single-axis IC accelerometers rated for ±38 *g*.

These accelerometer chips differ in architecture and circuitry, but both work on the same principles. The surface micromachined sensor element is made by depositing polysilicon on a sacrificial oxide layer that is etched away, leaving the suspended sensor element. Figure 2 is a simplified view of the differential-capacitor sensor structure in an ADI accelerometer. It can be seen that two of the capacitor plates are fixed, and the center capacitor plate is on the polysilicon beam that deflects from its rest position in response to acceleration.

When the center plate deflects, its distance to one fixed plate increases while its distance to the other plate decreases. The change in distance is measured by the on-chip circuitry that converts it to a voltage proportional to acceleration. All of the circuitry, including a switched-capacitor filter needed to drive the sensor and convert the capacitance change to voltage, is on the chip. The only external component required is a decoupling capacitor.

Integrated-circuit accelerometers are now used primarily as airbag-deployment sensors in automobiles, but they are also finding many other applications. For example, they can be used to monitor and record vibration, control appliances, monitor the condition of mechanical bearings, and protect computer hard drives.

Three-Axis Inertial System

When the Defense Advanced Research Projects Agency (DARPA), an agency of the U.S. Department of Defense, initiated a program to develop a solid-state three-axis inertial measurement system, it found that the commercial IC accelerometers were not suitable components for the system it envisioned for two reasons: the accelerometers must be manually aligned and assembled, and this could result in unwanted variations in alignment, and the ICs lacked on-chip analog-to-digital converters (ADCs), so they could not meet DARPA's critical sensitivity specifications.

To overcome these limitations, BSAC designed a three-axis, force-balanced accelerometer system-on-a-chip for fabrication with Sandia's modular monolithic integration methods. It is said to exhibit an order of magnitude increase in sensitivity over the best commercially available single-axis integrated accelerometers. The Berkeley system also includes clock generation circuitry, a digital output, and photolithographic alignment of sense axes. Thus, the system provides full three-axis inertial measurement, and does not require the manual assembly and alignment of sense axes.

A combined *X*- and *Y*-axis rate gyro and a *Z*-axis rate gyro was also designed by researchers at BSAC. By using IMEMS

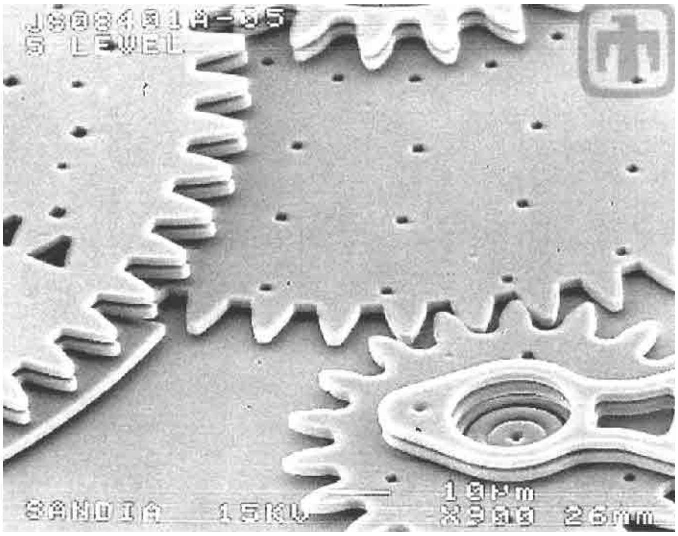


Fig. 3 This linear-rack gear reduction drive converts the rotational motion of a pinion gear to linear motion to drive a rack. *Courtesy of Sandia National Laboratories*

technology, a full six-axis inertial measurement unit on a single chip was obtained. The 4- by 10-mm system is fabricated on the same silicon substrate as the three-axis accelerometer, and that chip will form the core of a future micro–navigation system. BSAC is teamed with ADI and Sandia Laboratories in this effort, with funds provided by DARPA's Microsystems Technology Office.

Micromechanical Actuators

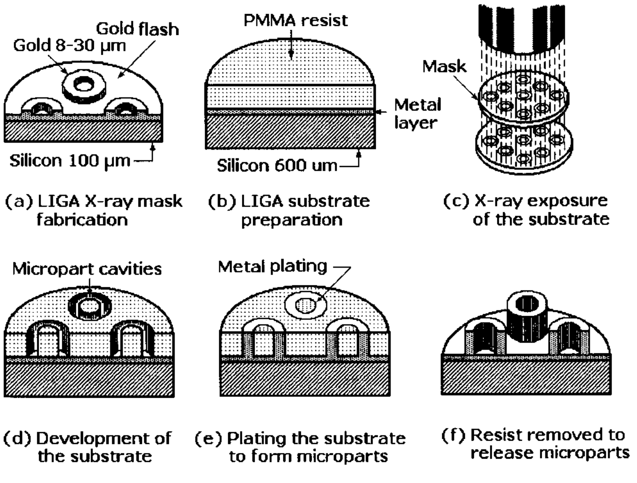
Micromechanical actuators have not attained the popularity in commercial applications achieved by microminiature accelerometers, valves, and pressure sensors. The two principal drawbacks to their wider application have been their low torque characteristics and the difficulties encountered in coupling actuators to drive circuitry. Sandia has developed devices that can be made by its SUMMiT four-level polysilicon surface-micromachining process, such as the microengine pinion gear driving a 10 to 1 transmission shown in Fig. 3, to improve torque characteristics.

The SUMMiT process includes three mechanical layers of polysilicon in addition to a stationary level for grounding or electrical interconnection. These levels are separated by sacrificial silicon-dioxide layers. A total of eight mask levels are used in this process. An additional friction-reducing layer of silicon nitride is placed between the layers to form bearing surfaces.

If a drive comb, operating at a frequency of about 250,000 rpm, drives a 10-to-1 gear reduction unit, torque is traded off for speed. Torque is increased by a factor of 10 while speed is reduced to about 25,000 rpm. A second 10-to-1 gear reduction would increase torque by a factor of 100 while reducing speed to 2,500 rpm. That gear drives a rack and pinion slider that provides high-force linear motion. This gear train provides a speed-reduction/torque-multiplication ratio of 9.6 to 1.

LIGA: AN ALTERNATIVE METHOD FOR MAKING MICROMINIATURE PARTS

The Sandia National Laboratories, Livermore, California, is using a process called LIGA to form microminiature metal components as an alternative to producing them by the surface micromachining processes used to make microelectromechanical systems (MEMS). LIGA permits the fabrication of larger, thicker, and more durable components with greater height-to-width ratios. They can withstand high pressure and temperature excursions while providing more useful torques than polysilicon MEMS.



(a) LIGA X-ray mask fabrication
(b) LIGA substrate preparation
(c) X-ray exposure of the substrate
(d) Development of the substrate
(e) Plating the substrate to form microparts
(f) Resist removed to release microparts

Fig. 1 Steps in fabricating microminiature parts by the LIGA process.

The acronym LIGA is derived from the German words for lithography, electroplating, and molding (Lithographie, Galvanoformung, and Abformung), a micromachining process originally developed at the Karlsruhe Nuclear Research Center in Karlsruhe, Germany, in the 1980s. Sandia Labs has produced a wide variety of LIGA microparts, including components for millimotors and miniature stepping motors. It has also made miniature accelerometers, robotic grippers, a heat exchanger, and a mass spectrometer. Sandia is carrying out an ongoing research and development program to improve the LIGA process and form practical microparts for various applications.

In the LIGA process, highly parallel X-rays from a synchrotron are focused through a mask containing thin 2D templates of the microparts to be formed. The X rays transfer the patterns to a substrate layered with PMMA (polymethylmethacrylate), a photoresist sensitive to X rays, on a metallized silicon or stainless-steel substrate. When the exposed layer of PMMA (better known as Plexiglas) is developed, the cavities left in the PMMA are the molds in which the microparts will be formed by electroplating. The thickness of the PMMA layer determines the large height-to-width ratio of the finished LIGA microparts. The resulting parts can be functional components or molds for replicating the parts in ceramic or plastic.

The highlights of the LIGA process as illustrated in Fig. 1 are

(a) An X-ray mask is prepared by a series of plating and lithographic steps. A metallized silicon wafer coated with photoresist is exposed to ultraviolet light through a preliminary mask containing the 2D patterns of the microparts to be produced. Development of the photoresist dissolves the resist from the plated surface of the wafer, forming the micropart pattern, which is plated in gold to a thickness of 8 to 30 µm. The remaining photoresist is then dissolved to finish the mask.

(b) Target substrate for forming microparts is prepared by solvent-bonding a layer of PMMA to a metallized-silicon or stainless-steel substrate.

(c) PMMA-coated substrate is then exposed to highly collimated parallel X rays from a synchrotron through the mask.

(d) PMMA is then chemically developed to dissolve the exposed areas down to the metallized substrate, etching deep cavities for forming microparts.

(e) Substrate is then electroplated to fill the cavities with metal, forming the microparts. The surface of the substrate is then lapped to finish the exposed surfaces of the microparts to the required height within ±5µm.

(f) Remaining PMMA is dissolved, exposing the 3D microparts, which can be separated from the metallized substrate or allowed to remain attached, depending on their application.

The penetrating power of the X rays from the synchrotron allows structures to be formed that have sharp, well-defined vertical surfaces or sidewalls. The minimum feature size is 20 µm, and microparts can be fabricated with thickness of 100 µm to 3 mm. The sidewall slope is about 1µm/mm. In addition to gold, microparts have been made from nickel, copper, nickel–iron, nickel–cobalt, and bronze.

An example of a miniature machine assembled from parts fabricated by LIGA is an electromagnetically actuated millimotor. With an 8-mm diameter and a height of 3 mm, it includes 20 LIGA parts as well as an EDM-machined permanent magnet and wound coils. The millimotor has run at speeds up to 1600 rpm, and it can provide torque in excess of 1 mN-m. Another example of a miniature machine built from LIGA parts is a size 5 stepper motor able to step in 1.8-deg increments. Both its rotor and stator were made from stacks of 50 laminations, each 1-mm thick.

According to Sandia researchers, the LIGA process is versatile enough to be an alternative to such precision machining methods as wire EDM for making miniature parts. The feature definition, radius, and sidewall texture produced by LIGA are said to be superior to those obtained by any precision metal cutting technique.

In an effort to form LIGA parts with higher aspect ratios, researchers at the University of Wisconsin in Madison teamed with the Brookhaven National Laboratory on Long Island to use the laboratory's 20,000-eV photon source to produce much higher levels of X-ray radiation than are used in other LIGA processes. The higher-energy X rays penetrate into the photoresist to depths of 1 cm or more, and they also pass more easily through the mask. This permitted the Wisconsin team to use thicker and stronger materials to make 4-in.-square masks rather than the standard 1- × 6-cm masks used in standard LIGA. Working with Honeywell, the team developed LIGA optical microswitches

The primary disadvantage to LIGA is its requirement for a synchrotron or other high-energy sources to image parallel X-rays on the PMMA covered substrate. In addition to their limited availability, these sources are expensive to build, install, and operate. Their use adds significantly to the cost of producing LIGA microstructures, especially for commercial applications.