

# RAPID PROTOTYPING

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## SYSTEM SELECTION & IMPLEMENTATION GUIDE

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PUBLISHED BY MANAGEMENT ROUNDTABLE

# **Rapid Prototyping: System Selection and Implementation Guide**

**Edited By  
Marshall Burns, PhD**

[www.Ennex.com](http://www.Ennex.com)

**Published By  
Management Roundtable, Inc.  
Boston, Massachusetts**

[www.Roundtable.com](http://www.Roundtable.com)

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ISBN 0-932007-23-6**

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I find people need to fondle parts before they really understand them.  
Drawings just don't do it.

—*Phillip Ulerich*, Westinghouse, page 129.

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## INTRODUCTION

# Introduction to Desktop Manufacturing and Rapid Prototyping

Marshall Burns, President, Ennex Technology Marketing, Inc., Austin, Texas

Marshall Burns conducted a study of the desktop manufacturing industry last year, including its various technologies and their applications. He came to the conclusion that automated fabrication is the high-tech field that holds the most promise for a tremendous market, while offering many challenging technical problems, yet being feasible for immediate development.

Dr. Burns formed Ennex Technology in 1982 to do research and development on market technologies. Its first project was marketing the then-new IBM Personal Computer to business customers across the United States. The success of that venture funded the second project, which was a program of Ph.D. research for Dr. Burns, just completed in April, 1991. A third project is under consideration.

Dr. Burns has a B.S. in Physics from the Massachusetts Institute of Technology and a Ph.D. in Atomic Physics from the University of Texas at Austin.

*Desktop Manufacturing (DtM)*<sup>1</sup> refers to a set of modern technologies that automate the processes for fabricating objects from raw materials. With roots in the pre-computer automated loom, this burgeoning industry now boasts laser-driven solidification of specialized polymers and powders, guided by 3-dimensional CAD designs drawn by engineers on ordinary desktop computers.

Terry Wohlers, a CAD industry consultant, points out that "desktop manufacturing" is a misnomer for two reasons. Firstly, you would not want to put any of the currently available systems on your desk. And secondly, none of the processes is yet practical for manufacturing production. But Wohlers approves the use of the term, saying that in the future we *will* have true desktop manufacturing. Many other names are also being applied to this new set of technologies:

- Rapid prototyping,
- Automated fabrication,
- Free-form fabrication,
- Tool-less manufacturing,
- Additive fabrication, and
- 3d hardcopy.

The terms "tool-less" and "additive" stress the major difference from numerically controlled machining, the previous state-of-the-art automated manufacturing process. The new processes build an object by successively adding more material to the solid volume, rather than by carving it out of a block of material. The older machining processes, such as lathing and milling, are now known as "subtractive."

The first commercial entry into this market, 3D Systems, Inc., had \$30 million in sales in 1990, and now offers a line of three models of *StereoLithography Apparatus (SLA)* ranging in price from \$95,000 to \$385,000. At least ten other companies, including at least seven in the U.S., introduced competing technologies during 1989 and 1990. Several research projects underway at government, university and industry laboratories are gearing up to offer improvements in the speed, precision, material versatility and other factors important to users of desktop manufacturing systems.

The *Industry Survey* starting on page 52 lists over twenty companies and organizations that are either selling systems or preparing some form of DtM technology for ultimate release in the marketplace. The machines coming out are getting faster and more accurate, and the range of fabrication materials is getting wider. At least three systems have the potential to work in metals, although they all face formidable technical difficulties. At the

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<sup>1</sup> The acronym *DtM*, with a lower case "t," is used here to avoid confusion with the name of the vendor, DTM Corp.

current pace of development, we would see machines capable of short-run production of metal and plastic parts with 1 mil accuracy in the next three to five years.

Wohlers estimates a market of at least \$1 billion for DtM systems, as soon as the price comes down to the \$20,000 to \$30,000 range. "With 400,000 operating mechanical CAD stations, if one DtM system is installed for every ten CAD stations, at \$25,000 per system, that makes \$1 billion." Peter Sferro of Ford Motor Company has said that at that price, he would want *all* of his engineers to have one.

Sferro has a vision of this technology in which it is not just engineers who use it. In a recent interview, he described an auto showroom, perhaps 20 years in the future. A customer sits in front of a terminal that shows him a model of a car that fits his requirements. The computer program has an envelope of design ranges, such as the shape of the fenders, and the customer can specify the design within that envelope. Then the car is made exclusively for him. For a fleet buyer, a unique truck design may become a rolling trademark, in a high-tech elaboration of today's familiar brown UPS trucks.

### The processes<sup>2</sup>

Fabrication processes fall into three categories, subtractive, additive and compressive. In a subtractive process, a block of material is carved out to produce the desired shape. An additive process builds an object by joining particles or layers of raw material. A compressive process forces a semi-solid or liquid material into the desired shape, in which it is then induced to harden or solidify.

The subtractive processes include the old standards of milling, lathing and grinding, as well as more modern techniques, such as electro-discharge machining (EDM). They were the first to be subjected to computer control, and the resulting NC (numerically controlled) machining industry is now quite mature. Although limited in the complexity of shapes they can produce, NC machines are legitimately included in the DtM field when they are small and inexpensive enough to qualify as CAD peripherals. One major problem with subtractive processes, that the cutting tool wears down from use and the accuracy of its cuts is thereby degraded, is fixed somewhat by modern software that can calculate the rate of tool wear and account for it in programming the tool path.

The various methods of molding and casting are compressive processes. There is as yet no technology for directly controlling these by a computer. However, one of the major applications of DtM is the generation of patterns from which molds can be made. (See applications, below.)

The new technologies in desktop manufacturing are additive processes. These again fall into three categories according to the materials used to build the structure: photopolymers, thermoplastics, and adhesives.

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<sup>2</sup> This is a very basic overview of the processes on the market and under development. All of the companies and organizations mentioned are listed again, with more detailed information on their processes (where available) and with addresses and phone numbers, in the *Industry Survey* starting on page 52. The addresses and phone numbers are also given in the *Industry Directory* starting on page 147.

### *Photopolymers*

A photopolymer is a material that originates as a liquid resin, but under the influence of light of a particular wavelength undergoes a chemical reaction which turns it into a solid. The DTM technologies work by directing light to specific regions in the liquid resin to solidify it into a 3-dimensional shape.

Photopolymers were invented over 40 years ago in the laboratories of Du Pont. The first attempt at using them in the fabrication of solid objects was at Battelle Memorial Institute in the late 1960s. That technique used two laser beams to solidify a pinpointed region in the middle of a vat of liquid. In about 1982, a small company called Chem-Form began working with a process to mask light from an ultraviolet lamp to define 2-dimensional patterns in a shallow tray of resin. Today's crowning commercial success in this industry was started in 1986 when Chuck Hull, co-founder of 3D Systems, scanned a single laser beam across the surface of a vat of photopolymer to define the shape of a layer of an object to be built. The object sat on an elevator platform which was lowered deeper into the vat as each layer was built at the liquid surface. This process is now known as *StereoLithography*.

Many variations on these ideas are on the market or soon coming to market. A machine from QuadraX scans the resin with a laser, but applies each new layer of resin with a wiper system instead of working in a vat. An Israeli company, Cubital, uses a masked lamp to cure (solidify) the resin. They also do away with the vat of liquid by sucking away the uncured resin in each layer and replaced it with wax that serves to support overhangs in higher layers. Another masked lamp device is available from a company called Light Sculpting.

Other methods of irradiating the photopolymers are under investigation, besides lasers and masked lamps. It is also possible that this category may expand beyond light-based processes. There are other ways of inducing solidifying polymerization, including chemical, thermal and electrical stimuli. Light is used now because it is easiest to control, but other methods are likely to be developed in time.

### *Thermoplastics*

A thermoplastic is a solid material that softens and fuses when heated. This property of metals has been used since World War II in the sintering (melting and resolidifying) of powders to fabricate complicated shapes. Until recently, however, this was done by pressing the powder into a hardened steel mold and raising the temperature to melt the powder. In 1987, Carl Deckard, then a student at the University of Texas at Austin and now a principal in DTM Corporation, devised a process of scanning the beam of a laser across a thin layer of powder to sinter a selected pattern. Another layer of powder is then laid over top of the previous one, and another pattern defined by the laser. In this way, a 3-dimensional object is built up layer by layer.

Another process, developed by Scott Crump and marketed by his company, Stratasys, uses thin thermoplastic filaments instead of powders. The filament is raised to very near its melting point and guided by a robotic device to form the desired shape. Babcock and Wilcox are working on a similar concept.

Closely related to these ideas are processes based on liquid droplets. These are still quite primitive, but hold a great deal of promise for the future. William Masters of Perception Systems uses an ink-jet-like mechanism to deposit material in a desired shape. Application of a similar process using tin metal is under development by David Gore of Incremental Fabrication Technologies. Going to another level of sophistication, Fritz Prince and Lee Weiss of

Carnegie Mellon University spray an atomized stream of metal from an arc gun through a mask that determines the shape of each layer of an object.

### *Adhesives*

In the final category are processes that use an intermediary material to bind the primary construction material. One such process, developed by Michael Feygin and marketed by his company, Helisys, stacks layer upon layer of a sheet material precoated with adhesive, and uses a laser beam to cut a shape into each layer as it is placed on the stack.

Another technique is under development by Emanuel Sachs and his colleagues at the Massachusetts Institute of Technology. This process sprays a binding material onto a layer of powder through a mechanism resembling an ordinary ink-jet printer. With the geometry of each layer defined in this way, a 3-dimensional object is constructed.

### *Future developments*

The industry is still young. Other exciting ideas will emerge for fabricating objects under computer control. One example under development at the University of Texas at Austin, laser chemical vapor deposition, precipitates carbon out of the vapor phase onto a substrate in patterns on the scale of ½ mil.

## **Applications of desktop manufacturing**

### *Industrial models and prototypes*

The first major market for desktop manufacturing systems gave rise to the alternative name for the industry: *rapid prototyping*. Building models of items to be manufactured is a huge industry, fueled by manufacturers' needs to know whether a new concept (a) will work, and (b) will sell. Models range all the way from rough mockups to full scale, functioning prototypes. At every level, the processes of building the models have historically been expensive and slow because they could not take advantage of the efficiencies of mass production. Desktop manufacturing is changing that.

Hundreds of companies in the automotive, computer, medical and other industries are now using StereoLithography, either in-house or through service bureaus, to view and test new designs before committing them to expensive manufacturing programs. Each of the three U.S. automobile manufacturers owns several StereoLithography machines on which they model new parts. Digital Equipment Corporation uses theirs to test new keyboard designs. Mattel uses the process in the design of new toys. Another potential market for this application, which may be as yet untapped, is architectural models.

While building models and prototypes is an application of DtM, there are several different applications for which the models themselves are made:<sup>3</sup>

- *Concept*. Find out how a particular idea translates into a real-world object. Ensure that all members of the team understand the design.

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<sup>3</sup> See page 119 in David Trimmer's paper for a case study that demonstrates the integration of all these applications at DePuy.

- *Fit.* Test the design dimensions of a part to check that it fits into the intended assembly.<sup>4</sup>
- *Form.* Check how a proposed design looks (aesthetics) and feels (ergonomics). Perform comparison tests on variations of a design using focus groups.
- *Function.* Check that a product or part meets its specifications. Run wind tunnel, use cycle and harsh environment tests. (This application requires that the model be made in the design material, and so is not yet generally possible to do *directly* with DtM techniques. But the ability to make patterns and molds for secondary processes (see below), which can then be used to make prototypes in the design material, makes this an indirect application of DtM.<sup>5</sup>)
- *Bid requests.* Help prospective subcontractors understand the design they are bidding on, in order to get faster, more reliable and lower quotes.<sup>6</sup>
- *Marketing presentations.* Let the customer hold the proposed product in his hands, for better understanding of the proposal.

These applications are not specific to desktop manufacturing. They are the purposes for which models and prototypes have been built since the beginning of the industrial era. What DtM does is make it practical to satisfy these applications faster, cheaper and earlier in the design cycle than could be done before.

#### *Patterns, molds and dies*

The next major application for DtM technologies is in making patterns for secondary manufacturing processes, and even in making patterns for digitizing numerically controlled machine tool paths. The molding and casting applications are just beginning to attract a lot of interest, and that interest is likely to grow with the introduction of new materials for StereoLithography and other DtM processes, designed specifically to withstand (or submit to, in the case of investment casting) the torturous conditions that molds and casting tools are subjected to.

Some secondary processes which have been successfully used with patterns made by StereoLithography are:

- Silicone rubber molds,<sup>7</sup>
- Spray metal molds,<sup>8</sup>
- Epoxy tooling,<sup>9</sup> and
- Direct investment casting.<sup>10</sup>

Other applications which have been proposed are:<sup>11</sup>

<sup>4</sup> See page 65 in Dennis Medler's paper for an example of this application at Chrysler.

<sup>5</sup> See David Tait's paper (page 107) for several examples of this application by various industrial customers.

<sup>6</sup> See the footnote on page 101 for a story of dramatic savings from this application at Ford.

<sup>7</sup> See page 109 of David Tait's paper for an example of the application of this process by Ford, and page 130 of Phillip Ulerich's papers for comments on the results of the process at Westinghouse.

<sup>8</sup> See page 130 in Phillip Ulerich's paper for a discussion of the use of this process at Westinghouse.

<sup>9</sup> See page 109 of David Tait's paper for an example of his application of this process for General Motors, and page 119 of David Trimmer's paper for an example at DePuy.

<sup>10</sup> By "direct" investment casting is meant a process which directly makes the casting master, rather than making a mold from which the master is made by one of the other secondary processes.

See page 66 in Dennis Medler's paper for examples of this application of StereoLithography at Texas Instruments and Hughes Aircraft, and page 37 in Myron Bezdicsek's paper for several references on research on this subject. See page 79 in Kent Nutt's paper for a discussion of using Selective Laser Sintering to make wax masters, and page 91 in Emanuel Sachs' paper for a proposal that goes even further, using 3-D Printing to make ceramic shells and cores directly, eliminating the need for masters.

<sup>11</sup> See page 80 in Kent Nutt's paper for a proposal of these applications of Selective Laser Sintering. They would not all be, however, unique to that process.

- Plaster cast tooling,
- Vacuum form tooling,
- NC tool path generation and verification,
- Electro-discharge machining (EDM) electrodes, and
- Forging dies.

### *Imaging*

This is a field that has seen some activity, but has a long way to go to reach its potential. DtM processes can be used to build bone models directly from CAT-scan data. The same technique could be used by surgeons to model the organs and a tumor in an individual patient in preparation for a particularly complicated operation. Orthodontic surgeons could use it to model a patient's teeth in order to design well-fitting corrective hardware.

Many fields now served by 2-dimensional representations of their data will see better in 3d. Chemists studying the interaction dynamics of an enzyme and mathematicians working to unravel the topological complexities of knot theory are two immediate examples. Forest rangers will plan better fire-fighting strategies when they can see the mountains and valleys they have to contend with in full, reduced-scale, relief.

Schoolchildren will understand the Rockies and the Himalayas better when they build models of them themselves. Engineering students will understand the intricacies of engines and other complex machines when they can build cut-away models defined by any chosen cross-sectional plane.

Finally, just as color is now used to view 3-dimensional data on paper, coloring of 3-dimensional models will facilitate the understanding of 4-dimensional data.

### *Manufacturing*

The long-term dream of the inventors who have brought us desktop manufacturing is for their processes to be used in actual production. There are several cases where this is even practical in the near term.

The obvious applications of desktop manufacturing are in making unique items, small batches or items where the ability to make frequent modifications is desirable. Already, the properties of objects fabricated in new resins from Ciba Geigy and Du Pont are probably good enough to make it practical for a manufacturer with a warehouse full of infrequently called-for spare plastic parts to replace that inventory with a machine and a parts design database. This will be all the more practical for an inventory of metal parts when fabrication materials are available to match metallic properties, including possibly metals themselves. The philosophies of just-in-time and flexible manufacturing will rise to new heights as manufacturers will be able to make their own customized parts from stocks of raw materials, instead of placing advance orders with parts fabricators. Moving from the industrial to the consumer marketplace, entirely new kinds of jewelry and personalized curios will become possible.

The medical field is one industry for which DtM is particularly suited. Since each patient is unique, products such as prostheses and braces are best made individually. (In fact, the old fashioned plaster cast is an individually manufactured restraining device made by a lamination process.) In cancer radiation treatment, a patient is fitted with a lead filter that matches

the contours of his body. These filters are slow and expensive to fabricate by conventional processes and have been proposed as an application of Selective Laser Sintering.

The additive processes have a flexibility of fabrication geometries that is radically new in manufacturing technology. Complex designs with convoluted surfaces and nested structures that are impossible to generate by any previous technology are now possible. Many of the DtM vendors exhibit this capability by showing off novelty items, such as DTM's seamless whistle and a Geneva mechanism made in one piece with no assembly by Cubital.<sup>12</sup> In time, as engineers become more accustomed to using DtM processes, they will begin to conceive important new mechanisms that cannot be manufactured by the old processes. With the ongoing improvement of material properties for the fabricated objects, these mechanisms will be functional and durable. And with the growing competition in the industry, they may not even be all that expensive.

### Art

Any technology with a major economic impact eventually becomes knit into the cultural fabric of society. Radio was originally invented to transmit messages in Morse code, but later became an important entertainment medium. The laser became a traveling road star when set to music in the popular *Laserium*. And computers have given us fractal images of breathtaking beauty.

Desktop manufacturing, when it becomes accessible to artists, will revolutionize sculpture. Artists will benefit, just as do engineers, from the freedom to experiment with designs, and to fabricate previously impossibly complicated structures. Already, 3D Systems has promoted this application of its technology by co-sponsoring a StereoLithography sculpture contest with an art college. The results are indeed novel and appealing.<sup>13</sup>

### The software challenge

As has usually been the case in the computer industry, software development for DtM is lagging far behind the hardware. The StereoLithography apparatus is fairly simple to operate, but it is a tedious process for a trained engineer to enter the CAD design that specifies the object to be built. Dozens of CAD packages are now available that write in the .STL format (the widely-used data format originated by 3D Systems), but there is a terrible lack of standardization among them, and most of them have very steep learning curves.

Desktop manufacturing will not truly become a mainstream technology until it is as easy to create a design as it is to type a document into a word processor. Typing is a skill, and it does require some manual dexterity, but once you get the hang of it you spend most of your concentration on composing sentences and pay very little attention to the requirements of the software, except when you format chapter headings, etc.

Accomplishing this level of user ease will probably take a radical new generation of CAD software, possibly based on virtual reality technology and real-time holographic projection. To use this futuristic DtM design software, you will put on a pair of sensor gloves and literally sculpt the shape of your desired object in thin-air; you will watch the results take shape in a

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<sup>12</sup> Previously, the housing of a whistle had to be made in two pieces to allow the ball to be inserted and trapped. In the seamless whistle, the ball and housing are fabricated simultaneously, with the ball already inside. A Geneva mechanism transfers rotary motion into stepwise motion, as in a movie projector.

<sup>13</sup> *Laser Focus World*, June 1989, page 104.

3-dimensional image projected in front of you. Just as your computer keyboard has certain short-cut keys, such as Caps Lock and Tab, you will have short-cut gestures to, for example, render a certain surface cylindrical or to hollow out a volume.

This type of software is a long way away, but it is feasible, and something like it is necessary to make desktop manufacturing accessible to people without specialized training for it. If it sounds far fetched, just ask yourself what you would have said fifteen years ago (in 1976, when a computer with 16 MB of RAM was a room-sized affair worth several million dollars) if someone had proposed a StereoLithography device to you.

### Organization of this report

This report brings together the latest information on the industry for current users of desktop manufacturing equipment, prospective users, and technology developers considering entering this lucrative and competitive market. It is largely based on papers presented at the *Second International Conference on Desktop Manufacturing* held in Minneapolis, Minnesota on May 6 and 7, 1991. However, it is supplemented with other data not available at the conference.

The report is divided into three major segments:

- Technology implementation and technical issues,
- Information on the offerings of current vendors of DtM equipment, and
- Case studies from actual users of the systems.

The first page of each segment gives a brief summary of the contents of the papers in it.

This industry is exciting because it is still so new and yet holds the promise of enormous expansion into all sectors of every other industry. The authors of the papers in this report represent many of the major players, including vendors, research institutions and the pioneering service bureaus and end-users. Many of the 120 attendees at the DtM Conference were users of SLA systems. Since there are just over 200 systems in the world today, the conference was a gathering of a substantial portion of the entire industry. It is hoped that this report gets across some of the excitement that was in the air at the conference, while conveying the important data needed to make purchasing, utilization and development decisions.

**TECHNOLOGY IMPLEMENTATION AND TECHNICAL ISSUES**

## TECHNOLOGY IMPLEMENTATION AND TECHNICAL ISSUES

This part of the report begins with an introduction to implementing rapid prototyping technologies by industry consultant Peter Marks. Marks gives practical suggestions for using a DtM system to enhance the performance of an engineering team through better innovation, communication and product evaluation. He includes this technology in what he calls the "new engineer's toolbox," along with desktop publishing, E-mail, virtual realities and other emerging techniques. ... *page 11.*

The University of Dayton (Ohio) has acquired a reputation as a major center of academic research on StereoLithography. In the second paper, Allan Lightman discusses the issues affecting the accuracy of models produced by this method. Sources of error include the tessellation of CAD data, stresses (shrinkage) induced by the polymerization process, and others. Dr. Lightman and his colleagues at Dayton are working to better understand and alleviate these problems. ... *page 24.*

The data that drives a DtM system is a CAD file in any one of several formats. The user has a wide latitude in choosing a CAD package to generate this file. Bernie Battaglin discusses the software and hardware available within one major CAD category, *solid modeling*, giving the various pros and cons of each package and workstation. ... *page 29.*

The raw material in StereoLithography, the major technology in this industry, is a liquid resin that polymerizes under the influence of light. The technical issues to be considered in choosing a resin are covered by Myron Bezdicek of DSM Desotech, a major manufacturer of photopolymeric resins. The important issues covered are green strength (rigidity during curing), viscosity, photosensitivity, post-cure durability, and toxicity. ... *page 34.*

John Metelnick reminds us that it is not yet time to throw out our machine tools and casting equipment. Metelnick's large model shop in Chicago has decided not to go into DtM just yet, but offers many services that complement it. He explains that some projects are still done best by numerically controlled machining. In particular, this is still the only way to directly produce a metal part. In addition, the accuracy is superior to that of SLA, and for simple geometries it is likely to be faster. ... *page 40.*

As one example of a supporting technology that can be used to generate multiple copies of a DtM-generated master, David Key explains the ProMold process available from a subsidiary of 3M Corp. ... *page 46.*

# The Rapid Prototyping Revolution: Better Products Sooner?

Peter Marks, Managing Director, Design Insight, Los Gatos, California

Peter Marks is known for his expertise in computer aided design and manufacturing, and information technology. He has helped more than 100 companies in the U.S., Europe, and the Pacific Rim to improve their competitive positions. His previous experience includes product planning and design, manufacturing engineering, quality assurance, and operations.

Design Insight is a consulting firm specializing in the application of CAD/CAM technology to world-class product development, manufacturing, and support. For users, Design Insight helps managers select and implement the best methods to streamline their operations, improve product quality, and achieve a competitive edge. For computer software and hardware vendors, Design Insight helps promising new technologies and companies achieve earlier growth and sustained success.

Mr. Marks was the University of Cincinnati's first independent studies student, doing undergraduate and graduate work in the Design, Engineering and Medical Schools. He was granted a B.S. and M.S. with highest honors.

Spend a day in the lobby of any manufacturing enterprise. Passing through, you see a stream of vendors promising products and services to help that company build better products faster, and cheaper.

Newcomers to this scene include computer-based capabilities for solid modeling, simulation, visualization and rapid prototype production. Are these new tools worthy of special attention? Can they truly help speed better products to market? Or are they simply a high tech attempt to sell us a new bill of goods and services? The purpose of this paper is to provide answers to these questions.

## What is rapid prototyping?

Rapid prototyping methods include both hard prototypes (3d hardcopy) and soft prototypes (3d computer simulation and visualization). This definition includes a wide variety of applications and technologies, such as software solid modeling, finite element analysis, simulation, 3d hardcopy, and quick turnaround manufacturing processes.

Compared to building prototypes in tool rooms and model shops, many computer-based systems are relatively compact and likely to be run by white collar professionals. Thus the name "desktop manufacturing" is also used to describe many of these new applications. This attempt to borrow interest from desktop publishing, desktop video etc. should not be taken too literally. While comparatively quick, compact, and safe, most of today's processes belong more "down the hall," or in a service bureau, than on a desktop.

Design and manufacturing engineers have always faced tough questions about whether to build a prototype to assure understanding or to forego a prototype to save time and cost. Rapid prototyping tools are changing the "right" answers. Whether "hard" or "soft," the promise of rapid prototyping is to gain greater knowledge of product performance earlier in the development cycle.

## The hoopla about desktop manufacturing

As background, the basic objective of this emerging generation of desktop manufacturing systems is to make the reproduction of 3d parts as easy and natural a process as plotting a drawing from a CAD file. The manufacturing station is, basically, a computer peripheral output device.

Most of the devices work by building layers of material, somewhat like the model builder's practice of building a topographic model by cutting and placing layers of cardboard one upon another. The differences here are that the layers are typically much thinner and the process of defining layers is directly automated from 3d CAD data. A laser scanning device is most often used to polymerize, fuse, carve, or cut the layering material. (Off-the-shelf laser technology is mature, so this is a cost-effective way to accurately deliver an intense beam of energy). In the future we may see alternative scanning and layering technologies derived from plasma spraying, electron beam welding, jet cutting or ???.

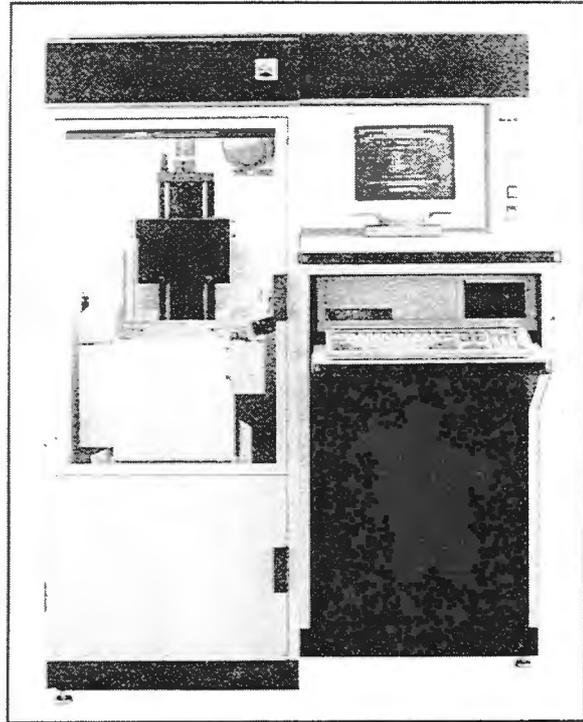
The prospective user should understand that all the new desktop manufacturing systems have limitations: size and geometric limitations due to the scanning/layering mechanism, long times to make a copy, limited resolutions, possible shrinking or warpage with some processes, finicky operation, high costs, and often dismal material properties. However, much like the prior evolution of 2d plotters from costly flat bed units to electrostatic and Xerographic speedsters, we expect to see gradually increasing sizes and improved speed, resolution, and material properties.

Even if today's layering-based system is able to reproduce the size and detail of your parts, it is not likely to be fast enough for a production system. Rather, it can convey the look and feel of a proposed part, or perhaps provide short run tooling to mold a few parts out of a more suitable material. Depending upon the application, these can be ideal tools for many companies, and useful to others on a service bureau basis.

### Can rapid prototyping save time?

Many attempts have been made to analyze how professional and engineering time is spent. Here is one view, based on a variety of sources including Booz-Allen:

- **Creating/innovating: 25%.** Creative design-to-manufacturing tasks, including researching new ideas, staying current with the technology, problem solving and design. Many engineers also add some of their free time to stay abreast of their field.
- **Communicating: 50%.** While engineers view themselves as designers and problem solvers, most spend twice as much time attending meetings, traveling, reading, writing reports and letters, answering phone calls, filling out time sheets, posting E-mail,



3D Systems' StereoLithography Apparatus.<sup>1</sup> This is one of a new generation of desktop manufacturing systems. These systems are driven from CAD data, like other computer peripherals such as plotters. Providing 3d hardcopy, they build solid objects layer by layer.

<sup>1</sup> See Dennis Medler's paper (page 64) for a discussion of this apparatus. —Editor.

processing engineering paperwork, advocating, persuading, and asking and answering questions. Even engineering drawing is primarily a communication process. Only a fraction of the time spent at a drawing board or on a CAD system is original design. The rest goes to creating a communication document.

- **Evaluating: 25%.** Checking work and making sure errors do not creep into the process. This time goes to analysis, simulation, double-checking results, analyzing engineering change requests, checking for conformance to standards, evaluating suppliers, and so on.

While the exact percentages will vary from company to company and job to job, all of us would like to use our time more effectively. We want the company apparatus to run itself with a minimum of fuss. We would like more time to innovate. We would like to become outstanding communicators, providing persuasive and impossible-to-screw-up gems of wisdom at the speed of light. We would like to catch every potential error, particularly our own, before it has the slightest impact. Can rapid prototyping help?

Our experience is that better use of both hard and soft prototypes can save time and errors in all three areas of engineering effort:

- Prototypes are an essential aid to creativity and innovation. As much as we complain about lengthy development cycles, without prototypes the alternative may be “never.” Today’s computer-based prototyping methods can save as much as half the time of traditional prototype development.
- 3d visualizations and hard copy help assure clear and rapid communication. Good use of 3d tools and computer aids can save an hour a day for many engineering professionals.
- Errors that hide in the words and numbers of reports—or in a maze of engineering drawings—become painfully obvious in three dimensions. The real time savings come from doing the job right the first time, and catching the remaining errors as soon as possible. Delays to rework designs, tooling, and production schedules can add months to the development schedule. These delays can often be avoided through early and rapid prototyping.

### Can rapid prototyping help us build better products?

Saving time is one thing. But does rapid prototyping just shorten the development cycle, or can it also help improve the product? While the vendors of rapid prototyping software and systems answer with a resounding “yes,” the question merits careful consideration. To answer the question—and to make best use of these new tools—it makes sense to consider just what goes into making a better product.

Design Insight recently completed a study of world class manufacturers. The objective of the study was to get behind the hype of computer automation and find out what the leaders are doing better than the average companies. For example, General Motors has similar technology to Honda, Toyota, Ford, Chrysler, and others. There is no lack of CAD systems, MAP networks, and so on. In fact, GM probably spends more on this technology than most of its competitors. One GM division even won the Baldrige National Quality Award. So why does GM not dominate the market in each class of car it builds? As the Design Insight study shows, it is how you use the tools that counts.

The methodology of the study was first to identify “great products.” Products chosen for the study lead their industries in terms of quality, independent reviews, market share, and

profitability. Then we looked at differences in design and manufacturing between the producers of the great products and their less successful competitors.

To get a feel for the differences, compare and contrast these two lists of famous name products. Which would you buy today?

	Brand X	Brand Y
Family sedan	Chrysler K car	Honda Accord
Luxury sedan	Jaguar	Lexus
Passenger van	Volkswagen Van	Chrysler Minivan
Laptop computer	IBM	Toshiba or Compaq
Laser printer	Fujitsu	HP LaserJet III
Word processing program	WordStar	WordPerfect 5.1
Personal CD or tape player	G.E.	Sony
Athletic shoes	Keds	Nike
Professional power tools	Stanley	Bosch

Each of the brand names listed above is fairly well known, and each has its loyal customers and specific product advantages. Even so, the products in the Brand Y column have been the winners in recent years. Some are "great products." They have had better independent ratings for quality and performance. Customers like them and buy them, and buy them again, so they have achieved majority market shares. As a result, their makers enjoy greater financial success.

Naturally, there will always be arguments about which product is best. One finding of the study was that tough competition actually helps good products get better. Yet even in tightly contested markets, it is possible to distinguish the top products from the rest of the pack. First, these products win the independent reviews for quality and performance. Second, they beat the competition in market share or "own" their niche. Third, they earn higher profits than average competitors. Great products are measurably ahead in product performance and quality, market share and customer loyalty, and profitability.

The trick, of course, is figuring out how to design and build great products. If it were easy, all our companies would be uncontested champs of the universe. Our study shows that a variety of rapid prototyping methods are an important part of these successes.

### **The best practices behind great products**

Among the findings of the Design Insight study was that market-leading companies share several "best" practices. These include:

#### *Teamwork organized around a product vision.*

Great products are designed and built by teams with a strong product vision. While success does breed success, it does not always extend to an entire company. For example, Chrysler's Minivans win praise from reviewers, dominate their market, and provide most of Chrysler's profits. Yet, not all Chrysler car programs have been as successful. Similarly, HP dominates the world of laser printers but is only an average competitor in personal computers. IBM dominates many areas; but is clearly behind in others like laptop computers. Product managers—if they provide the vision and build their teams—may have a more direct impact on company growth and profits than many CEOs.

*Innovation and quality.*

Companies that design and build great products have a culture of innovation. They want to be first with the best. Manufacturers like Sony, Honda, Toyota, Compaq, 3M, and Nike work hard at finding elegant new ways to meet customer needs. They are open to new ideas and opportunities, and are creative and persistent in solving old problems. These companies take pride (and earn economic benefits) in being first to market—but never at the expense of quality and reliability.

*Shared information.*

Teams that design and build great products get to market fast because they are organized for clear and open communication. There is a small company feel to even the largest great products producers. They eliminate red tape, cumbersome engineering change processes, and layers of bureaucracy, and they value meetings and messages that get to the point. They make effective use of technologies like E-mail and 3d modeling and adopt processes like concurrent engineering to speed clear communication.

*Continuous product evaluation and improvement.*

Great products companies make their own products obsolete. They continually eliminate problems, defects, and customer-annoying details. They make sensible investments in technology to understand customers, test products, analyze defects, and simulate alternatives. The newest Chrysler Minivan is a direct response to customer requests and should do well in holding off increasingly tough competition. The Honda Accord keeps getting better, rated among the “Ten Best” for years in a row. Hewlett Packard stays ahead in laser printers by making its own products obsolete; they are now in their third generation. The best computer companies strive to double performance every year. Sony’s audio products keep squeezing more electronic functions into smaller packages. Compaq continues to obsolete its own, and IBM’s, portable computers.

**Role of rapid prototyping in enabling the *best practices***

What impact do rapid prototyping methods have on these four *best practices* for designing and building great products?

*Clear vision and teamwork*

Rapid prototyping methods cannot assure that you have a clear vision and a talented team. They can, however, tell you how you are doing a whole lot sooner.

We found that leading companies have a clearer vision, greater emphasis on teamwork, and a more disciplined approach to establishing, measuring, and meeting development milestones. Both traditional prototypes and newer “soft” and “hard” prototyping methods are an enabling technology to give product development teams the benefit of early and continuing progress reports.

### *Quality and innovation*

New ideas are somewhat like babies—often difficult for older companies to conceive and fragile when newborn. Ideas must be nurtured to grow into mature products. Leading companies treat the conception, care, and feeding of new ideas as a top priority.

Prototypes are a stimulus to innovation. They encourage creative thinking and hasten product development at every stage. We found that companies with a good track record of quality and innovation tend to make good use of early prototyping and simulation methods.

### *Shared information*

If a picture is worth a thousand words, a 3d prototype may be worth a thousand bit-mapped pictures. Seeing, turning, touching, bending, stressing, checking for interferences, gauging customer reaction, discussing manufacturability. All of these communication activities work better with 3d visualizations and prototypes.

The Design Insight study found that 3d-based communications are often used in great products companies to help streamline engineering change processes, speed improvement on learning curves, and shorten product development cycles. Clear communication with customers, colleagues, and suppliers is especially valued in leading companies.

### *Continuous evaluation and product improvement*

Many of the important details required for continuous improvement cannot even be examined without a 3d model. Given that a problem well defined is half solved, prototypes have an important role in every kind of evaluation from customer focus groups to product testing, Taguchi analysis, and computer aided simulation.

Our study showed that 3d modeling methods play an important role in achieving lower defect rates, higher quality ratings, and a track record of continually improved product versions. Rapid prototyping processes also speed the transition to newer generations of technology.

Role of Rapid Prototyping in Developing Great Products		
"Best practice"	Typical approaches	How rapid prototyping helps
Vision and teamwork	Able leadership. Strong team. Clear objectives.	Get customer feedback. Check early milestones.
Innovation and quality	Involve key people. Make R&D investment. Reduce "not invented here" syndrome, adapt ideas. Brainstorming, etc. Speed to market.	Brainstorming. Simulate system performance. Analyze component performance. Facilitate communication between groups. Facilitate team processes.
Shared information	Minimal politics. Few layers. Meritocracy. Well-run meetings. Good project managers.	Visualization. Design reviews. Concurrent engineering. Early supplier involvement. Purchasing aids. 3d visual aids.
Continuous evaluation and improvement	Customer feedback. Measurement. Testing. External audits. Quality control. Warranty reports. Just-in-time manufacturing.	Customer feedback. "Design for x" groups. Computer aided analysis. Computer simulation (slice-of-life software). Evaluation samples. Short-run tooling. Rapid prototype testing.

Leading companies work especially hard on the process aspects of getting products to market. While they are aggressive users of new technology, they often stay somewhat behind the cutting edge. In contrast, the follower companies tend to think the magic is in the tools; they pay less attention to the process aspects. For this reason, it makes sense to view rapid prototyping tools—both "hard" and "soft"—as part of the design process.

**Think of rapid prototyping as part of an improved process,  
rather than as a widget-making peripheral.**

The application and process is more important than the elegance of the tool. Great products companies often use simple approaches to create, communicate, and evaluate new product concepts. For example, average competitors may have outstanding technology in their research labs, but little of it in production. Outstanding competitors may have lots of comparatively simple technology (simple 3d mock ups in design, simple robots on the floor, etc.), but used it widely and wisely in production.

It is easy to lose track of the best role for 3d hard and soft prototypes amidst all the hype. A variety of "desktop manufacturing" processes have recently become the object of enthusiastic articles in *Business Week*, *Machine Design*, *Design News*, *CAE*, *High Technology Business*, *Computer Graphics World*, *Plastics Technology* and other publications. Unfortunately, these articles have not provided guidance on the best applications and the alternatives.

## Rethinking the role of visualization, simulation, and hard prototypes

Perhaps the greater benefit in all this is rethinking the role of 3d visualizations, simulations, and hard prototypes in your own development process. In some cases, a computer simulation can provide significant insight, even replacing a hard prototype. In others cases, new technology makes hard prototypes cost effective earlier in the process. Combinations of soft and hard prototyping technologies are especially useful in reducing trial and error. For example, traditional prototype evaluation can be combined with Taguchi analysis or simulation to gain greater information from experiments.

## The psychology of modeling

Product developments start as a glimmer in the eye of an innovator and may take years to complete. The new Toyota/Lexus sedan took six years in development. In all the years from concept to production, engineering progresses only through models.

These models include words, renderings, analyses, and physical prototypes. Development starts with rough models and proceeds to increasingly precise and complete models. The development of a luxury sedan may start with a product specification (words) for a new car to compete with Mercedes and BMW. Soon, sketches and drawings (renderings) begin to appear. Somewhat later, numerical models (analyses) enter the scene: costs, weights, simulations, and production schedules. As the new car concept takes shape, the first hard prototypes are built. These include individual components, clay models, dashboard mockups, crash models, and so on.

One can spend a lifetime trying to understand the psychology of modeling. It involves the wiring and systems architecture of our brains, our senses, perception, language, culture, skills, and education. There are individual differences to understand: aptitudes, learning styles, and communication preferences. How do we spend our time? All of it is spent using various modeling tools to create, evaluate, and communicate.

Without appropriate models and modeling tools, no new product, no scientific discovery, not even normal human communication would be possible. "Modeling" may have started eons ago with the first words, the first cave paintings, counting on fingers, and using stones as carving and smashing tools. It certainly has changed since then. Each new modeling tool, from the printing press to the calculus, has opened up new possibilities. Like a carpenter's toolbox, engineers reach into a set of tools to build new products.

The problem is that many of us, and many of our companies, have done too little to look into that toolbox, to sharpen our tools, to discard the old and obsolete, reorganize the useful, and learn the best of the new modeling tools. Reach deep down and you may come up with t-squares and slide rules. Look to the side and you may find user-hostile CAD systems or software still in its shrink wrap package. It is all a jumble.

## The new engineer's toolbox

Emerging with a B.S., the typical new engineer has a "toolbox" containing some familiarity with English, ForTran, algebra, calculus, engineering drawing, physics, materials, and processes. While most of the fundamentals remain the same, computer aided methods have changed almost everything about the creation, evaluation, and communication of product information. Now we need to make room for tools like desktop publishing, networks and E-mail, object-oriented databases, hypertext, software solid modeling, computer-assisted

engineering, simulation, virtual reality, materials databases, laser digitizing, flexible manufacturing, holographic polymerization, and many others.

It is easy to get too wrapped up in one or more computer technologies, to the exclusion of other potentially more productive tools. Whole departments (MIS, CAD, CAE, CAM, analysis, testing, ...) are created to look after individual tools. Blinders on, they often lose sight of the end objective: designing and building better products.

Compare this to a construction crew. Imagine centralized construction service departments structured along the lines of "keepers of the big blue hammers" or "fixers of the rapid prototyping saws?" Certainly, good carpenters delight in more productive tools. But just as we look askance at the carpenter who bashes everything into place with a large hammer, so we need to know when—and when not—to use the new rapid prototyping tools. Some companies use the new tools where they do not belong. Others fail to use the best new technology. Like any skilled craftsman, it makes sense to consider the best tool for each job.

For example, reverse engineering may be important application in your company. A wide variety of new technologies like CAD, laser digitizing, or automated tolerance analysis might aid your efforts. Rather than jumping right in with the first computer tool that comes to mind, a first task is selecting the most appropriate tools.

So, which rapid prototyping tools belong in your toolbox? Here are some of your options related to rapid prototyping:

- **3d computer modeling (CAD):** 3d wire-frame, surface modeling, solid modeling, 3d digitizing, rendering/visualization, ...
- **Stereo viewing:** Stereo computer displays, holography, 3d space scanners, virtual reality, ...
- **3d analysis and simulation:** Kinematic, dynamic, finite element structural, fatigue, thermal, computational fluid dynamics, controls,...
- **Simulation and visualization:** "Slice-of-life" applications, ...
- **Physical models:** Cardboard and foam mock ups, block models, hi-tech erector sets, rework existing product, rework competitor's product.
- **Traditional prototypes:** Model shop, tool room, desktop NC machines, early supplier involvement, ...
- **3d Hardcopies:** StereoLithography, Selective Laser Sintering, Laminated Object Manufacturing, 3-D Printing, Ballistic Particle Manufacturing, Photochemical Machining, others yet to be commercialized.
- **Use of 3d hardcopies to make molds.**
- **Short run production processes:**
  - **NC and CNC fabricating:** Turning, milling, tracer lathes and mills, flame/laser/beam/hydro cutting, ultrasonic, EDM, ECM, sheet metal fabricating, welding processes, ...
  - **Low-volume plastics:** Hand or spray lay-up, vacuum or pressure bag, filament winding, casting, ...
  - **Soft tooling for molds and dies:**
    - **Plastics:** Compression/transfer/injection molds, extrusion/pultrusion, rotational and blow molding, RIM and structural foam.
    - **Metals:** Sand mold metal casting, plaster/investment/die casting, powdered metal, metal forming and forging, ...

These technologies offer good opportunities to develop better products, and to do it faster and cheaper.

- **Better products** come from the use of 3d models in concept design, team processes, and continuous evaluation and improvement programs.
- **Faster-to-market benefits** come from the time savings noted earlier; with the greater savings coming from a reduction in errors and changes late in the development cycle. If you do not make errors and never pad your development cycles, then only slight time savings should be expected.
- **Cost savings are mixed.** Early engineering costs may actually increase slightly; perhaps as much as 1% on an overall product basis. These increases should be offset by overall cost savings (typically 5 to 30%) from better design for manufacturability and early supplier involvement. The key in all this is managing the tools and processes for the right results. Remember, great products can earn significant profits while large cost savings in developing “me too” products are essentially meaningless.

Rapid prototyping and simulation tools can help develop better products, faster, and possibly cheaper. Remember, the key to success is achieving effective practices to build great products, not in simply speeding up the old prototype development and testing cycle.

### What are the important trends in rapid prototyping?

The first important trend in computer aided modeling is the emergence of hybrid modeling tools. Recall, the four kinds of modeling tools that most engineers use:

<b>Words</b>	Messages, presentations, reports, specifications, parts lists, catalogs, databases, and bills of material, ...
<b>Renderings</b>	Sketches, drawings, blueprints, images, photographs, graphs, maps, charts, visual aids, displays, ...
<b>Analyses</b>	Calculations, projections, spreadsheets, analyses, simulations, optimization, and other mathematical models.
<b>Prototypes</b>	Mock ups, scale models, parts, components, test items, full scale prototypes, ...

Over the past few decades, computer applications have tended to stay within these four modeling categories. For example, word processors and databases barely handled the inclusion of graphic information. CAD systems had rudimentary ties to attribute databases. Analysis programs provided graphic input and output in separate and cumbersome companion programs. Automated manufacturing cells were islands of automation.

Now that is changing. The most powerful new computer tools span modeling categories. If you are considering investing in new systems, resist the system integrators' promises to hook everything to everything through file transfers. Instead, consider the following:

<b>Words + Renderings =</b>	Desktop publishing, hypertext systems and object-oriented databases with graphic data types. A purely alphanumeric database will soon be a bad choice for engineering applications. In ten years, everyone will wonder why there was such a fuss about SQL (Structured Query Language).
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Rendering + Analysis =	“Soft” prototypes and “slice-of-life” applications. Rendering programs without close ties to underlying mathematical models and analysis programs will soon be obsolete. Soft prototypes to simulate specific problem domains will provide many companies with a competitive advantage.
Rendering + Prototypes =	Desktop manufacturing from a CAD database.
Analysis + Prototypes =	Smart prototypes, and integrated analysis and testing. In the past, prototypes were produced in one department with little regard to how they would be tested. Now, integrated approaches make more sense. For example, unit testing of composite materials provides good data for analytical models. Overall structural testing of roughly similar products (car suspensions, etc.) can provide loads for new product analyses. Taguchi and experimental design methods provide more information from fewer tests. In the near future, companies will combine their analysis and testing departments into product evaluation groups.

### Reorganization of design for manufacturing

A second important trend is the streamlining of design and manufacturing processes to make better use of new modeling tools. Rigid functionally-divided organizations (design, analysis, test, ..., with walls in between) were once necessary to build a critical mass of knowledge in functional disciplines. Like-minded specialists needed to be co-located to allow communication. Computer systems now make it easier to put the critical mass into databases and to rapidly communicate with peers. Remember when there was no fax, no Federal Express, telephones were shared between engineers, master drawings were caged in a central location, and access to suppliers was by happenstance? It was probably back then that your present organizational structure was defined.

There is no one right way to organize. Successful companies are finding new ways to retain deep pockets of technical expertise and still communicate with the ease of much smaller companies. A number of the approaches were listed earlier: design for manufacturing, “design for  $x$  (any particular product requirement),” early supplier involvement, technical data interchange, design to customer specification, just-in-time manufacturing, and quality circles. Each of these approaches proves successful only when taken with an equal sensitivity to process, organizational, people, and technology issues.

### The changing structure of industry

A related issue is that the structure of industry is changing. Large, vertically integrated companies were once the models of success. Now the model is likely to include a smaller core organization served by an able coalition of component suppliers, consultants, and services. This new model for success places a premium on finding good partners and assuring clear communication between coalition members. This, in turn, makes the use of rapid prototyping tools even more important.

## Selection and justification

Obviously, no company can afford the time to pursue every application and the cost to purchase every tool. Each company needs to decide which rapid prototyping applications and tools offer the highest payback.

First, you need to choose applications based on what it takes for your company and your product to beat the competition. There are a variety of useful methods for doing this analysis, including critical success factors, quality function deployment, and customer "\$APPEALS" analysis. These methods are the subject of other papers, books, and conferences.<sup>2</sup>

Second, you need to understand the range of alternative technologies and methods. You and your team should have a good working knowledge of most of the alternatives listed above. For many engineers, it is time to learn about new modeling and visualization tools, plus the latest materials and processes of manufacturing.

Remember, too, that a new tool is only as useful as the people that use it. There is little sense in buying a StereoLithography system for concurrent engineering in an organization whose designers never visit the factory floor.

Third, you need to evaluate alternative technologies in light of their ability to help you perform like a "great products" design and manufacturing enterprise. Test them as tools to create, evaluate, and communicate product concepts early in the process. Get your people involved in this evaluation.

Fourth, you need to guard against over-reliance on any one modeling approach. Better to employ a variety of easy-to-use modeling and rapid prototyping tools, than to build a giant rapid prototyping hammer and hammer away at every problem.

### Guidelines for success in desktop manufacturing:

Trying-before-buying, using a service bureau, is highly recommended for this young and rapidly changing technology. Expect today's systems to be replaced by better and more cost-effective systems, much like the changes in color copying devices over the past decade.

If you are going to buy a system, once you have narrowed your selection down to a few systems, plan to visit a user or a users' group meeting, if such a group has formed. This is the fastest way to get a balanced perspective of the potential pitfalls. When your selection is down to two or three systems, get volunteers to act as internal champions to learn the systems and run a pilot program to meet specific application objectives.

Most systems claim support for IGES and .StL file input, typically derived from solid modeling systems. (An .StL file is a sliced representation originated by 3D Systems.) Users should expect, at a minimum, a few trial runs to work out error-free exchange between their modeling system and the rapid prototyping hardcopy device.

Understand the limitations in accuracy, surface finish, speed (including dependence on complexity), material properties, need for special handling or post curing and maximum build size when comparing the cost-effectiveness of various processes.

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<sup>2</sup> Peter Marks, *Managing computer aided engineering*, American Management Association, New York, 1983, pages 22..40.

Optimal use of a system may require changes to your normal modeling practice, for example, building in a different orientation, incorporating structural supports, or breaking a large model into smaller parts which can be fabricated within volumetric limitations.

Factor in environmental considerations (venting, dermatological effects of materials, etc.) and maintenance costs when considering in-house purchase. Remember, too, these systems are not yet "desktop" peripherals, comparable to a laser printer.

The best payback often comes from using the technology to support early feedback and/or teamwork. Be sure to consider how the process and organization should change to achieve the best payback.

Consider how rapid prototyping can improve communications with customers, prospective customers, colleagues in design-for-manufacturing, and suppliers.

Consider the benefits of using rapid prototypes as master models for short run molding/casting operations. Mold materials include silicone rubber, epoxy, metal spray coatings etc. For example: "3M Tartan-Tooling," "Vulcanite Molding" (silicone rubber molds and liquid urethane molding resins), and others.

The best payback may also come from combining software solid modeling, rapid prototyping of masters and short run molding or casting operations. Understand and exploit all three technologies. It is often possible to gain considerable insight with software solid modeling and analysis programs without a hard prototype. It is also often desirable to use the prototype as a master to produce a short run of parts with improved material properties.

Keep your eye on the end objective: great products that meet your customers' needs.

Best wishes building great products, aided by "soft" and "hard" prototyping tools from the new engineer's toolbox!

# Tool-Less Manufacturing—Accuracy Issues

Allan J. Lightman, Rapid Prototype Development Laboratory, University of Dayton, Dayton, Ohio

Alan Lightman is a physicist in the Research Institute of the University of Dayton and a principal investigator in the Rapid Prototype Development Laboratory of the Center for Advanced Manufacturing at the University. He specializes in developing optical and laser based systems for test, measurement and manufacturing applications. Research and development are performed for both industrial and government sponsors.

Dr. Lightman has more than 25 years experience in experimental and applied physics. Recent interests have focused on the needs for advanced manufacturing and rapid prototyping being developed in an effort to improve the competitive position of American industry.

Dr. Lightman has a B.A.Sc. and an M.A. in Physics from the University of Toronto, and a Ph.D. in Applied Physics from the Weizmann Institute.

## Introduction

In order to meet the challenges of foreign manufacturers in the coming decade, American industry will need to increase its productivity markedly. A major obstacle in bringing new products to market is the long time required to produce the prototype parts required to visualize and test new designs. In many industries prototyping is the single most time-consuming element in the development cycle. Recently, several new tool-less manufacturing products have been introduced to produce prototypes rapidly, directly from computer files generated by CAD.

The most mature of the devices for rapid prototyping is the StereoLithography process. This process produces a prototype from polymeric material by *photopolymerization*, using a material-additive procedure. There are now available several other material-additive fabrication processes.<sup>1</sup> In the commercialized systems, the prototype is fabricated using a build-by-layer strategy, starting from the bottom layer and adding one layer at a time until the top layer is built. Each layer is constructed by writing the layer description either as an outline or by tracing every location where solid material is to exist. In StereoLithography a UV laser is directed over the surface of a liquid photopolymer curing the polymer at each location. In this system the depth penetration is adjusted to insure adhesion to the previous layer, thereby forming the model of stacked layers.

The University of Dayton is currently conducting a program (funded by the State of Ohio and a consortium of 14 industrial companies) investigating the potential for this technology and, also, introducing it to industry. The research aspects of this program investigate fundamental limitations resulting from current implementations of computer design, computer descriptor and laser controls used in the build-by-layer techniques. Also under investigation are limitations associated with the materials' physical properties, with their dimensional characteristics as they transform from liquid to solid, and with the laser-resin interaction. Our program has shown that there are several unresolved issues in the technology that contribute imprecision in the finished part dimensions. The major factors are photopolymer cure shrinkage and related frozen stresses, non-optimal layer building procedures, and inadequate 3d surface descriptors. Our program is promoting the evolutionary growth of StereoLithography into a manufacturing process that will produce precise parts more quickly, and one that can accept input data from a variety of sources, including scanning devices as well as CAD models.

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<sup>1</sup> A. Lightman, *Tool-less rapid prototyping technologies—An overview*, in *SAE Aerospace Atlantic 1991*, April 1991, Dayton, Ohio.

The issues related to system improvement can be divided into two interacting areas, computer related issues and laser-material interaction issues. The computer issues include the format and accuracy of surface descriptors, the format of the slice-layer outline and computer processing accuracy. The laser-material interaction relates to the formation of the solid material (shrinkage, embedded stresses, etc.). A mutual concern is the facile modification of the computer file of the design shape to account for the material modification in accordance with the build technique selected.

A key element in refining the process is the development of an accurate model for the process so that the results of the laser-material interaction can be evaluated prior to the start of building the object. It is essential to be able to predict the finished shape and material properties of the prototype part, and to take material modification parameters into account in the CAD description. Full characterization of the laser-resin interaction and the resulting polymer properties are required. These details would then provide the input for a system guiding the build phase in a manner that would yield more accurate parts.

### CAD issues

Software solid models based on parametric patches are superior to polygonal models because they accurately represent curved surfaces with a greatly reduced data set. Polygonal models are acceptable in displaying solid shapes because shading algorithms produce smoothly shaded pictures. Hardware prototypes from polygonal models retain unwanted facets. Surface patches provide an extension of the facet model that allows smooth blending of curved shapes.

Current rapid prototyping systems use data taken from CAD surface and solid models which are made up of slice files of vector data. There are two major ways of defining complex parts, *surfacing* and *solid modeling*. In surfacing there are four major methods used, the most commonly known being Bezier and NURBs.<sup>2</sup> Each method has its own particular advantages and disadvantages. Constructive solid geometry uses techniques such as: Euler geometry, boundary representation, and analytical. Some software uses a combination of these mathematical representations. In the current commercial software used for StereoLithography, files become so large and unwieldy that standard MS-DOS machines limit the size and complexity of the part being constructed due to the limitations of disk file memory and addressable core memory. Data files based on parametric surface patches are typically much more compact.

A major advantage of a geometric model over a model based on a raster pattern is that geometric models may be scaled. The best analogy is to the case of computer displays and printers. Bit-mapped fonts are used to provide a complete description of a character set, but only for one size. Describing fonts by Bezier polynomials, as popularized by the Postscript language, allows fonts of any size and orientation to be generated, in real time if the appropriate hardware is available.

Scaling adjustment in rapid prototyping equipment affords the advantage of being able to dynamically adjust the boundary locations to account for shrinkage that occurs during the build process. The goal is to predistort the shape so that the final part is correct. This predistortion is not a simple uniform enlargement as the shrinkage is nonuniform in each direction and will depend on the local geometry.

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<sup>2</sup> C. Potter, *NURBS vs. Bezier*, in *Computer Graphics World*, pages 77..83, October 1990.

## Laser-monomer interaction

Real-time characterization of a laser photopolymerization reaction by conventional methods is difficult because the reaction occurs quickly. Optical diagnostics, however, are well suited to the task and can be adapted to measure many of the properties of interest.<sup>3</sup> It is essential to investigate the formation of the polymer and the stresses that result during the cure reaction. These cure stresses are frozen into the material and result in shape distortion of the final part. It is also necessary to characterize the formation of the polymer material in order to attempt to tailor the process to provide the desired material properties. The data gathered in these studies will be used to validate computer models of the process that we currently have under development, and also to adjust the CAD model to account for the influence of the process on the final part.

## Infrared spectroscopy

A key element in characterizing the formation of the polymer is to obtain an accurate measurement of the degree of polymerization as a function of the incident laser energy. This is accomplished by monitoring a selected absorption feature in the infrared region. Polymerization changes the material's bond structure thereby altering the IR absorption characteristics. Monitoring a spectroscopic feature to measure the photopolymerization provides the advantages of speed and in-situ measurement needed for these reactions. The laser-activated reactions typically occur in 30 to 50 msec. Studies are underway for real-time polymerization characterization for different resin systems. The polymer is being monitored during the UV laser exposure and during the subsequent period of dark polymerization.

## Interferometry

Preliminary computer modeling of the laser polymerization process has shown that there will be a substantial increase in temperature in the region where the laser is incident. The spatial distribution of temperature is measured using a Mach-Zehnder (MZ) interferometer system. The time dependent spatial (radial and axial) distribution of the index of refraction is determined in a resin specimen that has been illuminated with an appropriate laser pulse. Correlating the index of refraction to the resin temperature permits interpretation of the data as a temperature field. An array detector measures the varying interference field data and stores the data in a computer. The data is analyzed, frame by frame, to obtain the time dependent evolution of the temperature field. This study will be expanded to include various resins and photoinitiators, and to investigate the issues related to the moving spot required for practical applications.

## Index of refraction

Interpretation of the data from the interferometer studies requires characterization of the index of refraction of the resin, both as a function of temperature and as a function of chemical conversion.<sup>4</sup> These measurements are made using the critical angle technique. The resin is supported as a thin film held in a temperature-controlled cell. The indices of refraction of the various resins are then measured as the temperature is varied. The system is also

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<sup>3</sup> A. Lightman and R. Anderson, *Studies of photopolymerization for StereoLithography using optical diagnostics*, in *SAE Aerospace Atlantic 1991*, April 1991, Dayton, Ohio.

<sup>4</sup> R. Anderson and A. Lightman, *Measurements of the refractive-index variations with temperature of a photomonomer*, submitted to *Applied Optics*, 1991.

used to measure the index variation as a function of conversion. UV laser exposure is adjusted for a predetermined fractional conversion of monomer to polymer.

### *Shrinkage*

Linear shrinkage of the resin, due to polymerization, relates directly to dimensional accuracy. We will be measuring this parameter using an interferometric technique developed for use with thin films. The film thickness is monitored during the polymerization. This parameter will be correlated with the fraction of conversion in an effort to optimize the fabrication procedure.

### *Multiple rewriting for reducing frozen stress*

Frozen cure stresses can be reduced by modifying the process of "writing" the polymer. The goal is to change the current practice, writing the entire layer thickness in a single pass, to a mode in which only a fraction of the monomer to polymer conversion is achieved on writing the layer in any one pass and several writing passes are made to achieve the final conversion desired. This will permit the stresses to relax between write cycles. There are many issues that need to be investigated here, including optimal time between rewriting, in order to yield the best stress relaxation results. Important considerations are the energy deposition and photoinitiator concentration required to ensure that gelation is achieved throughout the thickness in the first pass, fixing the layer in place by adhering it to the layer below. One form of this procedure has recently been released by 3D Systems (the *Weave* technique<sup>5</sup>).

### **StereoLithography process modeling**

An important factor in improving both the precision of the StereoLithography process and the polymeric materials available is to obtain a basic understanding of the laser photopolymerization process. To this end mathematical modeling of the StereoLithography process has been systematically undertaken<sup>6</sup> with first consideration given to simplified situations. This approach develops a level of confidence in the existing parts of the model prior to the addition of new components.

The first model formulated described the physical and chemical changes that occur in a small cylindrical volume of monomer/polymer mixture illuminated by a stationary light source having a Gaussian intensity profile, simulating a laser source. The mathematical model developed follows the time-dependent profiles of light intensity, absorbed light, extent of conversion of monomer to polymer, and temperature. The differential equations that describe change in light intensity are coupled with depth, rate of chemical reaction, and heat transfer within the small cylindrical region.

Initially, the coupled set of partial differential equations was solved numerically for an HDDA (hexanediol diacrylate) monomer reaction system. The results indicated that model performance and numerical solution procedures provide realistic results. The model is quite general and can be programmed with kinetic data for any monomer system and any set of processing parameters. Current investigation includes the effects of changes in physical and

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<sup>5</sup> See page 67 in Dennis Medler's paper for a description of the *Weave* build technique. —Editor.

<sup>6</sup> L. Flach and R. Chartoff, *A computer model for laser photopolymerization*, Solid Freeform Fabrication Symposium, August, 1990, Austin, Texas.

chemical parameters, the effect of changes in the dimensions of the exposed segment, as well as the effects of changes in the laser light intensity and exposure time.

The model does not take into account the refractive index changes in the monomer/polymer mixture. These refractive index changes are due to conversion of monomer to polymer and thermal effects. If significant, they will affect light penetration and therefore light intensity distributions at various depths into the monomer mixture. This, in turn, will influence polymerization and heat generation rates. The modular structure of the existing computer code will allow addition of the subroutines required to compute the modified light intensity profiles. Prior to inclusion in the model, the changes in refractive index due to polymerization and temperature effects will need to be quantified experimentally.

The central component of including optical effects into the model will be the development of a computer model of the interaction between the optical field and the material medium. The problem involves refraction of the incident light by a deformed surface followed by propagation of the radiation through an inhomogeneous, anisotropic material. As a result of polymerization both the refractive index and the absorption coefficient will vary spatially. Since the physical properties of the polymer are quite different from those of the monomer, the liquid surface may be expected to have a deformed shape. The refractive index will depend on temperature and there may be stress-birefringence effects. All of these need to be included in order to fully consider the problem.

It is anticipated that the proposed enhancements to the existing model will significantly improve the accuracy of the computed results. This will not only lead to a better understanding of the physics, chemistry and dynamics of the process, but will also be of direct use for prediction of laser dwell-time, depth penetration, uniformity of polymer formed, and optimum laser power.

## **Summary**

The development program underway at the University of Dayton is participating in the advancement of tool-less manufacturing technologies. Key issues identified relate to accuracies associated with the computer descriptions of the model and, also, material issues. The university is working with industry in an attempt to define acceptable standards for communication between CAD systems and build-by-layer systems. The goal is to define more robust, higher accuracy data protocols which are also more data efficient. In addition, a research effort is underway to provide a better understanding of the laser-material interaction so that parameters affecting dimensional accuracy can be incorporated into the design to provide final parts with better accuracy and a wider range of material properties.

# Solid Modeling and Today's Design Environment: Visual Prototyping on the Computer

Bernard H. Battaglin, Jr., Senior Consultant, Albert Consulting Group, Saratoga, California

Bernie Battaglin is responsible for developing many of ACG's techniques for CAD/CAM system benchmarks and workstation throughput testing. Using these tools, Mr. Battaglin has worked with many key industry clients, assisting them with their product and marketing decisions. He has a thorough understanding of the capabilities of the major CAD/CAM products that are currently available.

Mr. Battaglin has specialized in the application of computer technology to solve design and manufacturing problems. His experience includes work as both a user and supplier of CAD/CAM/CAE products. His prior experience includes responsibility for the evaluation and selection of CAD systems to assist industrial engineers in the Buick Motor Division of General Motors. He also has worked on various projects for RCA Astro Electronics Company, Storage Technology Corporation, Vulcan Software, Inc. as well as Daisy Systems Corporation.

Mr. Battaglin has a B.S. in Mechanical Engineering and Computer Science from Cornell University.

*Software solid modeling* is an enabling technology for the other technologies presented in the rest of this book. Ideally, it will allow you take full advantage of the ability of a rapid prototyping system to implement frequent changes in a product design. This is important because in addition to the design changes that come about when the engineering or marketing department changes the product or part specifications, you also have changes arising due to the mechanical issues involved in building the prototype, such as shrinkage and laser scanning accuracy.

This paper covers three main topics:

- Where *software solid modeling* technology is now, and where it is going,
- Overview of commercial solid modelers on the market today, and
- Comparison of conventional, parametric and variational modeling technologies.

At the Albert Consulting Group, we conduct hardware and software benchmarking tests for our clients. In hardware performance testing, we run various models on different workstation platforms and measure the net throughput. So aside from numbers of MIPS and megaflops, we actually take some real solid modeling programs and let you know as a user what kind of performance you can expect to get. In software testing, we have developed a test of capabilities for solid modelers. It is a design for a turbocharger assembly, and we have run it on many different CAD/CAM systems. No one system has yet passed the whole suite of tests, so we think we still have a good test. Much of what is said in this paper has been gleaned from our experience in running tests like that on various platforms.

## Solid modeling today and tomorrow

Solid modelers today are predominantly an add-on capability. Most of the modelers and CAD systems on the market started out as wire-frame surface modeling systems, then added on solids capability. As a result, applications, such as NC, finite element or StereoLithography apparatus, are poorly integrated. This poor integration means that the solid model serves mainly as a data base for the *extraction* of information, such as surface information for NC machining or finite element modeling, or slice data for StereoLithography. This extraction process hampers design fluidity, because changes cannot be propagated without redoing the extraction.

Another problem with most current systems is that they use a *faceted* or *quadratic* mathematical basis and work with geometrical primitives, such as cubes, spheres, cones, etc. These were originally used because the computing power was not available to handle the complex calculations arising in, for example, a NURBs approach. They make for a poor user interface, because few mechanical systems are built up from geometrical primitives. An engineer would rather sketch the design in freeform. They also make changes difficult because, for example, to change the size of a hole you have to first fill it in with some other solid, then redrill the hole with another primitive.

The newest and future solid modeling systems form the core of a CAD system. This allows applications to be tightly integrated. So, for example, dimensioning is done directly on the solid model. Similarly, StereoLithography would come directly off the solid model, not through some intermediate processes. Parametric and variational technologies, discussed below, allow you to change the design just by changing the dimensions of the design. This is a logical way for engineers and designers to work.

Another major change, at least in the United States, is the use of NURBs (nonuniform rational B-splines) to represent surfaces. This allows a more natural interface, allowing the engineer to work with sketched shapes rather than geometrical primitives.

### Survey of the solid modeling market

The following is a discussion of some of the major players in the market, not a comprehensive list of all the products available.

#### *Turnkey vendors*

This is a dying breed, makers of both hardware and software in a combined package. Two companies that still do this are CV and Intergraph, and there are constant rumors that they are going to add another platform. This is naturally because you the customer do not want to be locked into one hardware platform. You want the flexibility to choose whatever happens to be the best workstation at that time. Right now these companies do not allow that, but we see that changing.

**CV.** This runs only on Sun hardware, and has the widest application base of anyone. By applications are meant all the tools that sit on top of the model. They also have a very strong emphasis right from the beginning on an integrated database. They have a new assembly modeling capability. In CADD5 5X, their next generation product, you will see a parametric/variational approach.

**Intergraph.** We have some questions about them. Are they really a hardware vendor? Right now they make workstations and they make software. Can they keep up with the fray in the hardware industry? We think probably not. There is just too much competition, too many resources being devoted to increasing workstation performance for someone who is not 100% dedicated to it to keep up. They have a new NURBs-based modeler that incorporates both surface and solid technology. Right now we see their weaknesses in CAM and in their lack of a market focus. Intergraph has been spread between mechanical, architectural and mapping applications, whereas someone like CV is clearly focused on mechanical engineering concerns. On the plus side, they are the first vendor to come out with a full NURBs-basis modeling system.

*Software suppliers*

**Parametric Technology Corp.** PTC really started the whole parametric/variational design frenzy a few years ago when they introduced their ProEngineer. And now everyone is rushing to copy this technique. This is because most engineers looking at a PTC demo say, "Yes. That is exactly what I want my CAD system to do." We still see them as having some limited application breadth, meaning they have a core modeling capability but we do not see all of the NC, all the finite element, all of the other applications that we would like to see tied on top of that. They have had some significant buys. It is no longer just people buying one of these and saying, "I'll just try this out." People are coming back and they are buying significant quantities of Parametric Technology software.

**Structural Dynamics Research Corporation.** SDRC is a very engineering-strong company, and they are the leader right now in variational technology. Their new versions 5 and 6 are strong on the ability to modify dimensions and have the model update. They have a good, strong assembly modeling capability. They are weak in their links to manufacturing. This is a significant weakness, because it is one thing to model an object, but to maintain this concurrent engineering concept you have got to have strong links to all of your applications. They do have strong drafting links and strong analysis links, and they are probably the leader when it comes to analysis links with their modeler, and they are doing things such as feeding back from the analysis into the design to automatically make design changes based on analysis results. So they do seem to have some exciting new ideas. We would like to see some improvement on the user interface, which we see as cumbersome. They are having good success with their latest two releases, versions 5 and 6, and we think they are going to become a stronger player in the future as they expand from just being an analysis company to being more of a full CAD/CAM modeling company.

**McDonnell-Douglas.** They have a new parametric core modeler called Parasolids, and a new variational modeling front end called UG Concept. We see problems with this in that right now it is not fully integrated with the rest of their line. We also see problems with them having an old style user interface.

*Hardware vendors*

IBM and HP have taken different approaches to the CAD/CAM and modeling issues and it will be up to the market to decide who has really got the right idea.

**IBM.** They offer software for IBM hardware. Their three products are CATIA, CAEDS, and CADAM. CATIA is a very strong surface modeling package. We think it is the best surface modeling package available. They have a broad application base and they are optimized for the IBM hardware. Unfortunately their solids modeling is not nearly as well integrated as we would like it to be. So for surface modeling we think CATIA would be a good selection. CAEDS is the same as SDRC, weak in NC, strong in analysis, a good modeling package. CADAM is a little bit confused right now. They have PC products, workstation products and mainframe products. There does not seem to be a coherent plan on where to position the CADAM products.

**HP/Apollo.** In contrast to IBM, they take an open systems approach. They will go into a customer and say, "We want to provide you with a CAD/CAM solution, and you can pick the solution you want." They seem to be having good success with that. They have some impressive workstation technology that has come out recently.

### *New approaches*

The following is a brief discussion of three innovators who are showing technology that we think will drive this industry. Another company in this category is Parametric Technologies, which is mentioned above.

**Ashlar.** Ashlar has probably the most innovative user interface that we have seen on the market in recent times, and in fact SDRC version 6 has incorporated a lot of Ashlar's ideas. The idea is that with a dedicated workstation running at 20 to 30 MIPS, that workstation can do a lot of thinking about what you might want to do with your design, and anticipating what your next move might be, rather than just waiting for you to pick 1, 2, 3, 4 or 5. So we think Ashlar's done a good job of pointing the way to a dynamic user interface. We expect to see most of the major vendors will be incorporating some of these ideas into their products in the near future.

**AutoCAD.** AutoCAD has revolutionized the CAD industry with two major ideas: wide distribution through low cost, and open architecture. AutoCAD has been making CAD available to the masses, and they also have a solid modeler at a fairly low cost. More significant is the way AutoCAD has pointed the way with an open architecture. Everything in the AutoCAD system—the menus, the commands, the databases—is very open so that all third party developers can easily access that base and add on their own products. In the '90s, we do not see how any one software developer is going to handle the modeling, the NC, the analysis, all of the different aspects that should be part of concurrent engineering. The only way to tackle this is with an open architecture that allows third parties to work with your system. We do not think AutoCAD is necessarily the answer for a professional CAD system, but it certainly points the way for this open approach and how it can be used to get the best solutions from numerous different people incorporated onto one common platform.

**Spatial Technology.** This company is doing interesting work with solids-based machining. You have probably heard it said that solid modeling technology will allow you to machine a part automatically from a CAD file. But by now you know that it is never that simple. Well, here comes Spatial Technology with some products that look at a solid model file and make some feature-based manufacturing decisions and help you machine the model based on the data file. So we think that is a good technology.

### **Modeling technologies/methodologies**

Now we will wrap up with a short discussion of the three types of modeling mentioned above: conventional, parametric, and variational.

#### *Conventional*

This is the technique that builds a design out of geometrical primitives, such as spheres, cubes and cones. It is probably what most of you are using right now. Its advantages are that it is available today, and that it is suited to workarounds. Anyone who has worked on a solid modeling system has spent a lot of time fudging the design—moving something a little bit off so that it doesn't screw up the modeler, moving the edges so they match, playing with different ideas. You have the flexibility to do that in a conventional modeler. The disadvantages are that spheres and cones are not a natural way to design things, it is difficult to modify designs, and it is difficult to integrate with other applications.

### *Parametric*

This approach is conceptually simple because it is a step-by-step process. This makes it easier to develop, as is evidenced by the appearance of several parametric solutions on the market. There is a speed advantage achieved by limiting the number of equations to be solved by the workstation. And it is suitable for a range of common parts and geometry. The argument you will hear against the parametric approach is that it is inherently sequential in nature. When you design a model, you go step by step through the design process. If you have to change that step-by-step process, it can give you problems. That can make it difficult to modify the design once the sequence is set. It is also difficult to do tolerance and sensitivity analyses.

### *Variational*

The variational approach is not sequential. In designing a part, you can dimension it one way, then modify it in another way. It is more suitable for design analysis, such as tolerance analysis and sensitivity studies. These techniques answer the question, "How much can I slop up the tolerances on this part, making it thereby less expensive to manufacture, but still maintain my design intent?" The variational approach also makes it easy to modify constraints in the design, and to integrate different design rules, which can be useful in doing StereoLithography. This approach is more difficult to implement and can give rise to pathological cases, so it may be a while before we see some really good software based on this method.

The parametric and variational methods are both immature technologies. Software based on the parametric approach is available today to fill some immediate needs. We think variational technology looks like a better long-term solution. Both approaches will create new data transfer problems well beyond what IGES provides for now in transferring a model. What happens when all your design intent and methodologies are wrapped up in the model? IGES does not begin to address such data transfer issues.

### **Summary**

Application integration is the key to preventing the traditional schism between engineering and manufacturing. Once you have a software model, how tightly your applications are integrated determines the productivity of your environment. Variational solid modeling and integrated applications are the enabling technologies of the future for concurrent engineering.

## Criteria for StereoLithography Resin Selection

Myron J. Bezdicek, Market Development Manager, Rapid Prototyping Resin Program, DSM Desotech Inc., Des Plaines, Illinois

In the Fall of 1990, DSM Resins, a Dutch company, bought the Photocurable Polymer Group of DeSoto, Inc. The result is DSM Desotech. Myron Bezdicek was formerly employed by DeSoto, where his responsibilities included coatings research, research management, Stereo-Lithography resin sales, and management of a rapid prototyping service center.

Mr. Bezdicek received his B.S. in Chemistry from North Dakota University.

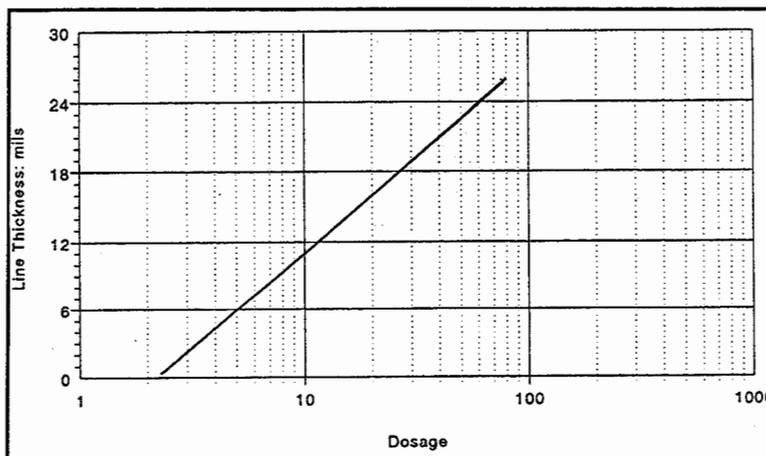
In order for rapid prototyping systems to live up to expectations, they must provide more than a crude representation of an idea or concept. The primary objective is to produce an accurate model, usually with tolerances of  $\pm 5$  mils or less. Of nearly equal importance are the fabrication speed (throughput) and functional properties (e.g. durability) of the finished model. Resin is one of the variables in the StereoLithography process that can impact the satisfaction of these requirements. This paper will discuss key resin selection criteria and the resulting benefits.

### Processing constraints

To compare StereoLithography resins, it is essential that the resin processing constraints be understood. Rapid prototyping systems using lasers and liquid resins currently exhibit the following shortcomings:

- Inability to achieve complete cure in the vat,
- Limited workable viscosity range, and
- Toxicity of the liquid resin and associated vapors.

*Partial in-vat cure.* Cure, or resin solidification, occurs only at the surface of the liquid, with each exposure of the beam generating a bullet-shaped solid. The depth of cure is dependent on the applied dosage, the units of which are  $\text{mJ}/\text{cm}^2$  or  $\text{mW}/(\text{cm}^2 \text{msec})$ . The longer the focused beam shines on a specific



Line thickness vs. Dosage for Resin 4473-124-1.

area, the deeper the bullet-shaped solid becomes (see graph above) without increasing the overall cure percentage. Rather than being a uniform solid mass, there is a spatial variation in the degree of cure with the air/solid interface being the most thoroughly cured.<sup>1</sup> The cure at the liquid/solid surface is so low that these surfaces are basically a soft gel.

<sup>1</sup> R.P. Chartoff and L. Flach, *An analysis of laser photopolymerization in RadTech 90 North America Conference Proceedings*, v. 2, p. 52..61.

To produce a 3-dimensional model, these partially cured layers are slightly overlapped to provide cohesion. As an example, to create a model with 10 mil thick layers, each layer is cured 12 to 16 mils deep to provide a 2 to 6 mil overlap. The degree of overlap can be precisely set by the operator, the advantages of which are not germane to this paper.

As might be expected, the physical properties of partially cured (green) models provide dramatically less structural strength than after a full cure. This is important when you consider that a green model must:

- Resist the distorting force of shrinkage due to crosslinking,
- Sustain its own weight upon removal from the buoyancy of the liquid resin, and
- Remain unaffected by handling during rinsing and any support removal in preparation for final post-cure.

*Viscosity.* Since models are made by combining layers, and thinner layers provide smoother, more accurate reproduction, accurate recoating is critical. It is quite common for StereoLithographers to produce models with 5 mil layers, and for more critical shapes, even thinner layers have been utilized. To prepare the next working surface, the process relies on a dipping step to fully wet the surface, a wiping bar to remove some of the excess resin and a delay to allow the resin surface to finish leveling. For these reasons, it is best to work with a resin of low viscosity.

*Toxicity.* Operator safety is achieved by minimizing exposure to the uncured resin and rinse solvents. Even if full cure could somehow be achieved in the vat, upon removal the model would still be coated with liquid resin. StereoLithography resins, usually multifunctional acrylates, are considered potential skin sensitizers<sup>2</sup> and, as a result, exposure should be minimized by utilizing protective equipment like disposable gloves, a lab coat and safety glasses prior to post-cure. Fully post-cured models can be safely handled without protective gear.

By selecting appropriate resins, the StereoLithographer can safely achieve his objectives of accuracy, increased throughput and improved durability. The key resin features that will enhance the process are as follows.

### Green strength

Green strength refers to the rigidity of the partially cured resin and can dramatically impact model accuracy. It has been demonstrated that higher green strength resins are less susceptible to distortion from the shrinkage that is generated by in-vat and post-cure crosslinking. High green strength is also beneficial since models must be handled during rinsing and support removal, prior to post-cure. It should be noted that higher green strength does not necessarily correlate with increased brittleness after post-cure.

### Viscosity

Low viscosity, especially less than 500 centipoise (cps) at 25°C, improves machine throughput and model accuracy. In a recent comparison, a 300 cps resin decreased the SLA-250 recoat time by as much as 75%, as compared to a common 1600 cps resin. The thicker resin required 60 seconds of combined wiping and dwell delay, as compared to 15 seconds for

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<sup>2</sup> A "skin sensitizer" is a material that can cause a rash or other adverse reaction on skin. The severity of the reaction varies from person to person. If the material is inhaled, the reaction can lead to restricted breathing.

the low viscosity sample. That 45 second per layer time savings translates to a five hour shorter production run on a two inch tall model (400 layers of 5 mils thickness).

Thorough leveling of the resin surface, which takes longer with higher viscosity, is especially critical for the fabrication of thin layers or large surfaces. As an example, if a model is constructed with 5 mil layers, a leveling inaccuracy of one mil is a 20% error. This deviation on a single layer may appear insignificant, but the cumulative effect over multiple layers can exceed tolerances.

Added benefits of low viscosity are faster and more thorough draining of high-aspect-ratio features and generally easier rinsing. Fast, easy removal of excess resin prior to post-cure improves the accuracy of models and shortens processing time.

### Draw parameters

The proper draw speed, the speed with which the laser scans the vat, which depends on the photosensitivity of the resin, in turn determines the fabrication time for a model with a large horizontal cross-section.<sup>3</sup> Therefore, the faster you can cure a specified thickness, the quicker the production.

Recently it was discovered that some resins have a higher sensitivity to in-vat swelling of the green model. These resins would have been avoided, except that they offered significantly improved durability. Therefore, upon further investigation, it was learned that the swelling was dependent on composition,<sup>4</sup> but could also be prevented by utilizing solid wall construction techniques. Solid wall construction cannot, however, always prevent swelling and possible distortion of thin walled (less than 20 mils wide) features and supports.

Solid wall construction is a draw technique in which essentially the entire slice of the model is cured as opposed to a honeycomb pattern. A honeycomb pattern of cure leaves pockets of resin unreacted until the post-cure step. Solid wall construction is generally more accurate in terms of shrinkage prediction but, all parameters being equal, takes much longer because the laser must make many more passes over the surface. The ideal resin is capable of being used with either draw technique, without measurable swelling.

### Functional properties

The method of cure and other processing constraints keep photopolymers from matching the properties of engineered plastics. However, the durability and flexibility of StereoLithography resins has improved tremendously, and further improvements are expected.

Many StereoLithographers have demonstrated that combining this technology with RTV (room temperature vulcanized) molds and spray metal tooling can also provide multiple copies in a wider variety of functional properties.<sup>5</sup> When using StereoLithography models as

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<sup>3</sup> For a model with a small horizontal cross-section, more time is spent leveling the resin and loading the file than scanning, so the draw speed is less significant.

<sup>4</sup> E.J. Murphy, M.G. Sullivan and M.J. Bezdicek, *Swelling distortion in StereoLithography* in *Proceedings of The Second International Conference on Rapid Prototyping*, University of Dayton (Ohio), June, 1991.

<sup>5</sup> F. Prioleau, *Beyond prototypes: Using StereoLithography for production-quality parts* in *National Conference on Rapid Prototyping*, June, 1990.

See also page 130 of the paper by Phillip Ulerich for an example of using StereoLithography in conjunction with spray-metal molding. —Editor.

patterns for secondary tooling, durability of the pattern is still a concern. Durable patterns are less likely to be broken or cracked prior to completion of the secondary tool.

A use for StereoLithography that has yet to be fully exploited is the construction of direct investment casting patterns. Feasibility has been demonstrated using both flash and shell casting techniques.<sup>6</sup> Further formula modifications are expected to enhance the process by shortening the burnout cycle.<sup>7</sup>

## Safety

Generally, the resins utilized in the StereoLithography process are considered potential skin sensitizers. They can, however, be safely handled on a day-to-day basis if proper precautions are taken. This includes the use of proper eye protection, lab coats and disposable gloves.

In 1990, a common resin component, 1-vinyl-2-pyrrolidinone (V-pyrol), was linked to the occurrence of benign and malignant nasal tumors in an inhalation study using rats. As a result, steps should be taken to minimize inhalation exposure to this component. Alternatively, ask your resin supplier to provide products that do not contain 1-vinyl-2-pyrrolidinone.

An often overlooked aspect of process safety is the rinsing of excess uncured resin from the green models. Preferred resins can be cleaned with isopropyl alcohol rather than other more abrasive or toxic solvents. To minimize exposure to wash solvents, low viscosity resins are recommended since they generally provide faster and easier rinsing.

## Summary

Resin selection makes a difference! To achieve the best possible results for a variety of modeling needs, the StereoLithographer should look for the following resin features:

- High green strength.
- Low viscosity (less than 500 cps @ 25°C).
- Fast cure speed.
- Durability.
- Investment castability.
- Not containing 1-vinyl-2-pyrrolidinone (V-pyrol).
- Can be cleaned up with isopropyl alcohol.

You must consider trade-offs. Right now, there is no one resin that can give you all of these features together. There are, however, resins that can do most of them or various combinations. It is a matter of what you want to do and how often you want to do it, because these resins can be interchanged in the machines by draining one and refilling with another.

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<sup>6</sup> S. Kennerknecht and D. Sifford, *New dimensions in rapid prototyping explored for aluminum investment castings in INCAST*, March, 1991, p. 5..10.

<sup>7</sup> E. Murphy, et al., *StereoLithographic vat compositions for investment casting patterns*, U.S. Patent Number 4,844,144.

Myron J. Bezdicek, *Investment casting with Desolite® SLR®804 & SLR®805*, DSM Desotech Inc., November, 1, 1990.

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**Question:** Are any of the StereoLithography resins affected by catalysts that could speed up the curing?

The question assumes that resin curing is the bottleneck in the system. But actually, we can make resins considerably faster than they are right now. The more important issue is how fast you can run the system. There are mechanical constraints in terms of how fast you can move the beam and different things like that.

When this technology first started, resin curing was definitely the rate limiting process, but, partly due to higher available laser powers, that is no longer the case. We actually can run resin too quickly; it can be too reactive and cause problems under some circumstances.

**Question:** Are there other ways to cure a resin, other than using light?

Sure. There are a lot of other ways to cure resin, such as thermally and chemically. But those methods do not give you the specific advantage of photocure, which is the ability to cure in a very small, well defined area. Wherever light of the appropriate frequency and intensity hits is where you get cure. If you start using a thermal process with a liquid like this, you have to worry about heat dissipation. We and some other people have also taken a look at chemical curing. Those processes are just not quite ready to go, and they do not give you the level of control we have with photocure.

**Question:** Have you had much experience with the new *Weave* software?<sup>8</sup>

Yes. The new *Weave* software is designed for use with resins where swelling can be a problem. Actually, *Weave* is just another term for solid wall construction, where you have very tight cross-hatching instead of having your hatch spacing at 20, 30 or 40 mils and leaving little pockets of uncured resin. People use our resins and other people's resins both with *Weave* and without. But some resins have to be used only with *Weave*, or *Weave*-type construction.

**Question:** Would you comment on the tank life of the resins.

That is a really good question. I wish we knew what the tank life is. The resin is constantly being cycled, with part of it being cured into models, and new resin put in to replenish it. But over a long period of time, there can still be some of the original batch in there. We have had instances where tanks have gone bad, but in each case we have found a cause which is outside the sphere of normal usage. On the other hand, there are people who have been running tanks now since the first machines came out in 1987 without ever having a problem.

**Question:** Would you comment on the material used in Cubital's process.

The material for the Cubital machine is considerably different than that used for Stereo-Lithography. The concerns or the features that you worry about here with these resins are not

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<sup>8</sup> See page 67 in Dennis Medler's paper for a description of the *Weave* build technique. —*Editor*.

the types of things that you would worry about with the *Solider* process. Since they do not work in an open vat, they are able to work more easily with higher viscosity materials. They get total cure on every layer of the part, so green strength is not an issue. Odor is not really an issue, and handling is not as much of an issue because when the part comes out, it is already cured. Their concern is to get it out of the block of wax.

**Question:** Do you see any consolidation coming to distribution in the materials market? If you are doing StereoLithography today, you have two or three resin suppliers you go to, then if you are going to make a mold, there are four or five places you can go for those materials. Do you see the emergence of a kind of rapid prototypers' one-stop materials supply outlet?

I do not think that is going to happen any time soon, only because the people who are developing materials, Loctite, Allied Signal, Ciba Geigy and DSM, have all taken a different approach to what we are going to do in terms of the types of products we are going to develop. At DSM, we have spent a lot of time working on investment castability, and we have spent a lot of time working on low viscosity material development. Other people are working on the higher viscosity side because of the features they think they can build in. To get all of these people together in a room and have them agree on something is a long shot. I do not see that happening any time soon.

On the other hand, consolidated distribution is not something that vendors have to agree among themselves on. If you want to buy our products for distribution, we will be happy to sell them to you. But I do not see any movement in that direction.

# The Unique Role of the Traditional Model/Prototype Shop in Today's Product Design World

John Metelnick, President, Wielgus Product Models, Inc., Chicago, Illinois

Wielgus Product Models has earned an international reputation, in over 40 years of prototyping, for quality work and timely delivery. With four shops, in Chicago and California, they do \$4 to 5 million annually in full-service model making. This work includes product prototypes, from golf tees to garden tractors, architectural models and courtroom models. In the early 1970s, Wielgus pioneered the use of rigid polyurethane in RTV molds to produce precision prototype copies.

John Metelnick bought Wielgus from its founder, Raymond Wielgus, in 1967. Prior to that, he had set up and operated Garco Canada Ltd. and went to Chicago to become the General Manager of the Garco Light Division.

Mr. Metelnick holds a B.S. in Mathematics and Physics from the University of Manitoba and a Certificate of Business Administration from the University of Toronto, and is a member of the Industrial Design Society of America.

A few years ago, I wrote an article for *Plastics Design Forum* entitled *Prototyping today: Myths and realities*. At that time, 3d machining was rapidly emerging as the high-tech process of the future. There were dreamy articles in major publications giving very distorted pictures of what computer driven machines could do. These fairy tales told of designers who sat at computer terminals all day, and on leaving for home would download their data to a model shop below them. There, a CNC milling machine was waiting, and by the time they came in the next morning it had churned out a prototype for them. Within a few years, cold reality began to set in and this kind of hype died out.

Now, five years later, here I am in the age of Rapid Prototyping, and again we are seeing similar hype. RP as a computer technology is probably two orders of magnitude "higher" than CNC was five years ago, but the stuff in the air is still a lot of hype.

Just six months ago, an article in the Sunday *New York Times* was gushing all over about the magic of StereoLithography and how prototypes were being made in "minutes and hours instead of days and weeks." Another system banners across the top of its literature "Models in Minutes—Concept to Reality."

SLA and its cousins *are* powerful tools, but none of them is a magic wand.

The problem is that some CEO reads this on Sunday. On Monday morning, he buzzes his head of product development, waves the article in front of his nose, and wants to know "why don't we have one of these machines?" CEOs are often not easy people to convince that, whatever the article might say, it is not quite as easy as plugging in a new Xerox machine.

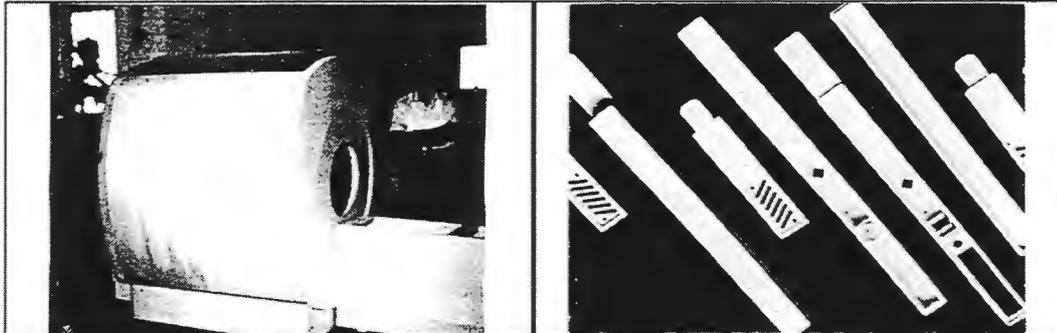
The SLA hype is following the same pattern as CNC's did. Now that it has been around for a couple of years, the lofty claims are toning down. This is true at least among the SLA operators, who have to perform real stuff for real customers. In the past six months we have done work for a half-dozen SLA people and have found them quite realistic about what they can and cannot do. In three cases they volunteered to us that they have advised clients that some parts would best be done by CNC.

## The prototyping spectrum

The word *prototype* can have quite a few different meanings to different people on different projects. Here are some examples of the great variety of services that a general proto-

type/model shop has to offer. The number of stars next to an entry indicates the extent to which desktop manufacturing or rapid prototyping systems can contribute to that category.

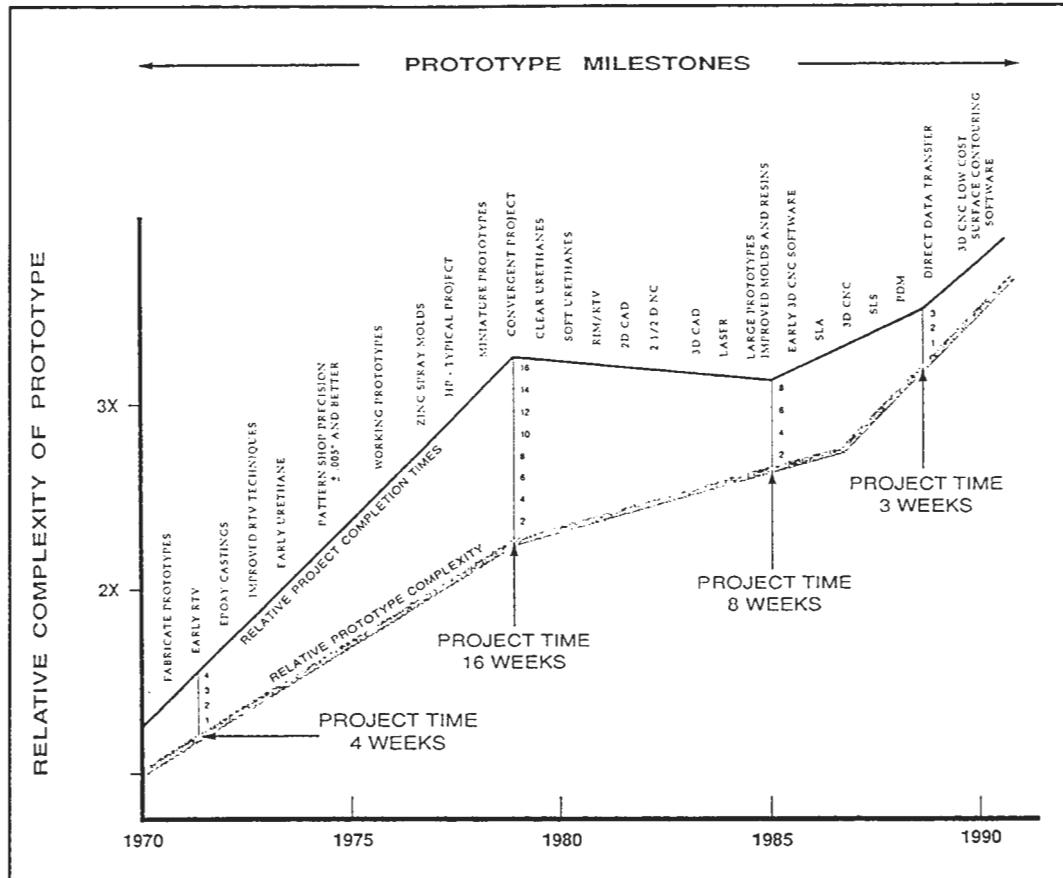
- “Soft” prototypes. 3-dimensional software solid modeling.
- “Hard” prototypes. To hold and feel:
  - Ceramics..... \*\*
  - Metal:
    - Cast or machined..... \*
    - Sheet metal.
  - Wood.
  - Plastic:
    - Miniature..... \*
    - Medium..... \*\*\*\*
    - Large. .... \*
    - Clear, tinted. .... \*
    - Soft, flexible.
  - Prototype copies..... \*\*
- Working prototypes.
- Field-test prototypes.
- Focus group prototypes.
- Political prototypes (to placate senior executives who cannot or will not read drawings and do not trust “pretty pictures”).



Sample prototypes. On the left is a wood prototype of a nuclear magnetic resonance imaging machine. Wood was used because it enclosed a 15-ton magnet and the shroud and patient transport table had to have an absolute minimum of aluminum or brass. On the right is a set of medical test strips done on CNC; we programmed and ran 20 pieces in one day.

### The modern history of prototyping

The following graph provides a short history of the recent development of prototyping, as we have seen it take place over the past 20 years.



The lower line in the graph represents the level of complexity for prototypes of that time. The distance between the two lines shows roughly the lead times that were normal at the time. Above the upper line is listed a series of milestone events in the progression from the simpler prototypes of 1970 to the sophisticated models demanded today. The graph is intended to show that complexity has increased about 3-fold over 20 years, while lead times have gone down by about one quarter. This is for all prototypes, not just RP.

Some highlights of the milestones:

1972: (Less than 20 years ago.) First known precision prototype cast in rigid polyurethane in an RTV mold.

1970s: Steady improvement in techniques and many attempts at better resins. Customers wanted higher precision, which called for even better mold methods, and patterns made with mold shop methods.  $\pm 5$  mils began to be the standard.

Mid 1970s: Designers continued to escalate their demands for precision and fast turn-around.

1978: Final days of the era of the leisurely project.

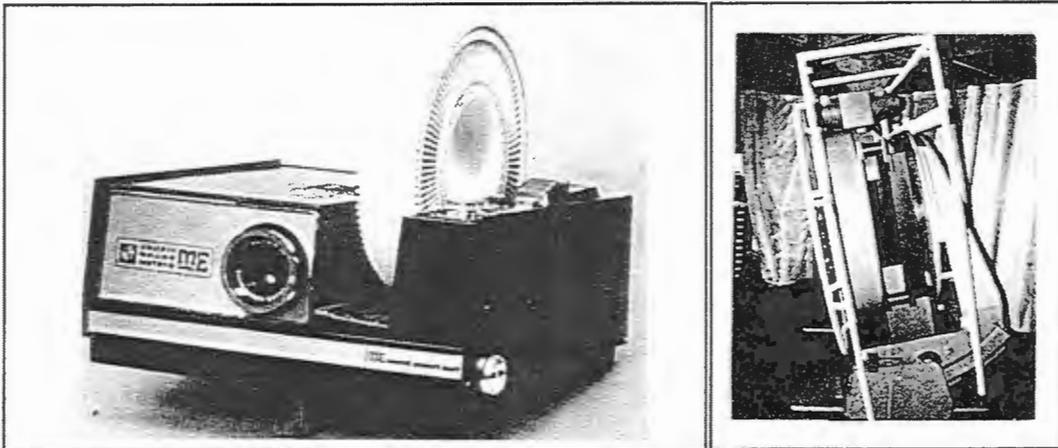
1979: Turning point in time-frame for prototyping projects. Convergent Technologies was a modern Silicon Valley start up, driven by time pressures from both venture capital and their successful first product. They warned us 6 weeks ahead of time that we and the tool-maker would start on the same day. We had 2 weeks to fabricate the first functional set of 14

parts for the toolmaker. We had another week to fabricate the second set for RTV mold and urethane copies. 3½ weeks from start to first set of 14 urethane parts. The normal time frame had been compressed to less than half! Our world and your world have never been the same since!

Late 1970s: Arrival of good, clear, tinted urethane.

Early 1980s: Availability of good, soft, flexible urethane. Also, projects were ratcheted up several notches in complexity.

Late 1980s: Techniques continued to improve, materials got better, projects got even bigger.



**Sample prototypes.** On the left is a sound-on-slide projector. We made some 15 of these in about 1970, hand-fabricated in acrylic because epoxies of the day were too viscous and too brittle for the purpose. On the right is a CAT scanner, including full front and back covers, completed in 12 days from some drawings and sketches. This version has many small parts are rigid foam massing shapes, but the rotating head structure and 15° trunion tilt mechanism are to print.

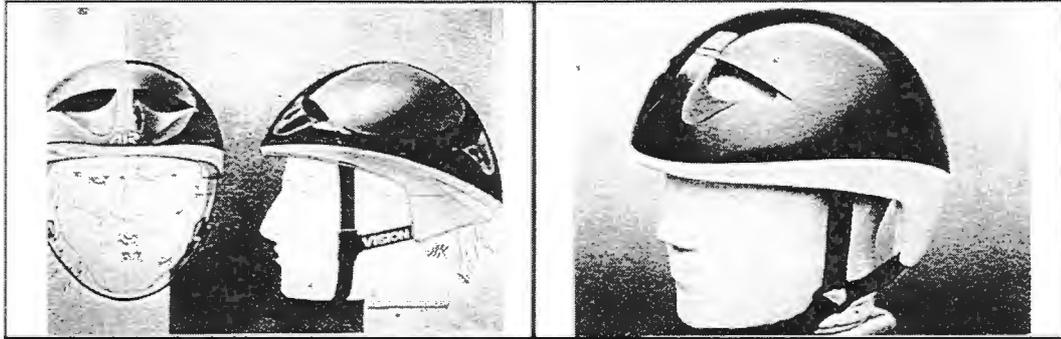
Now what this all means is that the movement to faster prototyping has been going on for at least 10 years. Do not be distracted by the claims that prototypes take “weeks and months” by old fashioned methods instead of RP. We get very, very few prototype parts today that run into weeks, and those we do get are almost always too big for systems such as SLA.

### A case study

Let me describe one typical project from last year. It is an excellent example of how, in the heat of the new product battle, one must scramble to use everything available.

A young design/engineering shop got a \$50,000 project from one of the two NFL helmet suppliers to create a new skateboarding helmet for the upcoming annual show. They had planned to have the helmet designed on Alias but it was out of their budget. Still more important, the designer realized he had to spend several days subtly refining the physical shape—in real space. They put it on 2d CAD and we shaped a styling model in 10 lb/ft<sup>3</sup> foam, which took a week to refine and tweak. They flew this refined exterior model to Santa Clara where it was digitized. Half of it was scanned vertically every few degrees of rotation, giving hundreds of thousands of points. This led to the first disaster of the project: their new 3d computer could not cope with all this data. Time was rushing by, and the show was fast coming up.

Instead of doing the helmet shell by SLA as they had planned, they asked us to make a two-part mold of the outer surface of the helmet model. We cast a helmet shell, finished it, then rushed it off to the client. Then came the second disaster. The supplier of foam liners had said he would do the liners for the prototype, but he had meant he would do them in 3 to 4 weeks! The time before the show was now down to some 8 days.



Low-tech rapid prototype skateboarding helmet. On the left are shown the early design sketches. On the right, the finished prototype. The process of producing the prototype is described in the text.

They rushed the shell back to us. We made a new inner plug and shot the liner in place, after a number of tries, using the very non-tech desperation method of the canned foam used to make mountains in model railroading. With many long nights worked, we finally delivered their sample helmets in time for the show.

After the show, high-tech finally caught up with the project and they digitized the helmet by stylus. The tools for that version and two other sizes were made from the CAD files used to make the first prototype.

### The role of the traditional shop in rapid prototyping

I was asked at the First Desktop Manufacturing Conference six months ago if we intended to go into SLA or one of the other systems. The answer was, and still is, "Not likely." That is a highly specialized area, the equipment is expensive, and there are already over 200 SLA machines out there—including at least five in the Chicago area alone. It services a somewhat narrow slice of the wide spectrum that has to be serviced by a shop such as ours.

We, as a specialized model/prototype source, can better use our skills to support the work of RP systems. Expert as the SLA people are at what *they* do, we find that they are not very expert at what *we* do. For instance, with a few notable exceptions, we find they are not terribly proficient at turning their patterns into a dozen urethane copies that look like production parts.

This is not surprising. RP is a high-tech computer business, an engineering discipline. (Although I must say it was most interesting to hear Dr. Lightman say that final accuracy with layering systems is an art and not totally an engineering exercise.) Making RTV or other types of molds, and casting urethane copies in a variety of formulations, are low-tech model shop activities. They are subject to the temperature and humidity of the day and even to the whim of the operator.

We are on the ground floor. All of the awesome computer stuff has been filtered down to us, and we have to make it all come together in the real world. In so many cases it still boils down to "Do whatever you need to do to get us first parts on Monday."

Therefore one of the prime services of a model/prototype shop should be to provide many forms of model services *before* the SLA phase and full-service mold and urethane copy services *after* the SLA phase. Our role should be to continue to develop better and faster mold materials, better and stronger casting resins, and better finishing methods. For instance over the past five years we have reduced finishing time and cost by 50% to 75% by improvements in our RTV mold methods.

The other, and much bigger, area of concern for us is continuing to improve conventional high-tech machining with new hardware and software programs. These already make full mathematical contour surfacing competitive in many cases with SLA and other RP systems, both in overall time and cost. The big desktop manufacturing noise of the past few years has drowned out the fact that the very same computer explosion that made computer-layering RP possible has done much the same thing for CNC machining. The traditional model/prototype shop can now run powerful software on a 386 computer at 33 MHz, with a 140 MB hard disk and 8 MB of RAM. They rake in the same 3d CAD files over high performance modems, through their IGES translators, into their machines.

I emphasize that I do not for a moment deny the importance of RP in your product management activities. It is fast, it is relatively accurate, and it does things that cannot even be contemplated by traditional prototyping methods. But studies by us and others show that on many parts a CNC machine can often match the *real* "minutes and hours" touted by SLA.

CNC has its own advantages to offer. The machine turns out a sturdy part in ABS, polycarbonate, composite, aluminum or whatever. The part is not fragile, does not need post-curing or much benching, nor does it need supports to fight sag, warp or curl. And, depending on the size of the part, you might well machine a half dozen copies in design material faster than you can make a mold and cast copies.

There is no question that a \$200,000 or \$400,000 SLA machine will do things a CNC cannot do. But a CNC mill *will do in house* many things the SLA will do. It may even do some things better.

Where do we go from here? It is hard to say if improvements keep coming as fast as they have been. Our guess is that experienced RP users will combine the various resources more, such as by using DtM for complicated sections to be inserted into large, traditionally fabricated, prototype patterns.

Your job is to use all of these systems wisely, to *your* best advantage. Our job is to help you achieve your prototyping goals, on time and under budget.

# Prototyping and Short-Run Molding Systems

David Key, National Marketing and Sales Manager, ProDesign Inc., Minneapolis, Minnesota

ProDesign, Inc. specializes in economical tooling and fast turnaround for prototype parts. David Key oversees the marketing and sales efforts of this wholly owned subsidiary of the 3M Company. Prior to his present responsibilities, Mr. Key was a marketing specialist for General Electric's Lexan Division and before joining GE was an application engineer for the Polymer Corporation.

Mr. Key holds a B.A. in Business and Economics from Coe College and a M.B.A. in General Management from the University of St. Thomas. He has been a member of the Society of Plastics Engineers since 1979, and served as councilman during the formation of the Eastern Iowa chapter.

This paper describes a technology that can be used to obtain low-volume copies of "rapid prototypes," and possibly also satisfy needs for short-run production quantities. This is a 3M technology, called *ProMold*, and it is useful for quantities of 1 to 500 where first parts are needed in 4 to 6 weeks. Molds can include most production features, and generally cost an average of 12 to 18% of comparable U.S. production P-20 steel molds.

The purpose of this paper is to explain the broad latitude of this technology and to describe some of the steps followed in using it.

## Two distinct systems

The technology can be broken down into two distinct "systems." For discussion purposes, we will refer to one system as "prototyping" and the other system as "short-run molding." Prototyping is normally used where 1-75 parts are needed to prove out designs, check form-fit and function, for marketing samples, etc. Short-run molding is normally used to satisfy production needs where annual production quantities are too low to justify the costs of production steel molds or where interim production is needed while production steel molds are being completed.

## Application variables

The system that you select will depend to a great extent on the requirements of your application, in terms of:

Material, complexity, quantity, finishing, flammability, texture, part size and delivery.

An understanding of each system's capabilities relative to your requirements will help you to select the best system for your application. We will come back to these after we outline the approach that each system follows.

## Starting points

Each system has a starting point that uses some form of 3-dimensional object. This could be a fabricated 3-dimensional model, a solid die model, a mold cavity or core, etc. Most commonly, a 3-dimensional precision master model is used. While any of these can be used as a starting point, the following discussion assumes the 3-dimensional master model approach since it is the most common.

This model is most commonly fabricated from plastic using a variety of NC, CNC and hand fabrication techniques. This model will incorporate all of your production features like snap fits, bosses and side core vent detail. This model, in essence, is identical to your final plastic molded part. This model will be a low- to no-shrink model for prototyping programs and a 4 to 6 mil/inch over-size model for short-run production programs. The oversized dimensional allowance is an offset to accommodate the shrinkage of the faster setting short-run molding materials.

This model can be fabricated using your 3-dimensional detailed drawings, scaling from mylars or by using your CAD tapes. We use a number of different CAD systems at 3M and most commonly will use IGES or DXF files. If you decide to follow the CAD approach, we can advise you on the proper format to obtain the best correct translation.

### **Master available in 2 to 4 weeks**

The master model will normally be available for your review in 2 to 4 weeks, depending on part size, complexity and the number of different parts involved in your program. This model can come with a complete inspection or, where time and costs are more critical, the model can be provided using in-process inspection and documented with a critical dimension inspection report. We often find that applications for "prototyping" normally utilize the in-process inspection approach while "short-runs" follow the full inspection report.

With this model, you are now in a position to fit together the mating parts, check form, fit and function and verify that everything in your design is accurate. This is the ideal time to make corrections or changes. This is true because although the mold building started at the same time as the master model build, the core and cavity are yet to be detailed. We find that better than 90% of the time, changes are made at this stage that, had they not been caught, would have resulted in changes in the final production mold. As you well know, changes in production tooling can be very expensive and time consuming.

### **You could provide the starting point.**

As another alternative, you could also provide the master model from your in-house shop or from one of your outside vendors. If you choose to follow this path, please contact one of our project engineers first so you can receive proper direction concerning draft, fillets, radii, etc. As a general rule of thumb, your model will be acceptable if you follow traditional design practices for plastic parts.

This model could also be fabricated via StereoLithography. We could provide the SLA model for you using your CAD data or by inputting your print design into CAD. You could also provide the SLA model if you have an SLA system or if you are using an outside vendor.

### **The process**

Using the master model, the process begins. Your master model, die model, 3d model, etc., is then used in 3M's tracing technology to produce a force and cavity composite tool. This is normally completed in 7 to 10 days. The composite tool is a proprietary 3M composite and the nature of the composite is proprietary and cannot be divulged. However, to dispel any misconceptions, we can tell you that the molds are neither epoxy nor silicone rubber. ProMold tools are more rigid in nature and consist of a core and cavity, totally closed, mold system. In prototyping, the molds can incorporate all of the slides, cams and coring action

that you would utilize in production. The only difference is that these molds would use hand-loaded inserts versus hydraulic movement in order to minimize cost and time. Nevertheless, the procedures and design guidelines for draft, design, etc., are identical to your requirements for production.

Prototype parts can include molded-in color, texture, ribs, bosses, etc. As a general rule of thumb for prototyping, if it can be done in production, it can be done in prototyping as well. Likewise, if it cannot be done in production, it would not be done in prototyping either. While the capabilities are somewhat more limited in "short-run," the concept is the same.

The completed force and cavity mold is next placed in a large clamping system about the size of a 10×10 foot room. The mold is then injected using custom-built, high pressure impingement mixing equipment. The injection head from the machine is locked into the mold and the mold is injected under low pressures and low temperatures. Typical pressures might be a 3000 PSI impingement mix with a pressure drop going through the head. Processing temperatures range between 120 and 140°F. Depending on the material selected, a typical 20 lb. bumper fascia might be injected in about 23 seconds and demolded in 10 minutes.

### **Materials**

All of the materials molded are from 3M's family of "engineered thermoset resins." These are not available for resale. These materials are developed in 3M's laboratories exclusively for use in the ProMold systems. While materials are being continuously developed, most materials used today are polyureas, dicyclopentadienes, polyurethanes, liquid nylons and various blends. These materials exhibit many exceptional physical, mechanical and thermal properties and have even been formulated to achieve 94VO flammability ratings.

For prototyping, approximately 90% of our customers, the IBMs, Xeroxes, GMs, etc., will be using an engineered thermoplastic when they go into production. However, for prototyping, high performance engineered thermosets are used to take advantage of time savings and cost savings associated with low pressure, low temperature molds. In addition, there are other benefits and savings due to the ability to make mold changes very fast and economically.

Since many of the engineering properties can be approximated, some structural testing may also be performed. In many cases the spec material properties can be duplicated although for prototyping we may offer a material about 15 to 18% lower than the anticipated "spec" material properties in order to build in a prototyping safety margin. This strategy is intended to show up any weaknesses there may be in the design, allowing for early corrective action. On the other hand, if the prototype performs well, then a nice safety margin has been incorporated for production.

### **Accelerated new product development**

For quantum leaps in new product development, speed is of the essence. Speed is not normally associated with prototyping in spec materials due to the time required to build tools that will withstand elevated pressures and temperatures; not to mention all of the required cooling lines, ejectors and other necessary production features.

Spec material becomes less of an issue when critical "needs" revolve around form, fit and function (function being the ability of the product to perform the tasks for which it was designed).

Material suppliers have been making polycarbonate, ABS, PPO, rims and other materials for decades. Designers have been designing in these materials for decades, and custom molders have been processing these materials for decades. Performance and processing characteristics are generally known.

What *is* an unknown each time, however, is whether or not the design is accurate. For purposes of our discussion, the *design* is the changing variable that needs confirmation prior to building expensive production steel molds.

In addition, numerous resources exist in the areas of mathematical modeling, mold-flow patterning and finite element analysis. There are also a myriad of industry resources with tremendous experience such as material suppliers, molders, prototypers and designers. These resources can be accessed and utilized very readily and, normally, at little or not cost.

The primary fit for the prototyping system is for form, fit, styling, proving out the design, proving out concepts and checking product functionality. Function being defined as the ability of the product to perform its intended function versus the functionality (performance) of the plastic part. This is made possible through the ability to build an actual unit with prototypes and put it into operation.

### Agency approvals

In fact, many companies will submit prototype units to UL, FCC, VDE in Germany, and other agencies for preliminary approval and to discover whether any conditions exist that would prevent the production parts from obtaining approval. Many tests can be performed like attenuation levels, probe tests, heat rise and others. Oftentimes, problems can be identified and corrected before the details of the expensive production mold have been cut.

There is a common misconception that these agencies will only evaluate production units. This is simply not true. We have a letter from UL's management encouraging the submission of prototype units. In the case of plastics, obviously the bake, break and burn tests cannot be performed on the prototype plastic but countless other tests and time consuming procedures can be completed. UL goes so far as to say in this letter that if a company has submitted early prototypes that approval can often be granted in 2 to 3 weeks after the final production units are submitted. We would be happy to furnish a copy of this letter to readers of this paper upon request.

### Short-run system

Perhaps the best way to describe the "short-run system" is to distinguish it from the prototyping system. The same mold building technology is used, but it is expanded to include ejectors, automation controls and process controls, and it is structured to achieve more long-term integrity. While mold life for a prototype mold might be 20 to 75 units, mold life for a short-run mold might be 100 to 500. An exact mold guarantee is provided after reviewing your specific design.

Tooling prices are normally 14 to 18% of a comparable production steel mold where prototype tooling is normally 10 to 14%. An average part price would be around \$60 versus \$150 for prototyping.

A few final distinguishing characteristics between the two systems would be in the area of part size and weight capability, quantity of parts per day and overall part complexity. Please

refer you to the chart at the end of this paper for a ready reference. Keep in mind that the short-run system capabilities are advancing very rapidly and this chart could be outdated rather quickly. Therefore, if you have specific questions, please call our engineering department.

### Fast and economical changes

Either mold system can accommodate your design changes very quickly and economically. These changes may be made directly in the mold, or significant changes can be performed in the model or on the data base. This makes changes very economical since the bulk of the model or data base is already completed and most of the mold can be saved since at this point we need only to resurface the core and cavity detail. Therefore, even if we were to introduce significant changes, the cost and time still might be only half of your original tooling cost, which as you might recall was only a fraction of your production mold cost.

### Satisfy low volume and interim production

Although the short-run molding system has only been available for the last two years, many smaller volume production requirements for many companies like Cray, John Deere, and Kodak are now being fulfilled. In fact, the process has been qualified under Xerox's very rigorous "supplier quality" program. (This program was instrumental in the recent awarding of the distinguished Malcolm Baldrige National Quality Award to Xerox.) In addition, many companies are satisfying interim production while production molds are undergoing changes and completions. We hope the technology can help you as well.

3M ProMold: Specifications		
	Prototyping system	Short-run system
Quantity of parts	1 to 75	50 to 500
UL rating (VO @)	.245 (others available)	.187 (others available)
Finish	molded-in color and texture	painted
Complexity	any	.090 minimum wall minimum side cores
Part weight	any	Rigid: 18 lb.; Flexible: 24 lb.
Mold price (% of P20)	10 to 14	14 to 18
Part price (average)	\$150	\$60
Master model completion	2 to 4 weeks	
Master model size	1:1	0.4 to 0.6% oversized
First parts	2 weeks after master completion	
Cycle time (parts per day)	1 to 2	10 to 15
Durometers	35A to 85D	60 to 83D
Flex modulus (psi)	10 to 420,000	33 to 304,000
Impact (ft. lb.)	0.5 to 6.3	2.16 to 29
HDT (°F @ 264 psi)	124 to 164	170 to 204

VENDORS

## VENDORS

We start with a comprehensive compilation of data on all the known DtM processes, both on the market and under development (page 52). After that are papers presented by four commercial manufacturers of DtM systems and one university laboratory with a process available for commercialization. This segment of the report concludes with a transcript of the industry panel at the DtM Conference (page 100). This gives readers an opportunity to compare the answers of the vendors to several topical questions posed by the conference audience.

The established leader in the industry is 3D Systems, with three models of their *Stereo-Lithography Apparatus* available. This process works by scanning a laser beam in a vat of photopolymer, which solidifies at the point of irradiation. Dennis Medler explains four recent improvements in their technology (page 64):

- A new scanning method, called *Weave*, that reduces various types of distortions that have plagued users.
- New releases of the control software, improving the accuracy and speed of the build.
- Several new resins, including one with enhanced flexibility and toughness that allows production of snap-fitting parts.
- Improved accuracy of the laser scanning system used in the top-of-the-line SLA-500.

The *Solid Ground Curing* process is described by Haim Levi of Cubital. Like Stereo-Lithography, this process is based on photopolymers, but it works by masking the radiation of a UV lamp instead of scanning with a laser. It also incorporates a technique of filling in the partially formed object with wax in order to support complex structures. This process is unique in the accuracy and complexity of objects it can build, such as a working universal joint constructed in one operation without assembly. Its disadvantage is in the size and complexity of the *Solider* machinery. ... page 70.

Kent Nutt describes what many consider to be the most promising new entry in the field, *Selective Laser Sintering* from DTM Corporation. Like StereoLithography, this uses a laser beam to build its objects, but the process works with a powder instead of a liquid, the laser fusing together the particles of the powder. Five beta systems will be delivered by the end of this year; current use is through two company-run service bureaus. One of the prime advantages of this process is material versatility, since it is not based on photopolymers. In particular, DTM is working hard to fabricate parts directly in metal. ... page 75.

The term "desktop manufacturing" anticipates the development trend of the rapid prototyping industry to machines that will sit on the corner of an engineer's desk. The company coming closest to this goal now is Stratasys with their *Fused Deposition Modeling* process, presented by Lisa Crump. This process works by laying down a thin filament of thermoplastic material at a temperature near its melting point. Like Laser Sintering, this works with a variety of materials, and work is under way to provide models in metal. The *3D Modeler* machine runs in an office environment since it uses nontoxic materials and plugs into an ordinary wall socket. ... page 81.

Emanuel Sachs and colleagues at MIT have developed yet another approach to the DtM problem, which they call *Three-Dimensional Printing* by analogy to ink-jet printing. This method builds objects by spraying a binding material on successive thin layers of powdered material. Sachs describes this process and its applications in some technical detail. ... page 86.

# Industry Survey and System Comparison Matrix

Marshall Burns, President, Ennex Technology Marketing, Inc., Austin, Texas

Marshall Burns conducted a study of the desktop manufacturing industry last year, including its various technologies and their applications. He came to the conclusion that automated fabrication is the high-tech field that holds the most promise for a tremendous market, while offering many challenging technical problems, yet being feasible for immediate development.

Dr. Burns formed Ennex Technology in 1982 to do research and development on market technologies. Its first project was marketing the then-new IBM Personal Computer to business customers across the United States. The success of that venture funded the second project, which was a program of Ph.D. research for Dr. Burns, just completed in April, 1991. A third project is under consideration.

Dr. Burns has a B.S. in Physics from the Massachusetts Institute of Technology and a Ph.D. in Atomic Physics from the University of Texas at Austin.

Desktop manufacturing is an industry in its infancy. The first commercial product hit the market less than four years ago. In the meantime, dozens of companies, universities and government laboratories have committed to developing new processes and new products for this market. 3D Systems' total sales of just over \$50 million in its first three years represents a tiny fraction of what is predicted to be a multi-billion dollar industry.

The introductory chapter of this industry report gave a brief description of the various processes that are being used or proposed for DtM<sup>1</sup>, and how they are being applied in industry. This chapter will focus on the machines themselves, and on the companies and organizations that are developing them. This will be done in three sections:

- 7 vendors currently offering DtM systems for sale, plus a selection of "desktop" subtractive machines for comparison.
- 4 vendors who are readying machines for market, and
- 10 organizations involved in development of alternative processes.

## Vendors offering DtM systems for sale

This part of the survey, a listing of systems on the market, comes in two parts. The first is a comparison of the most basic properties of the various machines side-by-side in a single table. The second goes into a little more detail on each machine. The two parts should be used together. For example, while the table lists the retail price for each machine, the detailed analysis lists what is included in that price.

The comparison table gives the following data for each machine:

- **Method.** Brief description of the process used.
- **Materials.** List of materials currently available for use in the machine.
- **Build size.** Dimensions of the largest object that can be built.
- **Cubes.** Results of a rudimentary benchmarking scheme for speed and accuracy, explained below. Also, the cost per fabricated cubic inch of the available materials.
- **Price.** Basic retail price for a complete system.

The detailed analysis goes on to provide the following information:

- **Method.** A slightly longer description of the process, including the central patent number.

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<sup>1</sup> As the acronym for "desktop manufacturing," *DtM*, with a lower case "t," is used here to avoid confusion with the name of the vendor, DTM Corp.

- **Availability.** Date of first shipment and number of units sold and shipped, if applicable. Otherwise current status, for example of beta program. Also, availability of service bureaus.
- **Cost.** Explanation of inclusions in the retail package, and options available. Also the cost of materials used in the machine.
- **Machine size.** The footprint, height and weight of the machine.
- **Utilities.** Connections necessary to operate the machine.
- **Address.** Address and phone number of the vendor.

#### *A rudimentary benchmarking scheme*

Since the industry is so new, no benchmarking standard has yet been established. Many vendors publish literature that says something on the order of, "This method of fabrication allows parts to be built much faster," with no definition of what "faster" means. When technical specifications of speed are given, they are in incompatible terms, such as rate per vertical inch, rate per cubic inch or laser scan speed. There are similar problems with the claims made for accuracy. This survey takes a very rudimentary step in the direction of benchmarking by asking all vendors to quote fabrication time and accuracy for a simple set of items. The items, a set of 1-inch solid cubes, are far too simple to take advantage of the diverse capabilities of the various machines. More elaborate benchmarks will be required in the future, but this is an important start.

The benchmarking questions asked of the vendors were:

- I would like you to build a single, 1-inch, solid cube with layers 5 mils thick.<sup>2</sup> How long will this take, excluding programming, but including all necessary computer processing, and including post-processing of the cube?
- Now, I would like you to fill the horizontal capacity of your machine with separate 1-inch cubes. How many cubes can you make, and how long will it take?
- Finally, fill your whole building capacity with separate 1-inch cubes. Again, how many can you make, and how long will it take?
- I asked you for 1-inch cubes. What am I going to get? How close to one inch will the dimensions of the cubes actually be?

The results are collected in the table in the following format:

Cubes	
Time	Accuracy Cost/cu in
1: $x$ min. $H$ : $y$ hr. $V$ : $z$ hr. ( $a$ min.)	$\pm q$ mil. $\$d$

$x$  is the time to build one cube.

$y$  is the time to build  $H$  cubes, filling the horizontal.

$z$  is the time to build  $V$  cubes, filling the whole capacity.

$a = 60z/V =$  average time to build each of the  $V$  cubes.<sup>3</sup>

$q$  is the reported tolerance.

$d$  is cost/in<sup>3</sup> of the fabrication material.

The most important numbers are  $x$ ,  $a$  and  $q$ . The numbers  $x$  and  $a$  give an indication of the variation of the build rate, in in<sup>3</sup>/min, from the worst case of tiny runs to the best case of runs that fill the machine. The number  $q$  gives a measure of accuracy.

<sup>2</sup> For Quadrax, which has an adjustable laser spot size, a 10 mil spot was specified.

<sup>3</sup> For Stratasy, which cannot stack the cubes,  $a = 60y/H$ .

One should not be too trusting of these benchmark results. The questions were answered by representatives of the respective vendors, without verification. While one vendor, Helisys, actually ran a layer of the cubes, all the other vendors gave their answers from calculations, some performed quite quickly. In fact, for Cubital and DTM, the production versions of the machines for which the calculations were performed do not even exist yet. The results, therefore, serve to compare *the vendors' own opinions (or predictions) of the capabilities of their machines*, as opposed to actual, verified performance.

All of the vendors said that computer processing time for the cubes would be negligible. However, when asked about this, 3D Systems pointed out that the computer processing would be part of a setup procedure that would include filling the vat, etc., and would take about a half hour. Since none of the other vendors mentioned setup time, this was not included in 3D's times, but it does represent an important element of the speed question that should be addressed in future benchmarking schemes. The setup procedure also relates to the issue of ease of use of the equipment.

DTM pointed out that the accuracy they could promise would depend on whether I gave them an .StL file from which to build, or simply gave them the dimensions of the cube to build. Their quote of  $\pm 3$  mils was based on the latter. Working from an .StL file, the tolerance would be larger. This important point is probably true of several, if not all, of the other vendors as well.

While the focus of this report is on additive processes, no one should buy equipment just because it uses the latest wizardly technology. Subtractive machines have to be considered, if only for a comparison of capabilities and price. There are several NC machines on the market that are small and inexpensive enough to be considered CAD peripherals, and many of them connect to personal computers. One example is included in the comparison table. Some others are listed in the detailed section following. The cubes data refer only to the time to machine a single cube; the idea of building the cubes in a horizontal or vertical array is not applicable to the milling process.

Comparison of desktop manufacturing machines							
Machine (Vendor)	Method	Materials	Build size (w×l×h, in)	Cubes		Price	
				Time	Accuracy Cost/cu in		
SLA-190 (3D Systems)	Laser curing of resin on descending platform in a vat	• Photo-polymer	7.5×7.5×9.8	1: 85 min. 49: 30.5 hr. 392: 244 hr. (37.3 min.)	±5 mil. \$0.87 to 1.73	\$95,000	
SLA-250 (3D Systems)			10×10×10	1: 65 min. 81: 20.5 hr. 729: 185 hr. (15.2 min.)	±5 mil. \$0.87 to 1.73	\$185,000	
SLA-500 (3D Systems)			20×20×23.8	For 100 or 200 in/sec scan speed: 1: 45 or 42 min. 361: 40.8 or 20.7 hr. 7942: 895 or 454 hr. (6.8 or 3.4 min.)	±2 or ±5 mil. \$0.87 to 1.73	\$385,000	
Mark 1000 (Quadrax)			Laser curing of resin applied from above	12×12×12	1: 130 min. 121: 76 hr. 1331: 833 hr. (37.5 min.)	±5 mil. \$1.41 to 1.71	\$195,000
Solider 5600 (Cubital)			Masked lamp curing of resin, then wax filling, milling	14×20×20	1: 118 min. 247: 4.3 hr. 4693: 48 hr. (0.6 min.)	±1 mil. \$0.43	\$490,000
LSI-0609 MA (Light Sculpting)			Masked lamp curing of resin on descending platform in a vat	6×6×9	1: 178 min. 36: 3.0 hr. 288: 19 hr. (4.0 min.)	±5 mil. \$0.76	\$99,600
SLS (DTM)	Laser sintering of powder applied in layers	• PVCs • Polycarb • Nylon • Casting wax	12 diameter ×15	1: 35 min. 84: 1.5 hr. 1176: 21 hr. (1.1 min.)	±3 mil. \$0.65 to 1.87	\$350,000 to 400,000	
3D Modeler (Stratasys)	Robotically guided thermoplastic filament	• Machinable wax • Casting wax • Nylon-like plastic	12×12×12	1: 10 min. 121: 20 hr. No stacking. (10 min.)	±5 mil. \$1.18	\$180,000	
LOM-1015 (Helisys)	Stacking and laser cutting of adhesive sheets	• Paper • Nylon-cellulose • Polyester	10×13×15	1: 32 min. 108: 3 hr. 1620: 46 hr. (1.7 min.)	±1 mil. \$0.05 to 0.76	\$75,000 (beta)	
TMC 1000 (Light Machines)	Computer controlled 3-axis milling	• Machinable wax • Plastics • Aluminum • Steel	5.3×11.3×6	wax: 2 min. alum.: 10 min. steel: 45 min.	±0.25 mil. wax: \$0.17 ABS: \$0.30 alum.: \$0.16 to 0.38 steel: \$0.09 to 0.13	\$11,995	

Now follows the more detailed information on each system.

<b>3D Systems, Inc.: StereoLithography Apparatus (SLA)</b>	
method	<i>StereoLithography</i> : An ultraviolet laser scans the surface of a liquid photopolymer, solidifying part of it to produce a layer of the desired object. This layer is submerged in the resin and the process is repeated. U.S. Patent # 4,575,330.
availability	Independent service bureaus: About 23 in U.S., 15 in Europe. 3 models: (Sales figures are worldwide and approximate thru June 1991.) SLA-190: Released June, 1990. 5 sold. SLA-250: Released November, 1988. 220 sold. SLA-500: Released November, 1990. 20 sold.
cost	SLA-190: \$95,000 SLA-250: \$185,000 SLA-500: \$385,000 Installation: 1% of price. 90-day warranty. Service contract: 8 to 9% for base coverage, about 18% for full coverage, including unlimited laser replacement. Training for 2 people included. 3 days for SLA-190, 5 days for 250, 500. Option (required): Post Cure Apparatus (ultraviolet flood oven), \$10,000. Resin: About \$350/gal from 3D Systems; \$200 to \$400/gal from other sources. (That is \$0.87 to \$1.73/in <sup>3</sup> ).
cubes notes	Times consist of build time + post-cure time. The estimated post-cure times are 25 min. for a single cube or horizontal array of cubes, and 4, 5 or 8 hours, respectively, for the full capacity of cubes in the SLA-190, 250 or 500.
machine size	SLA-190: Footprint: 2.3×4.0 ft. Height: 5.4 ft. Weight: 600 lb. SLA-250: Footprint: 2.3×4.0 ft. Height: 5.4 ft. Weight: 650 lb. SLA-500: Footprint: 6.0×11.0 ft. Height: 6.7 ft. Weight: 2,056 lb.
utilities	SLA-190 and -250: Electricity: 115 VAC, 60 Hz, 15 Amp or 220 VAC, 50 Hz, 8 Amp. SLA-500: Electricity: 208 VAC, 3 phase, 100 Amp/phase. Water: 2.5 to 10 gal/min @ 50 to 100 psi, 25 to 86°F. All three: Clean-up area ("finishing lab") needed.
address	26081 Avenue Hall, Valencia, California 91355; 805-295-5600.

<b>Quadrax Laser Technologies, Inc.: Mark 1000</b>	
method	<i>Laser Modeling:</i> A visible-light laser scans a thin layer of photopolymer, solidifying part of it to produce a layer of the desired object. Another layer of resin is applied with a coating bar and the process is repeated. Patent pending.
availability	Released January, 1991. 2 sold.
cost	\$195,000 includes machine, curing oven, installation, 2 weeks training, 1-year warranty (or 2,000 hr. on laser), 15 gal (full vat) of resin. Resin: \$325 to \$395/gal from Quadrax (\$1.41 to \$1.71/in <sup>3</sup> ). Second source available soon.
cubes notes	Times consist of building + post-cure: 1: (70+60) min., 121: (74+2) hr., 1331: (813+20) hr. Time could be saved by using a wider spot. For example, the 121 cubes could be built with a 50 mil spot in about 38 hr. instead of 74.
machine size	Footprint: 3×4 ft. Height: 7 ft. Weight: 700 lb.
utilities	Electricity: 208 VAC, 3 phase, 70 Amp. Water: 2.5 gal/min @ 50 to 90°F, 30 to 60 psi. (Can come from local water service, or from heat exchanger costing about \$8,000.)
comments	Laser spot size adjustable from 3.5 to 125 mils. Applying resin with coating bar is claimed to eliminate "parachuting," caused in SLA by lowering object through vat.
address	300 High Point Avenue, Portsmouth, Rhode Island 02871; 401-683-6600.

<b>Cubital Ltd.: Solider 5600</b>	
method	<i>Solid Ground Curing:</i> A strong ultraviolet lamp, masked by a toner on a charged glass plate, solidifies part of a thin layer of photopolymer to produce a layer of the desired object. The remaining liquid is sucked off and the void is filled with wax. The solid layer is milled down to the desired thickness. A new layer of liquid resin is applied and the process is repeated. U.S. Patent #4,961,154.
availability	Company-owned service bureaus in Detroit, and Zurich, Switzerland. First deliveries of machines to customers scheduled for 4th quarter, 1991. New sales available for delivery in first quarter, 1992. 6 sold (3 in U.S., 3 in Europe).
cost	\$490,000 includes machine, installation, 3 weeks training, 6-month warranty. Service contract: 10% of price per year, covering parts and labor. Resin: About \$100/gal (\$0.43/in <sup>3</sup> ).
cubes notes	Times consist of building in the machine + semi-manual removal of wax: 1: (108+10) min.; 247: (108+150) min.; 4693: (36+12) hr.
machine size	Footprint: 5.6×13.5 ft. Height: 4.8 ft. Weight: 9,000 lb.
utilities	Electricity: 440 VAC, 3 phase, 60 Hz, 40 kW. Compressed air: 103 psi. Air exhaust: 6-inch tube.
comments	Accuracy is quoted as 0.1% of overall size of object built. Smallest feature size: 0.16 inch (4 mm).
address	Post Office Box 330, Herzlia 46103, Israel; 971-52-529415. or: 23647 Ryan Road, Warren, Michigan 48091; 313-754-7557.

Light Sculpting, Inc.: LSI-0609MA	
method	<i>Light Sculpting</i> : An ultraviolet lamp is masked and irradiates a vat of liquid photopolymer, solidifying part of a thin layer at the surface to produce a layer of the desired object. The object is submerged in the vat, covering it with a new layer of liquid resin, and the process is repeated. U.S. Patents # 4,752,498, # 4,801,477.
availability	Company service bureau in Milwaukee, Wisconsin since 1986. 5 beta sites available at \$75,000.
cost	\$99,600 includes machine with computer, software, installation, training, 2-year parts-and-labor warranty and 5 gal of resin. Options: Mask plotter, \$25,000; Post-curing oven (required), \$10,000. Hardware upgrade allowance of price paid, less 3%/month. Resin: \$175/gal (\$0.76/in <sup>3</sup> ). Masks, per 24×36 inch sheet: \$3 for film if you own the plotter, otherwise about \$30 to \$35 for plotting and developing, including film.
cubes notes	Each time includes 30 min. for plotting and developing the mask, and 15 min. for post curing any number of cubes. Only one mask is needed since the cubes are uniform. If each layer of the cubes was different, then 200 masks would be needed. The time to prepare these would be about 2 to 3 hours for the single cube, or about 3 to 4 hours for the array of 36.
machine size	Footprint: 2.0×2.5 ft. Height: 6.0 ft. Weight: 600 lb.
utilities	Electricity: 110 VAC, 60 Hz, 5 Amp.
comments	Resolution: ¼ mil. Minimum feature size: 3 mils. Also available: <i>LSI-1115MA</i> and <i>LSI-2224MA</i> , which have larger fabrication envelopes.
address	4815 North Marlborough Drive, Milwaukee, WI 53217; 414-964-9860.

DTM Corporation: SLS™	
method	<i>Selective Laser Sintering™</i> : A laser scans a thin layer of powder, fusing part of it to form a layer of the desired object. A new layer of powder is spread and the process is repeated. U.S. Patent #4,863,538, #4,937,420 (withdrawn), #4,938,816, #4,944,817.
availability	Company service bureaus: Austin, Texas and Cleveland, Ohio since September, 1990. 5 beta sites selected, to be installed December, 1991. Production machines available 2nd quarter, 1992.
cost	Will be between \$350,000 and \$400,000 including machine, installation, warranty (duration TBA), training (1 week at DTM and some time on site), some supply of powder. Service contract: About 8 to 12% per year, depending on coverage. Powders: Will be between \$20 and \$40/lb. (At specific gravity, after sintering, in range of 0.9 to 1.3, this is \$0.65 to \$1.87/in <sup>3</sup> ).
machine size	Footprint: 3.3×11.7 ft. Height: 6.4 ft. Weight: 3500 lb.
utilities	Electricity: 208 VAC, 2 phase, 60 Hz, 100 Amp. Nitrogen supply: Nominal 1.5 cfm, maximum 5 cfm. Exhaust vent required.
comments	Materials under development: ABS (to be available by end of 1991), ceramics, metals, advanced composites.
address	1611 Headway Circle, Building 2, Austin, Texas 78754; 512-339-2922.

<b>Stratasys™, Inc.: 3D Modeler™</b>	
method	<i>Fused Deposition Modeling™</i> : A filament of thermoplastic material is heated to near its melting point and robotically guided to form the desired object. U.S. Patent Pending.
availability	4 beta sites selected. 2 installed May and June 1991. 2 to be installed July, 1991.
cost	\$130,000 for machine only. \$178,000 for machine with workstation and software. Both include installation, 3 weeks training for one person, 90-day parts-and-labor warranty. Software revisions: About \$4,000 per year. Filament: \$350/mile spool for waxes (about \$1.18/in <sup>3</sup> ). The "nylon-like" plastic will be more.
machine size	Footprint: 2.5 × 3.0 ft. Height: 6.0 ft. Weight: 250 lb.
utilities	Electricity: 110 VAC, 60 Hz, 7 Amp.
address	7411 Washington Avenue South, Minneapolis, MN 55439; 612-941-5607.

<b>Helisys, Inc. (formerly Hydronetics): LOM-1015</b>	
method	<i>Laminated Object Manufacturing</i> : A laser cuts a pattern representing a layer of the desired object in a sheet material pre-coated with adhesive. A new piece of material is laid over this one and bonded to it. The laser cuts another pattern and the process is repeated. U.S. Patent #4,752,352.
availability	Company service bureau in Torrance, California: \$75/hour. 6 to 8 beta systems to be placed.
cost	\$75,000 (beta) includes machine, installation, 3 days training, 1 year warranty, 1 year tech support, free hardware upgrade at end of year, free software upgrade every 3 months. This beta price also requires commitment to provide feedback to vendor on the machine. Materials/in <sup>3</sup> : Paper \$.05, Nylon-cellulose composite \$.15, Polyester \$.76.
machine size	Footprint: 2.5 × 3.7 ft. Height: 3.8 ft. Weight: 500 lb.
utilities	Electricity: 115 VAC, 60 Hz, 15 Amps. Outside venting with smoke filter.
comments	Also available: <i>LOM-2030</i> , which has a larger fabrication envelope and faster speed.
address	2301 205th Street, Suite 107, Torrance, California 90501; 213-782-1949.

Light Machines Corporation: TMC 1000™	
method	3-axis milling: A rotating tool cuts along a programmed path to form the desired object from a block of material.
availability	Previous model sold to educational market since 1984. TMC 1000 released August, 1989. About 180 sold.
cost	\$11,995 includes machine with control electronics, 1 tool, PC interface software, documentation for installation and training, 1-year parts-and-labor warranty and toll-free technical support. Options: Quick-change tooling, \$1495; Machinist's kit, \$1195. Materials/in <sup>3</sup> : Machinable wax \$0.17, ABS plastic \$0.30, Aluminum \$0.16 to \$0.38, Steel \$0.09 to \$0.13, depending on grade, configuration. (But these material prices are not comparable to those for an additive process because you pay for the block from which you cut, not just for the final volume.)
machine size	Footprint: 2×3 ft. Height: 2.5 ft. Weight: 300 lb.
utilities	Electricity: 110 VAC, 60 Hz, 15 Amp.
comments	Subtractive process: Cannot do undercuts or hollow structures. Also available: LMH 100 lathe, \$12,995.
address	669 East Industrial Drive, Manchester, NH 03103; 800-221-2763.

Some other small, inexpensive NC machines are:

- *Micromodeler* mill from Roland Corp., Los Angeles. \$20,000 for mill and PC software.
- *Mini-Mill* and similar lathe from Servo Products Co., Pasadena, California. Resolution of 0.1 and 0.05 mils, respectively.
- *Compact 5* lathe and similar mills from Emco-Maier, Columbus, Ohio. Interface for either PC or Apple.
- *Dyna Myte 2400* mill and similar lathe from Dyna/Mechtronics, Santa Clara, California. \$13,000 and \$14,500, respectively.
- *Techno 3-axis* gantry positioning table and choice of tooling from Techno Isel, New Hyde Park, New York. Systems with PC software from about \$12,000.

**Vendors who are readying machines for market**

Very little information is available about the following players in the industry, except that they are poised to enter the market.

<b>Sony Corporation (with Japan Synthetic Rubber): Solid Creation System (SCS)</b>	
method	Similar to StereoLithography.
availability	Authorized sales agent, D-MEC Ltd., is marketing machines and resin and operating a service bureau in Japan. No immediate plans for U.S. (D-MEC is a wholly owned subsidiary of Japan Synthetic Rubber.)
address	Sony: 6-7-35, Kita Shinagawa, Shinagawa-ku, Tokyo, Japan; 03-448-2797. D-MEC: JSR Building, 2-11-24, Tsukiji, Chuo-ku, Tokyo; 03-5565-6661.

<b>Mitsubishi Machinery Division: Solid Object Ultraviolet laser Plotter (SOUP)</b>	
method	Similar to StereoLithography.
availability	Unconfirmed report that Boeing is a beta site.
address	1201 Third Avenue, Seattle, Washington 98101; 206-682-0744.

<b>Mitsui</b>	
method	Similar to StereoLithography.
address	Japan

<b>Eos GmbH: Stereos 400</b>	
method	<i>Laser Modelling</i> : Similar to StereoLithography.
machine size	Footprint: 4.8×8.3 ft. Height: 6.4 ft.
utilities	Electricity: 220 VAC, 16 Amp.
address	D-8033 Planegg/Munchen, Pasingenstr. 2, Germany; 089-89-91310.

## Development on alternative processes

The following companies and institutions are currently, or have been in the past, working on proposed desktop manufacturing technologies, with the aim of bringing a product to market.

<b>MIT/3-D Printing Consortium</b>	
method	<i>Three Dimensional Printing</i> : An ink-jet passes over a layer of powder, selectively applying a binder to congeal a layer of the desired object. A new layer of powder is spread and the process is repeated.
availability	Negotiations underway for commercialization.
address	Prof. Emanuel Sachs Laboratory for Manufacturing and Productivity, 77 Massachusetts Avenue, Cambridge, Massachusetts 02139; 617-253-5381.

<b>Perception Systems, Inc.</b>	
method	<i>Ballistic Particle Manufacturing</i> : An ink-jet deposits droplets of molten wax, or other thermoplastic material, to form the desired object. U.S. Patent # 4,665,492.
availability	Available for licensing or coventure. At least one nonexclusive license for application to metals has been issued.
cost	Estimated \$15,000 to \$50,000, depending on required accuracy.
address	1110 Powdersville Road, Easley, South Carolina 29640; 803-859-7518.

<b>Babcock &amp; Wilcox</b>	
method	<i>Shape-melting technology</i> : Arc welding and robotics are used to shape the desired object in steel.
address	Alliance, Ohio.

<b>Battelle Memorial Institute (with Formigraphic Engine Co.)</b>	
method	<i>Photochemical Machining</i> : Intersecting laser beams solidify plastic gel. Works with volumes rather than layers.
availability	Battelle was by far the first laboratory to do work in this field, going back to the late 1960s. But nothing has been heard from them on the subject in years.
address	Battelle: 505 King Avenue, Columbus, Ohio 43201-2693; 614-424-5637. Formigraphic: P.O. Box 4995, Berkeley, California 94704; 415-868-1283.

<b>Carnegie Mellon University</b>	
method	Robotically controlled thermal spraying of metal on substrate or through masks.
address	Robotics Institute, Pittsburgh, Pennsylvania 15213; 412-268-7657.

<b>Chem-Form, Inc.</b>	
method	<i>Chem-Form</i> : An ultraviolet lamp irradiates a single layer of photopolymer through a mask to make thin structures. U.S. Patent # 4,929,403.
address	18 West Windermere Terrace, Lansdowne, PA 19050; 215-259-7576.

<b>Du Pont SOMOS™ Venture:</b>	
method	<i>SOMOS™ (Solid Modeling System) Solid Imaging</i> : Similar to StereoLithography.
availability	Available for licensing. Du Pont intends to concentrate on manufacturing resins, and wishes to license its set of ten hardware patents, including three which are specifically laser-based and seven which are more general. U.S. Patent # 5,014,206 and others.
address	Two Penns Way, Suite 401, New Castle, Delaware 19720; 302-328-5435.

<b>Incremental Fabrication Technologies</b>	
method	Similar to <i>Ballistic Particle Manufacturing</i> . Applications to tin metal.
availability	Under development.
address	1233 NW Lewisburg Avenue, Corvallis, Oregon 97330; 503-745-7739.

<b>Landfoam Topographics</b>	
method	Similar to Laminated Object Manufacturing, but incorporating color variations.
availability	Seeking partner for commercialization.
address	45 Brentwood Circle, Needham, Massachusetts 02192; 617-444-6910.

<b>Laser Fare Ltd Inc.</b>	
method	<i>Chem-Form</i> : Masked ultraviolet lamp on photopolymer. <i>Optical Fabrication</i> : Laser scanning of photopolymer.
availability	<i>Chem-Form</i> sold to Chem-Form, Inc., <i>q.v.</i> <i>Optical Fabrication</i> sold to Quadrax, <i>q.v.</i>
comments	Long-standing, established business in laser cutting, welding, marking and drilling for industry. Well funded. Strong commitment to R&D. Now working on a "next generation approach." No details available.
address	1 Industrial Drive South, Smithfield, Rhode Island 02917; 401-231-4400.

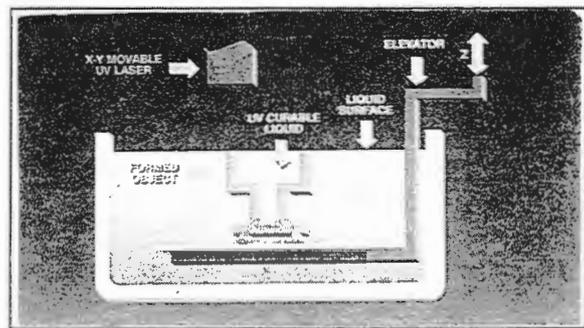
## Using StereoLithography in Prototyping and Manufacturing

Dennis Medler, Vice President for Sales and Marketing, 3D Systems, Valencia, California

Mr. Medler has more than twenty years experience in the computer and CAD/CAM industries. Prior to his position at 3D Systems, Mr. Medler was the National Sales Director at Cal-comp Inc. and the Vice President for Sales and Marketing at DTM Corporation. Mr. Medler holds a B.S. in Business Administration from Moody College.

Since its introduction four years ago, StereoLithography has revolutionized the making of models, prototypes, and masters and patterns for casting. The technology has dramatically sped the production of these parts and just as dramatically reduced their cost. Because of these benefits, StereoLithography has become a key enabling technology for concurrent engineering.

StereoLithography is the rapid building of 3-dimensional, hard plastic parts directly from CAD data. Proprietary software controls an ultraviolet laser beam focused onto the surface of photosensitive acrylic resin in a vat. The light beam draws the shape of a 2-dimensional slice of the solid object on the surface of the resin. The liquid resin solidifies wherever the light strikes it, resulting in a solid-material representation of one layer of the CAD design. The process repeats, layer by layer, until the object is completely built from the bottom up.



**StereoLithography Apparatus.**<sup>1</sup> The SLA builds physical models one layer at a time. A UV laser traces a thin cross section of the object onto the surface of a vat of liquid polymer, selectively hardening the photopolymer. The elevator then drops the forming part, recoating the top surface in preparation for the next cross section.

3D Systems, the company that pioneered this technology and holds the patents on it, has installed StereoLithography Apparatus (SLA) systems in major manufacturing companies in the automobile, aerospace, computer, medical, consumer and electronic components industries. To date, we have installed approximately 270 units in 17 countries. (See page 153 in the appendices for a partial list of customers.)

The technology was first developed back in 1982 by our president, Chuck Hall, who applied for the patent in 1984. When the patent was issued in 1986, Chuck joined with Ray Freed to form 3D Systems. At AutoFact in 1987, we introduced our first StereoLithography apparatus, the SLA-1. After beta testing this unit at five sites for six months, we started shipping production units. We then went to work on the second generation system, the SLA-250, which hit the market in 1988.

The SLA-250 builds parts up to 10×10×10 inches and has the largest installed base of any StereoLithography product. In the past 18 months, we have introduced two new systems as alternatives to the midrange SLA-250. The first, the SLA-500, can build objects up to 20×20×23.75 inches, and so can fabricate a full size automobile wheel or manifold, or a jet turbine blade in a single run. It is also faster and so can produce parts in greater volume. The second addition to the line, the SLA-190, produces objects up to 7½×7½×9 inches.

<sup>1</sup> See page 12 in Peter Marks' paper for a photograph of the machine. —Editor.

Driven from within and in response to customer requests, the company has achieved significant and impressive technological advances and improvements in materials, processes and software during the past year. StereoLithography has now moved well beyond the building of models and prototypes, and is beginning to challenge casting and molding processes for manufacturing. Because of continuing improvements in accuracy, speed and materials, StereoLithography may eventually supplant injected molded wax parts as patterns for investment casting to produce metal parts. Some prototype metal parts are now made this way and—in a few cases—some production metal parts as well.

Through the broadened applications of this technology, the narrow term of *rapid prototyping*, first associated with StereoLithography and similar processes, has evolved into the much broader one of *free-form manufacturing*, encompassing not only models, prototypes, masters and patterns, but also small production runs of final manufactured parts. StereoLithography has moved beyond being a tool for engineering and design to becoming a tool for manufacturing. With continued improvements in the technology, this shift will become more pronounced.

As a tangible example of the progress we have made in just the last year, a turbine blade made on our SLA-250 a year ago took about 61 hours. Today, the same blade made on the SLA-500 takes only 23 hours. More improvements, not only in how fast StereoLithography parts are built but also in building them in a better way, make for greater strength and better accuracy. In some cases, little or no secondary operations such as post-curing are needed.

### The product line

**SLA-190.** This is our entry-level system, and was introduced in June, 1990. It has a smaller working volume,  $7\frac{1}{2} \times 7\frac{1}{2} \times 9$  inches. But if you are building parts larger than that, you can build them in pieces and then put them together. The advantage of this machine, aside from lower cost, is in its simple user interface. It takes  $3\frac{1}{2}$  days of training to get you up to speed so that you can build parts on this system.

**SLA-250.** This is the workhorse in our product family. This has a 10-inch cube working volume. Its advantage over the 190 is a recoater system. This is a wiping blade on top of the vat that allows you to use higher viscosity resins. It is also faster. And it has a dual computer system. You can get an optional workstation to use as your slice processor, or you can put a separate CAD system on it.

**SLA-500.** This is our largest system. We have a little better than a dozen of these installed worldwide, and over two dozen of them have been sold. Its advantages are size and speed. You can build a part about 2 feet cubed on this one.

### Applications in manufacturing

The first applications of StereoLithography were in modeling and prototyping. The benefits were demonstrated by Chrysler when they used their SLA to model a starter. They took the model out of the vat, mounted the solenoid on it and said, "Gee, that looks great." But when they mounted it on the engine they discovered an interference problem because the CAD model had not shown all the hoses. They were able to go back to the "drawing board" before wasting any more time and money on this faulty design. There are now many stories about huge savings realized in this way.

But StereoLithography is now going beyond modeling and prototyping. It is establishing itself as a successful technology for creating masters and patterns for several types of casting processes, including sand casting, investment casting, and for creating patterns for soft and hard tooling.

### *Creating patterns*

StereoLithography can create patterns in several ways. These patterns may be consumed in the investment casting process, similar to wax patterns. Texas Instruments uses flask or block casting of the solid acrylic StereoLithography part to produce complex aluminum castings. Flask casting enables the "lost plastic" process to burn out the plastic without cracking the thin shell often used in investment casting. The thermal expansion of the acrylic is withstood by the thick ceramic slurry and a strong outer flask or container.

TI has taken their investment casting process from 20 weeks down to about 2 to 3 weeks consistently. In a rush situation, they can go from a concept CAD model to a flight-ready investment casting in metal in 7 days!

In the thin shell method of investing, a StereoLithography pattern is created that is not solid, but rather a honeycombed object filled with investment wax. As the wax melts out, and before the plastic can expand sufficiently to cause damage to the shell, space is created to compensate for the expansion of the acrylic. Hughes Aircraft Corporation and Plynetics Corporation, a Northern California-based service bureau, have built many patterns for this process. Patterns as large as  $7 \times 7 \times 3\frac{1}{2}$  inches, with 0.2 inch wall thickness, have been invested by this method.

### *Creating tooling*

StereoLithography can expedite several methods of producing multiple wax patterns for the conventional lost wax process. Once a StereoLithography part is completed, molds to produce wax patterns can be generated within days. Room temperature vulcanized (RTV) molds, for example, are inexpensive and can be used to produce wax patterns within three days after the SLA pattern is created. RTV molds can also duplicate fine surface texture and accommodate complex undercuts in the original pattern. RTV molds are also used to create limited production prototype parts from a variety of pourable plastic materials.

Spray metal molds have been used to produce wax patterns. StereoLithography greatly reduces the cost and time to produce the initial pattern. Cool arc metal spray coats the acrylic pattern with atomized metal. This process produces a tough metal cavity, reproducing fine detail, but does not raise the temperature of the pattern more than about 55°C. Once a pattern has been measured and approved, the spray metal process can create a mold cavity with great accuracy.

A particular benefit of the spray metal process is that it has virtually no size limitation. Multiple StereoLithography parts can be easily bonded together to create patterns larger than can be achieved in a single build in an SLA. Spray metal molds require one day to three weeks to produce and can generate thousands of wax patterns. Plynetics has created spray metal molds up to  $10 \times 10 \times 3$  inches, with 0.16 inch wall thickness, for creating wax patterns. Spray metal molds can also be used for blow molding, vacuum forming, thermoforming and low pressure injection molding. Cooling lines can be easily embedded into spray metal tools.

StereoLithography can also create the inverse of the part—cavities and cores—required in other processes such as acrylic tooling. The original CAD solid model can be used to create these inverse parts, with multiple parting lines added. The complex compound curved surface cavity tooling is produced. No second mold-making technique is required to produce wax patterns. This tooling can produce limited runs of wax patterns, with patterns produced in less than a day, depending on the size. By building this tooling in sections, different features of a pattern can provide optimum orientation in the vat for surface finish. The cores, cavities and slides can then be assembled.

These are just a few examples of the growing number of manufacturing applications for StereoLithography. StereoLithography patterns can be used to create tooling for any final machining of the casting. Design and testing of tooling is greatly improved when a 3-dimensional prototype is available at the beginning of the process. With reduced lead times for castings achieved through StereoLithography, manufacturers can also use the technology to reduce lead times for tooling.

### Major technological improvements in StereoLithography

Recent improvements in StereoLithography fall into four areas: the new *Weave* method of building parts, a new software release, new materials, and better laser performance.

#### *Weave*<sup>2</sup>

3D Systems has achieved a major improvement in accuracy for StereoLithography by a new method of building parts. Until now, the primary cause of part distortion was stress introduced during the post-cure operation. The new part-building method called *Weave* significantly reduces this distortion by curing more of the part in the vat while it is being built.

Just after a part is built with the standard scanning method (i.e., using tridirectional cross-hatching to fill a designated boundary), from 40 to 60 percent of the part still exists as liquid resin trapped within the walls of the cured polymer. The new *Weave* method uses two separate passes, perpendicular to each other, having very small cross-hatch spacing. This results in approximately 96% of the part being solidified in the vat, i.e., before it is subjected to the post-curing process.

The *Weave* technique dramatically improves the following characteristics sometimes found in SLA-produced and other free-form manufactured parts:

- **Post-cure distortion (warping).** Previously, post-cure distortion could be as large as 200 mils on a six inch part. Now, this distortion is reduced to less than 10 mils, for a factor of 20 increase in accuracy.
- **Post-cure shrinkage and the effects of nonuniform shrinkage.** Shrinkage could be as much as 20 mils per inch on parts built as recently as a year ago. It was also extremely nonuniform, varying from 10 to 20 mils per inch, and making it difficult to build a part to within 5 mil tolerances on multiple and varied dimensions. With a combination of *Weave* and some of the newer resins (see below), shrinkage has been reduced to 2.5 mils per inch with a variation of 1 mil. Furthermore, the overall 2.5 mils per

<sup>2</sup> See page 27 in Allan Lightman's paper for a discussion of some issues dealt with by this build technique (frozen stresses). See also one of the audience questions on page 38 at the end of Myron Bezdicek's paper for some comments on this build technique. —Editor.

inch shrinkage can be compensated for with software (see also below), leaving only the 1 mil variation as a real error.

- **Long term dimensional instability (creep).** Creep occurs over time as a part sits on a shelf. *Weave* dramatically reduces this effect by producing considerably fewer locked-in stresses in the post-cure. With about 96% of the part already solidified on leaving the vat, less of the part is available to shrink in post-curing.
- **Swelling.** Swelling can be a major problem in lower viscosity, higher flexibility resins. Swelling was sometimes rather large and significant in certain geometries, e.g. a tall part where the bottom sits in the resin for a longer time than the top. In flexible resins we have measured swelling at the bottom of a 10 inch high part to as much as 70 mils. *Weave* reduces this to 1 or 2 mils.

*Weave* also improves surface finish, especially on horizontal surfaces. It significantly reduces problems with voids. It increases green strength (the strength of the part coming out of the vat, prior to post-curing operations) because more of the part is solidified by the laser in the vat.

The company continues to perform extensive research in minimizing curl distortion, the one accuracy parameter that *Weave* has not significantly improved upon relative to standard (hatch) building techniques. The penalty paid in curl distortion for using *Weave*, however, is so small that the tremendous advantages in reduced swelling, shrinkage and post-cure distortion far outweigh it.

#### *New software releases*

**Release 3.81 for SLA-190 and SLA-250** provides significant improvements in accuracy and speed. The new software automatically determines the correct laser drawing speed at the start of each layer to be built. A new leveling algorithm was developed, and cure depths are controlled much more accurately, which also reduces curl distortion.

More user friendly than before, the 3.81 software release significantly increases the throughput of the SLA systems. The number of keystrokes for particular results has been reduced by 75%. The release is also more logical and uses prompts and pop-up menus. Preparation steps are fewer and more accurate.

It also speeds up the merge process. This is used when you want to combine two structures into a single object, as, for example, when you are building a part that needs support structures. A merge process that used to take two or three hours now finishes in a matter of minutes. So you can now bring in data from multiple CAD files very quickly and easily.

The new software also allows easy use of the *Weave* building technique. The time it takes to build a part is reduced as a result of improvements in disk access, vector calculation algorithms, and new improved algorithms.

**Release 1.2 for SLA-500** also increases accuracy and speed for this system. It supports laser control from the computer and improves cure depth calculation, vector drawing and beam profiling. File sizes are also reduced by producing binary format files.

#### *New materials*

3D Systems' machines use a variety of resins, offering a wide range of properties.

XB 5081-1 is a general purpose resin with high strength and moderate shrinkage. It is currently the most accurate resin and is appropriate for parts such as patterns for sand casting and molding. In many cases, this material is even suitable for investment casting applications.

XB 5131 resin is similar in its green and fully cured properties, but is tuned to the Argon Ion laser wavelengths for the SLA-500.

XB 5134 resin released during the past year provides additional flexibility and toughness. For parts requiring snap fitting or needing to withstand rougher handling (i.e., that do not break when dropped), this is the resin of choice.

XB 5139, with lower viscosity, was developed specifically for the passive recoating systems in the SLA-190 and SLA-1. This resin minimizes recoating time and has similar green and fully cured properties to XB 5081-1, although curl distortion is somewhat greater.

The company is vigorously pursuing research in new materials. For example, work is proceeding on a resin for a machinable part, one in which an accurate hole can be drilled, tapped and a screw put into it that would operate properly. This new material could also be used for sand casting, and is ideal for the pantograph because of its accuracy, toughness and surface hardness. It promises even greater dimensional stability, remaining accurate after a month or more on the shelf.

#### *Laser accuracy*

The accuracy with which the laser can lay down its traces is also improving. The inherent accuracy of the Argon Ion laser and scanning system of the SLA-500 is exceptional. It can draw vectors to positional accuracies of  $\pm 1$  mil over 20 inches. This machine approaches three times the drawing accuracy of the SLA-250.

#### **Conclusion**

The theme of this paper is that StereoLithography is a dynamic, constantly advancing technology. In less than four years, four unique StereoLithography systems addressing different market needs have been introduced. During the past year alone, both accuracy and throughput have improved significantly, three new resins have been introduced with more on the way, and the new software has made the system much more user-friendly. The scope of this technology continues to grow wider and broader. No longer just a tool for design engineering, it is fast becoming an indispensable tool for manufacturing and production as well.

The purpose of StereoLithography is to take you *from concept to reality*. Using StereoLithography in a diligent program of concurrent engineering will reduce your time to market, improve your product quality, reduce your costs, and maintain your competitive edge.

## How Solid Ground Curing Creates More Accurate Rapid Prototypes

Haim Levi, Chief Executive Officer, Cubital America Inc., Warren, Michigan

One of the founders of Cubital Ltd. of Israel, Mr. Levi is its Marketing Manager and serves also as CEO of its U.S. subsidiary. Mr. Levi is responsible for all the marketing, sales, training and customer support activities at Cubital America. Prior to joining Cubital, Mr. Levi was employed by Scitex Corporation as Marketing Manager for its Computerized Mapping Systems.

Mr. Levi has a B.S. in Mechanical Engineering from the Technion (Haifa, Israel) and an MBA in Marketing from Tel Aviv University.

The Rapid Prototyping industry is emerging from the first stage of its life cycle, where the novel technology of StereoLithography created a stunning impression in the marketplace. The second stage is now upon us, where customers and users have gained considerable experience and understanding of the technology, and the initial enthusiasm is giving way to a more serious and demanding approach. This has led to several new vendors introducing new products using different techniques or improvements on the original ones.

One of the main problems with StereoLithography is model shrinkage and distortion, considerably limiting the accuracy of the process. In this case, *accuracy* should have only one meaning: the degree to which the dimensions of the model match the intentions of the designer. Instead of this, vendors may speak in terms of the *accuracy of the machine*, quoting specifications such as the repeatability of the laser beam. They then leave it up to the operator to take into account the inaccuracies of the process due to shrinkage, distortions, the need for supporting structures, etc. This means that the accuracy of the model ends up depending on the experience of the operator.

The *Solid Ground Curing* process developed by Cubital is similar to StereoLithography in that we build an object by solidifying layers of a photopolymeric resin under the influence of light. However there are two very important differences:

- Rather than scanning with a laser beam, we use a strong ultraviolet lamp and a computer-programmable mask to cure a whole layer at a time.
- Rather than working in a vat of liquid photopolymer, we build in a solid environment.

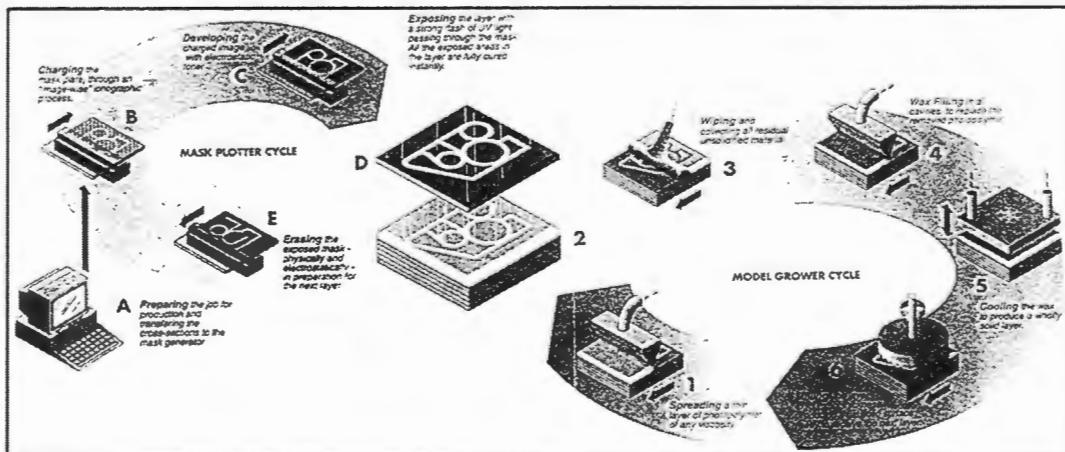
These differences solve several of the problems inherent in StereoLithography. The Solider 5600 system offers the following advantages:

- Models built on the system are accurate to 0.1% in all dimensions, without any dependence on the skills of the operator. Shrinkage is minimized due to the full cure of each layer as it is laid down.
- Since each layer is fully cured in the machine, there is no need for post-curing and no need for a curing oven.
- Again because the model is fully cured in the machine, there is no issue of "green strength." Models come out of the machine with full structural strength and stability and are not subject to the internal stresses caused by shrinkage.
- The solid environment supports the model as it is constructed, so there is no limit to the geometrical complexity of the models produced and no need for additional support structures.
- The spacious production volume of 20×14×20 inches can be used to produce one large model, or many different smaller models can be nested together throughout the volume and made in a single run. This 3-dimensional nesting allows for high throughput.

- Several resins, of any viscosity, can be used by the system. The high intensity lamp will cure almost anything. We have built models from regular UV glue and they work.
- Toxicity is minimized by the short period during which the resin is exposed in a liquid state. Cured photopolymers are nontoxic.
- By altering the process slightly, wax models can be made. We are currently testing the results for application in the lost wax casting process.
- In the event of an equipment malfunction, power failure or other cause of a fabrication error, the most recently laid down layer can be simply removed (by the milling operation; see below) and redone. You do not have to scrap the build and start all over again.

### The Solid Ground Curing process

The Solider machinery actually performs two processes in tandem: mask generation and layer building. The mask for one layer of the model is prepared while the previous layer is being processed and cured. These two processes are illustrated in the following diagram:



The Solid Ground Curing Process. Letters (A, B, C, ...) and numbers (1, 2, 3, ...) in brackets in the following text refer to the corresponding phases of the operation in this diagram.

The process starts with the creation of a software solid model of the parts to be made, and the choice of layer thickness. The Solider computer then slices the software model into layers, *preparing* a precise raster image of each layer (A).

This image is sent to the mask plotting unit. A glass plate is *charged*, using an "image-wise" ionographic process (B), and the charged image is *developed* with an electrostatic toner, a black powder similar to that used in Xerography (C). This generates a high resolution optical mask, which is a negative image of the surface area to be solidified.

A thin (usually 8 mils) layer of liquid photopolymer resin is *spread* on the workpiece (1). The optical mask is precisely positioned just above the workpiece and beneath a high-power (2 kW) UV lamp (D). A shutter is opened for about 3 seconds *exposing* the layer of resin to the light and curing it (2). The pattern of the cross section of the model at this layer is fully cured due to the high power of the lamp and the length of exposure time. Unexposed areas on the layer surface remain in the liquid state.

The mask moves back to the plotting unit and is discharged and *erased* (E), ready for the next cross section to be drawn. The same toner is reused to make the next mask. The workpiece passes under an aerodynamic *wiper* that “sucks” away all the residual liquid from the surface, leaving behind only the cured pattern (3).

A thin layer of melted *wax* is spread over the surface, filling in all the voids and cavities left after the removal of the residual liquid (4). A cold plate is lowered onto the surface of the layer, *cooling* down the wax and solidifying it (5). Now we have a fully solid layer that is made partly from plastic and partly from wax.

The workpiece passes under a 32-blade *milling* disk (6) that trims the layer’s surface down to the desired layer thickness (usually 6 mils but can be as small as 1 mil), creating a flat, smooth surface ready for the next layer. A new layer of liquid photopolymer is *spread* on the workpiece (1) and the whole process starts over again.

This process will be repeated hundreds or thousands of times to produce a finished object. After the last layer is done, we have a block of wax, within which the model, or models, are embedded. The wax is melted away in a microwave oven, and further removed by a hot air gun or just warm water because the wax is water soluble. The finished model is now ready.

The throughput is about 1½ hours per vertical inch.<sup>1</sup> With a bed of 20×14 inches, this builds about 190 in<sup>3</sup> per hour.

This is not a desktop machine, not a CAD peripheral. It is a machine tool with the speed, accuracy and capacity of a machine tool. We have built in the infrastructure needed to take it, in the next generation, one step further into the production of real plastic products, not just models and prototypes. As a machine tool, it has the corresponding size and weight. It occupies 12×5½ feet of floor space, stands 5½ to just over 6 feet high, and weighs more than four tons. One advantage of this weight is that the machine is insensitive to external vibrations.

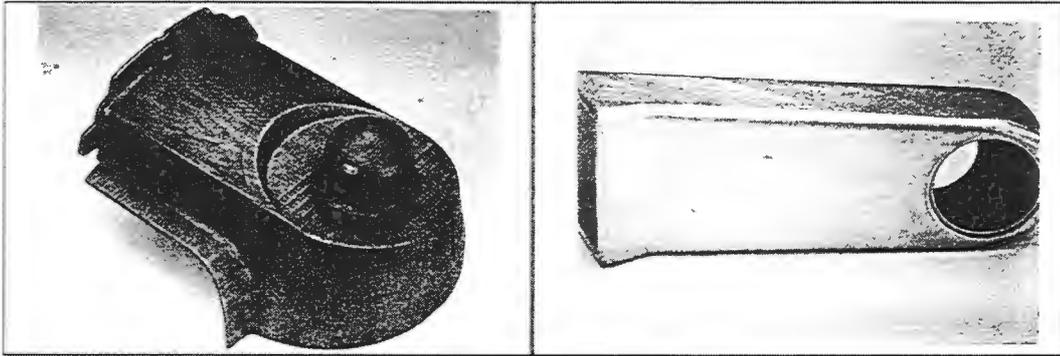
A word about the software. We accept data in the standard .StL format. But we have a very nice feature in an algorithm that checks integrity of the .StL file, meaning that it looks for cracks, gaps, missing facets, etc. in the software model. Then it corrects these errors by a semi-automatic process. Finally, it merges the files of several objects together for nesting in a single run.

### Results of the process

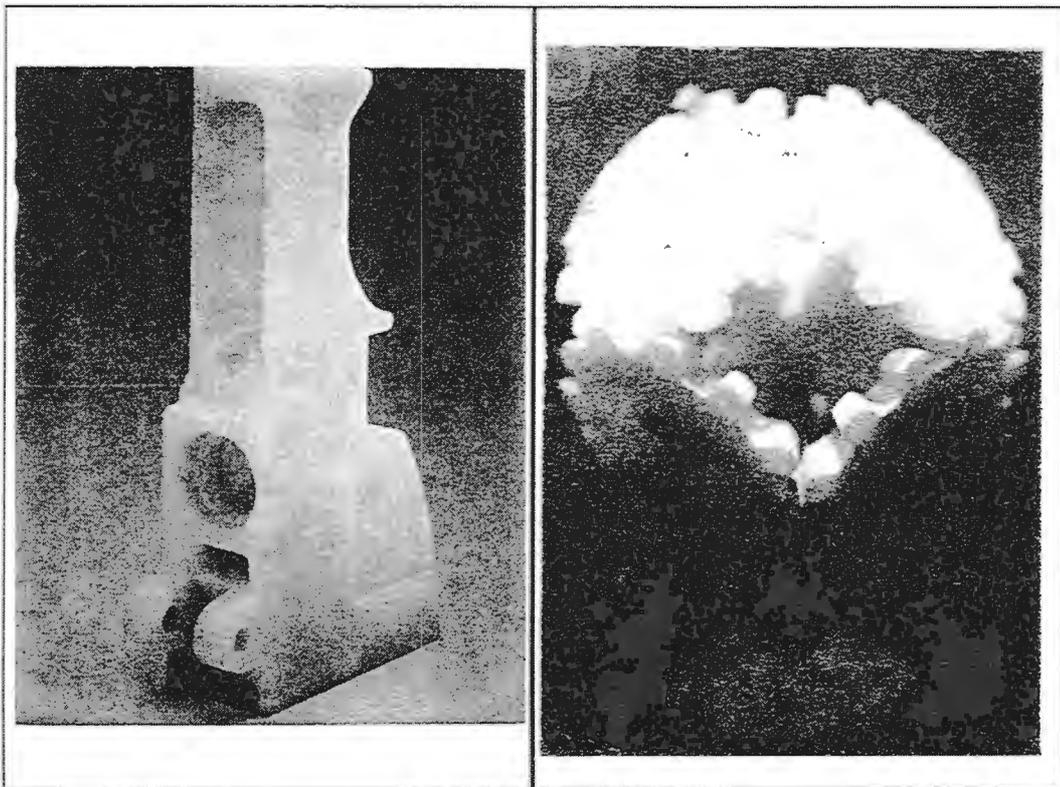
Here are some examples of objects made by Solid Ground Curing:

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<sup>1</sup> This is the design specification for the production machine slated to begin delivery in Fall, 1991. The prototype machine currently in operation has a throughput of 3 hours per vertical inch.



Parts made by Solid Ground Curing. Left: Thin-walled upper cover of an automotive front suspension unit. Right: Faucet pipe. Both of these items were made without support structures.



Objects built by Solid Ground Curing. Left: Trigger unit of a weapon system with very complex internal geometry. Right: Functioning eight-gear mechanism.

The last figure is of a mechanism consisting of eight functioning gears built together in a single run, with no assembly performed. It came out of the wax in one piece and worked immediately. Each gear has its own shaft, and there is a small handle. If you turn the handle, all the gears turn together in different directions. This mechanism has very tight tolerances in the shafts, and in between each shaft and the base. This is an example of the kinds of things you can do with the precision and geometric flexibility available from *Solid Ground Curing*.

### **Current business status**

Service bureaus are in operation in Warren (Detroit), Michigan and Zurich, Switzerland. The Detroit machine has been running at full capacity, 24 hours a day, 7 days a week, and has a considerable backlog of orders. Our production machine, the *Solider 5600*, will begin shipping in the 4th quarter of 1991. We have six confirmed orders for it, three each in the United States and in Europe.

## ***Selective Laser Sintering: New Dimensions in Rapid Prototyping and Manufacturing Technologies***

Kent Nutt, Marketing Manager, DTM Corporation, Austin, Texas

Kent Nutt is responsible for product marketing, marketing communications and market strategy at DTM Corporation. He has twelve years of high technology marketing experience at Datapoint Corporation, Dataquest and Aspect Telecommunications.

Mr. Nutt graduated with a B.A. in Sociology from the University of Texas.

With accelerating growth and competition in today's global marketplace, manufacturers face the daunting tasks of meeting changing market needs, maintaining market share, and reasserting a technological edge. Now, more than ever, adopting new technologies is a key component in ensuring the successful outcome of new projects—and in producing long-term market success.

Over the last decade, great strides have been made in the advancement of conceptual design technologies, including the development and maturity of 3-dimensional CAD and CAE software tools. Additionally, the development and implementation of CAM and CIM technologies have streamlined mass production processes.

Design for manufacturing (DFM), design for assembly (DFA), and concurrent engineering are additional techniques developed to enhance communications and interaction among design, marketing, and manufacturing personnel. The collaborative efforts cultivated by these techniques provide ongoing reality checks as products evolve from conceptual design to final form.

Amidst all this technology and innovation, remaining bottlenecks between conceptual design and mass production occur in:

- the rapid creation of 3-dimensional models and prototypes, and
- the cost-effective production of patterns, molds and tools.

These bottlenecks are especially prevalent where complex shapes or geometries are involved and occur primarily because traditional techniques, including manual methods, often require weeks, or even months, for completion.

Although product designers and manufacturing engineers must be able to visualize and assess designs for form, function, fit, and other factors before designs can be finalized for production, there is only so much time that companies can afford to spend on the creation of models, prototypes, patterns, and tools. This is especially true in industries where declining volumes and increasing varieties of parts and products must be produced.

What is more, lengthy delays can prevent designers and engineers from going through the reiterations and fine-tuning necessary to create a design with superior qualities, functionality, manufacturability, and market potential.

During recent years, several new technologies for quickly creating 3-dimensional representations have emerged to address these needs and challenges. They are known under a variety of names, including *rapid prototyping*, *desktop manufacturing*, *solid free-form fabrication* and *conceptual modeling*, among others.

These technologies offer the capability to rapidly produce 3-dimensional solid objects directly from designs created by CAD, CAE, or CAM systems. Instead of waiting several

weeks for a model, prototype, or pattern to be completed, these technologies can finish the job in a few days, or even hours.

### Testing for form, fit and functionality

As evidenced throughout the manufacturing industry, one of today's most critical requirements is the ability to quickly fabricate prototypes that allow both a review of the product's proposed form and the testing and verification of fit, function, and other specifications. To provide accurate results, however, these prototypes must employ materials with characteristics similar to those used in the final product.

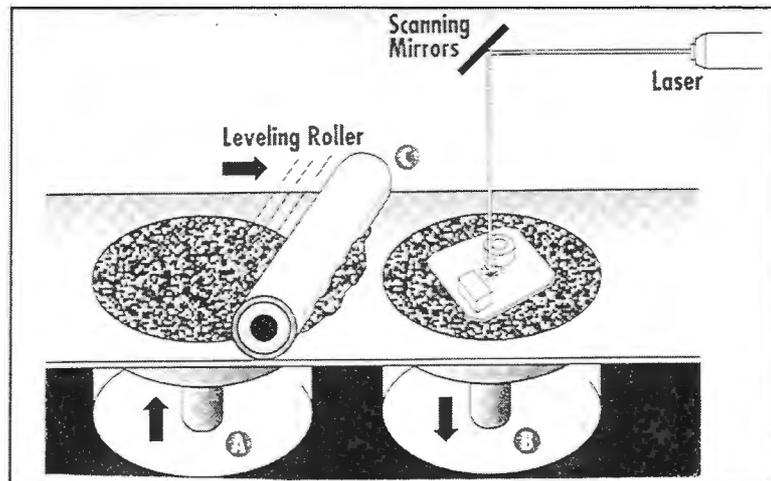
Unfortunately, early rapid prototyping technologies like StereoLithography, which use only photo-sensitive liquid polymers, have limited applications here.

Another technology, however, the *Selective Laser Sintering™* (SLS) process, developed by DTM Corporation, provides greater potential and a wide range of applications. In contrast to StereoLithography, the SLS process offers a multiple-materials approach to rapid prototyping technology, addressing the need for functional, comprehensive design evaluations, while at the same time offering the ability to generate patterns and tools—and the future potential for direct fabrication of parts using metals and other materials.

The SLS process was invented in 1987 by Carl Deckard, then a graduate student, in the mechanical engineering laboratory of Prof. Joe Beaman at the University of Texas at Austin. DTM is a joint venture among Deckard, the University of Texas and BF Goodrich Co.

### How the *Selective Laser Sintering* (SLS) process works

As the SLS process begins, a very thin layer of heat-fusible powder is deposited into a work space container and heated to just below its melting point. An initial cross-section of the object under fabrication is traced on the layer of powder by a laser. The temperature of the powder impacted by the laser beam is raised to the point of "sintering," forming a solid mass. As the process is repeated, each layer fuses to the underlying layer, and successive layers of powder are deposited and



The *Selective Laser Sintering* process. The process chamber contains two cylinders and a powder leveling system. The powder cylinder (A) delivers powder by moving upward. The part cylinder (B) prepares to receive the powder by dropping a distance equal to the thickness of the layer to be deposited. The roller (C) spreads and levels the heat-fusible powder.

Each layer is sintered with a laser beam, causing the powder to soften and quickly resolidify in the shape of the desired cross section. Sufficient energy is supplied to bond each cross section to the previous layer. Areas of powder where the laser is turned off remain unaffected and serve to support the object as each subsequent layer is applied and sintered.

sintered until the object is complete.

The laser beam intensity is modulated to sinter the powder only in areas defined by the object's design geometry. In areas not sintered, powder remains loose and serves as a natural support for the next layer of powder and the object under fabrication.

### **CAD and CAE: Conceptual design requirements for the SLS process**

The SLS process requires the use of CAD and CAE software, with designs created preferably in 3-dimensional surface or solid form. Designs created in 2-D CAD or CAE require modification prior to SLS acceptance and processing.

Design models created in CAD, CAE, or CAM software are entered into the SLS system through an .StL file. This file format is currently the industry *de facto* standard and is a method used to convert CAD databases into a form usable by rapid prototyping systems.

The .StL file is transferred to the SLS machine for computer-based processing. The modulated laser beam selectively describes the object's geometry based on the coordinate points. The design information is thus transferred from a computer representation to a real world, physical object through a unified, completely digital process.

### **The SLS process: A tangible reality**

The SLS process has several inherent advantages that address the basic requirements for fast modeling, prototyping, and pattern-making within industry. These include:

- Speed,
- The additive-layer nature of the part building process, and
- The ability to employ a variety of heat-fusible powdered materials.

#### *Speed*

Using the SLS process, a model or prototype up to 12 inches in diameter can be produced at the rate of ½ to one vertical inches per hour, depending on the complexity of its geometry. A 4-inch-high part can conceivably be finished in four to eight hours.

The SLS process software also allows concurrent slicing of the part geometry files while processing of the object is taking place. Non-SLS technologies currently require time-consuming, cross-hatching scans of various types of lasers interspersed with re-application of photopolymer resins. This must take place before the part can be removed for final curing.

Moreover, no post-production curing is necessary with the SLS process, except when ceramic materials are used. In contrast, StereoLithography requires post-production curing to completely harden the liquid photopolymer resins.

#### *An additive process*

Based on an additive-layer process, SLS technology does not require traditional dies or part-specific tooling and is particularly applicable where fewer, more complex designs are to be prototyped or modeled.

The additive-layer nature of the SLS process also allows for the creation of very complex parts without the need for external support structures, clamping, or repositioning of specific portions of the design geometry. Designs with internal cavities, overhangs, notches within notches, and other intricate geometries, which are difficult to achieve through other processes, are easily produced using the SLS process.

Moreover, the unsintered powder that surrounds the fabricated part during the SLS process provides a customized support structure that is easily removed upon part completion.

### *Multiple materials*

The SLS process can use a variety of materials. In fact, virtually any material that softens and has decreased viscosity upon heating can potentially be used. Materials currently available include polycarbonate, investment casting wax and PVC. Materials commercially available by the end of 1991 will include ABS plastic and nylon.

Additionally, low-temperature ceramic parts can be fabricated with the SLS process using polymer-coated ceramic powder, with curing as a secondary process. While not yet released for commercial use, ceramic materials will be available in the near future.

The natural evolution of the SLS technology is also heading toward the use of powdered metals and alloys. Current market research indicates that this capability will have widespread application throughout manufacturing industries, primarily because more than 80% of all design prototypes are currently made from various metals using conventional processes.

DTM is currently conducting tests using powdered metal with the SLS process. In fact, early laboratory research efforts in sintering brass, copper, aluminum, and cobalt at the University of Texas at Austin have proven very successful. These efforts are continuing with additional metal alloys and metal powder blends. Commercial use of metals is expected to be a reality in the near future.

### **Primary applications of SLS technology**

Primary applications of the SLS process are occurring in three major areas:

- Visual representations (models),
- Functional, durable prototypes, and
- Production capabilities, including the creation of the molds, patterns, and tools required for limited production run and on-demand batch manufacturing.

The SLS process can have a significant impact on product design capabilities in manufacturing organizations across many industries, resulting in shorter design cycles and superior design. In effect, the use of the SLS process serves as a time-saving, communication-enhancing bridge between design and manufacturing.

Specific industrial segments where the SLS process is in use include the automotive, aerospace, computer, consumer goods, electronics, foundry, and medical industries. SLS technology also serves as a front-end process to conventional machining, mold-making, and investment casting processes.

## SLS technology applied to investment casting

In addition to its ability to rapidly transform CAD drawings into 3-dimensional models and prototypes, the SLS process provides the ability to quickly create wax patterns directly from CAD drawings—without tooling. These patterns are then used with the lost wax method.

Eliminating the tooling stage translates into numerous benefits for investment casters, including:

- Minimized up-front tooling costs,
- Significant time savings, and
- The ability to produce complex shapes that were previously too difficult to produce via tooling.

The SLS process and wax pattern-making are extremely well-matched for a number of reasons:

- The SLS process is the only process that can utilize investment casting wax.<sup>1</sup>
- With average tolerances ranging from  $\pm 2$  to  $\pm 10$  mils, the SLS process offers the accuracy required by investment casting applications.
- The SLS process can easily create complex shapes and geometries that are difficult to produce via other methods.
- The problems, delays (as long as 100 hours for resin-based patterns), and complications sometimes associated with burnouts are virtually eliminated with the SLS process.
- Wax patterns created with the SLS process feature a surface finish that is suitable for most investment casting applications, typically 100 to 120 average micro inches RMS.

Specific applications where the SLS process can be useful to investment casters include:

- The creation of prototypes, short run parts, and marketing samples,
- Process development and refinement of gating and metal shrink requirements, and
- Prototyping and creation of production tooling.

## Additional applications for the SLS process—present and future

Because the SLS process utilizes an expanding and diverse variety of powdered materials and allows for the formation of complex geometries, a number of additional tooling and production applications become possible, including the following:

**Short run tooling and soft tooling.** Here, the SLS process can be used to create a master pattern from which various types of soft tools, including those made of silicone rubber and epoxy, can be made. These tools can then be used to generate short runs of parts for use in testing, marketing, and verification of fit and form. These short run parts also can be used, in some cases, to meet custom manufacturing requirements.

**Spray metal tooling.** An SLS-created pattern made of polycarbonate, is coated with a thin layer of protective material, followed by sprayed-on layers of liquid metal to further coat all surfaces. The metal-coated pattern is then put in a container filled with molten metal. The metal cools, and a tool for casting additional parts is created. Because the tool is made of

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<sup>1</sup> Lisa Crump's paper challenges this statement on page 84.

metal, usually zinc with epoxy or aluminum backing, it is more durable than soft tools and can produce runs of up to several thousand parts, depending on the application.

**Plaster cast tooling.** As with other tooling methods, an SLS-generated pattern can be used to create a plaster cast tool, which is then used to make steel and other metal parts.

**Vacuum form tooling.** The SLS process can be used to create the master form, from which the vacuum-formed object will achieve its final shape. During the creation of the form in the SLS process, the form's porosity can be adjusted. This is an inherent advantage because a master form created with a suitable level of porosity eliminates the extra step of drilling the dozens of tiny holes needed to allow air to pass through during the vacuum process. With the SLS-generated form, air from the vacuum passes directly through the porous material.

**Numerically-controlled (NC) tooling and path verification.** An SLS-generated part can be used to trace and program the tooling paths that run numerically-controlled machines.

**Electro-discharge machining (EDM).** Upon availability of carbon materials for use with the SLS process, it will be possible to quickly and affordably generate the carbon or graphite electrodes used in electrode EDM. Currently, these electrodes are difficult and time-consuming to produce.

**Forging dies.** Drop-forge dies are made of steel castings at a grade of 0.60% carbon open hearth. Dies of this steel will forge mild steel, copper, and tool steel. SLS-generated wax patterns can be used to produce forging dies of steel castings. A pair of these dies can then be used to produce up to 20,000 pieces.

### **Service bureaus: Bringing SLS technology to the marketplace**

To fully understand customer requirements and how SLS technology and applications can meet these requirements, DTM has opened two SLS sales and service centers. These facilities provide a low-cost, low-risk way for customers to utilize the SLS technology and receive customized technical support as needed.

The DTM service bureaus offer a staff of technical support personnel, advanced CAD equipment, and multiple SLS 125 Systems. Customer designs are accepted as physical drawings or 2d or 3d CAD files in .StL or IGES formats. The bureaus are located at the company's headquarters in Austin, Texas and in Brecksville, Ohio.

As far as selling the machines themselves, the SLS 125 is currently in the beta phase. We have now received letters of intent from most of our five beta customers. We will be shipping those units in December of this year for installation in December or early January. Then we will begin production-level shipments in the second quarter of 1992, domestically, and then, in Europe, later in the year.

## ***Fused Deposition Modeling: A Nonlaser-Based Rapid Prototyping Product***

Lisa H. Crump, Vice President for Marketing, Stratasys, Inc., Minneapolis, Minnesota

Stratasys was formed in 1988 by Lisa and Scott Crump. With more than nine years experience in technology-based companies, Ms. Crump directs the marketing and communications efforts at Stratasys. Ms. Crump helped co-found IDEA Inc., which provides automation equipment for the semiconductor industry, in 1982. She served as marketing manager for the now public firm until 1988.

Ms. Crump earned a B.A. from Washington State University and an M.S. from Portland State University, both in Education. She has since taken graduate level courses in Business and Management.

*Fused Deposition Modeling (FDM)* is a computerized lamination layering process, based on instantaneous solidification of the molten laminate material from nontoxic modeling filament. This technique was invented by Scott Crump, a licensed professional engineer. We are a privately held company with partial funding from Battery Ventures of Boston.

Our focus is on creating "models in minutes." This enables the design and manufacturing engineer to produce high quality, multi-material models very quickly, in an engineering environment, right at the CAD workstation.

Tim Gornet of the University of Louisville has done a study of the costs of implementing a change in a product early in the design cycle, versus making the change shortly before going into production, or after production has started. He found that a design change implemented right before production is ten times more costly than one made early in the design process because there are so many more elements that have to be changed at the later time. If the change is made after production has begun, it is a hundred times more expensive. FDM enables engineers to create multiple iterations of concept models in short order, enhancing the ability to make changes early in the design cycle.

The specific benefits of FDM technology are:

- The ability to create fast models in minutes.
- The ability to generate accurate, repeatable models from 3d CAD files.
- It works in an office environment, utilizing safe, nontoxic modeling materials. No exhaust hood or special facilities are required.
- No post-curing is necessary.
- Choice of three modeling materials: machinable wax, investment casting wax, and a nylon-like plastic.
- Low cost of operation. A typical per-part cost is around ten dollars.
- The 3D Modeler supports open systems to co-exist with other CAD systems and Unix-based hardware systems. Data can be input through IGES, as NC code, or in the .StL format.

FDM is a rapid, single step process, enabling you to do automatic model making right at your CAD workstation.

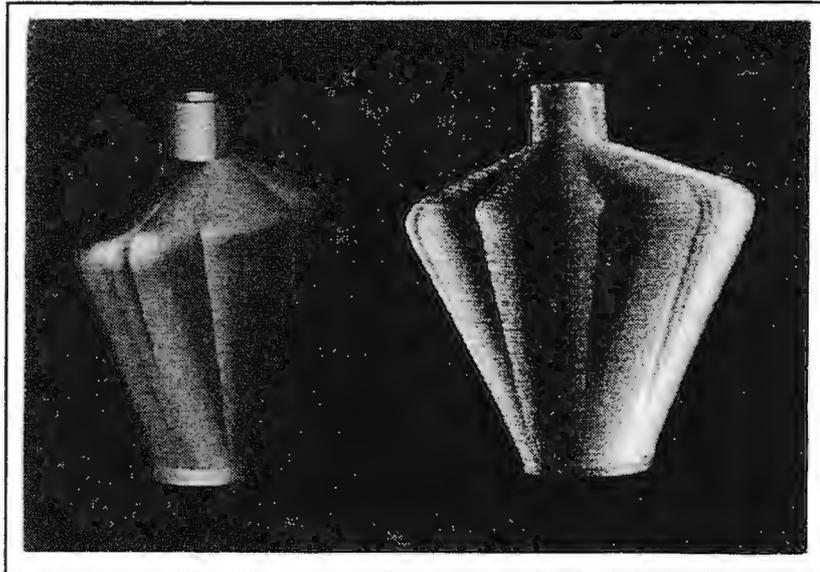
Rapid prototyping can be of key importance to a company implementing concurrent engineering, which allows product and process design to occur simultaneously, helping the company to hit a window of opportunity in the marketplace. The 3D Modeler supports concurrent engineering by reducing product time to market. Some of the applications of FDM are:

- Concept models,
- Fit, form and function models,
- Marketing visualization models,

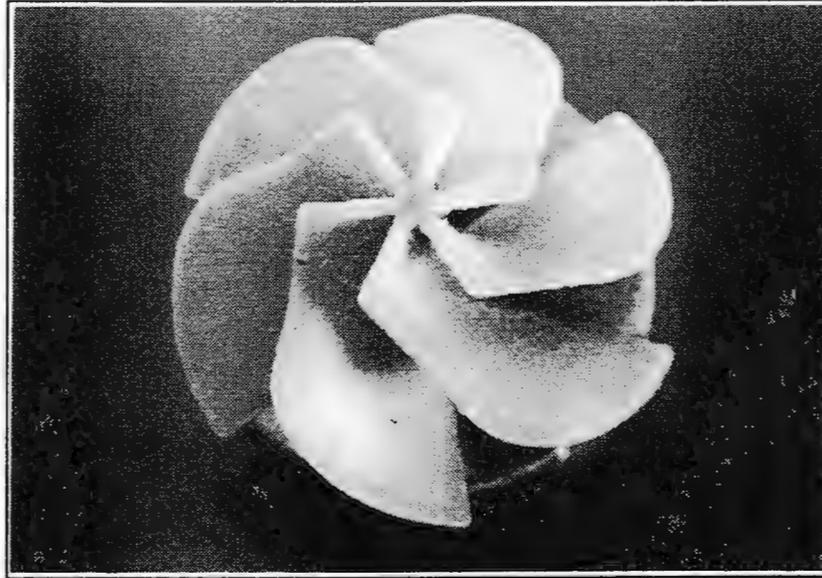
- Investment casting masters, and
- Masters for other mold applications.



The Stratasys 3D Modeler. The Modeler stands six feet tall, has a foot print of  $2\frac{1}{2} \times 3$  feet, weighs 250 pounds, and plugs into a regular wall socket.



A perfume bottle modeled on the 3D Modeler. On the left is a surfaced 3-dimensional drawing of a perfume bottle in the NURBs-based StrataSlice software program running on the workstation. The bottle was modeled in machineable wax (right) in 50 minutes with 10 mil layers.



**A fan blade modeled on the 3D Modeler. This was modeled in machineable wax in 2 mil layers in 27 minutes.**

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**An electronics utility box. This is made in investment wax for casting into stainless steel.**

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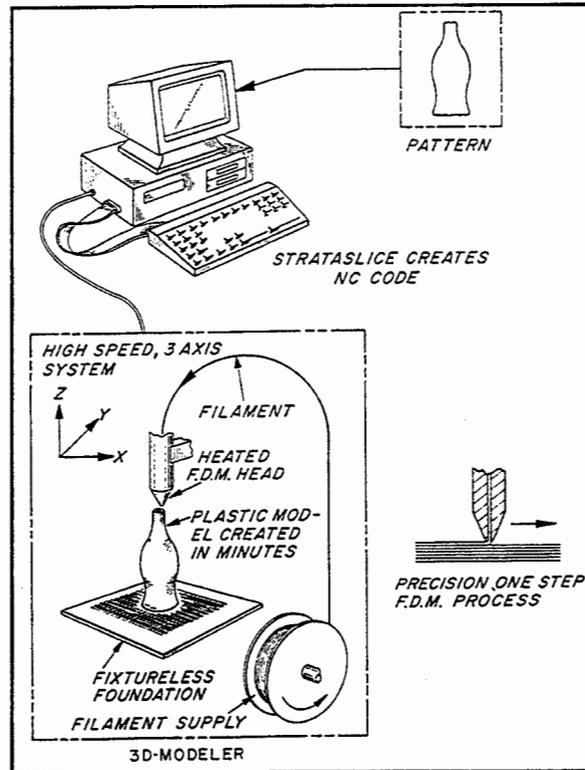
Here is how you go from your CAD file to a hands-on model. Wire-frame, surface and solid CAD data from standard CAD software packages can be imported through the IGES format. The file is brought into the NURBs-based StrataSlice software program, either through Ethernet or a tape. It can be edited, scaled, oriented or even surfaced if required. Supports can be added if necessary. The software model is then sliced at the layer thickness required and posted out to NC code. That code is then downloaded through a standard RS-232 serial port to the 3D Modeler and then the plastic part is created.

The model can be sliced into layers as thin as 1 mil along the z-axis. The wall thickness, or *road width*, can be between 10 and 250 mils in a single pass, or the object can be built solid. The material solidifies in about one tenth of a second. It is directed in place with an x-y-controlled extrusion head orifice that creates the precision laminate. As the FDM head extrudes the thermoplastic, the layer is sheared at the same time. No wiping step is required. So you have a streamlined operation.

Fundamental to the FDM process is maintaining the material just above its solidification point. We control the thermoplastic melt temperature to 1°F above its solidification point, and we employ precision volumetric pumping through the extrusion orifice. Then it is sheared and solidified, and each layer is bonded to the previous layer through thermal heating. Our overall tolerance is plus or minus five mils on the x, y and z axes, over a twelve inch cube working envelope.

Three different materials are available to date. We offer machineable wax, investment casting wax, and a tough nylon-like material. The machineable wax comes in blue and gray, and can be used to make patterns for injection molding by a spray-up metal process. The investment casting wax is red or aqua. It enables you to go directly to the investment casting process; the output of the Modeler is ready to be used as a pattern without any intermediate steps. The nylon-like material is white and is used for form, fit and function applications. Models in this material can be dropped without breaking. Of course, all three materials can be used for concept modeling. Filament spools can be changed out, for a different material, in one minute.

A unique quality of FDM is the ability to create a support in mid-air, like a spider building a web, rather than having to build supports up from the base. This allows for fast modeling because you do not have to spend time creating or slicing the supports in software. Furthermore, as a part is untouched by human hands, accuracy is not compromised.



The Fused Deposition Modeling process.

## **Summary**

Fused Deposition Modeling is a clean running, single step operation using nontoxic, biodegradable, thermoplastic, filaments. It eliminates liquid photopolymers, powders and lasers from the process. No post-curing is required. All CAD programs, wire-frame or solid, are supported through IGES, and the geometry is represented in exact dimensions.

Since the 3D Modeler does not use a laser, system maintenance costs and electrical consumption are substantially less than for the laser-based systems. We offer multiple modeling materials and colors. Our spooled filament system allows you to change material in one minute, because there is no vat to clean out. And Stratasys can produce a model stepped at one mil intervals in the z-axis.

So, the 3D Modeler enables companies to rapidly bring new products to market by providing concept models for design reviews and marketing presentations, component test models, and patterns for the casting processes.

## ***Three-Dimensional Printing and its Applications in Metal Castings and Composites***

**Emanuel Sachs, Professor of Mechanical Engineering, Massachusetts Institute of Technology, Cambridge, Massachusetts**

Elly Sachs received his Ph.D. in Mechanical Engineering from MIT in 1983 and has 6 years of industrial experience in manufacturing. His research is in the area of flexible manufacturing and includes efforts in rapid design and fabrication of prototypes and flexible process control. He teaches undergraduate and graduate courses in manufacturing and process control.

A process called Three-Dimensional Printing is being developed for the direct manufacture of tooling and functional prototypes from computer models. The process functions by the deposition of powdered material in thin layers and the selective joining of the powder with a liquid binder. The binder is applied by a method similar to that used in ink-jet printers. Following the sequential application of layers, the part is removed, yielding a 3-dimensional part.

Three-Dimensional Printing is being applied to the fabrication of metal and ceramic parts for applications including metal casting, ceramic preforms for metal matrix composites, prototypes of metal injection molded parts, and tooling for injection molding and other processes. This paper will focus primarily on the fabrication of ceramic shells and cores for metal casting. The elimination of the need for part specific tooling and elimination of many steps in the conventional ceramic shell process lead to a significant reduction in cost and lead time.

Materials used to make shells and cores are alumina powder and colloidal silica binder which form porous ceramic parts that have the same mechanical and thermal characteristics as conventional ceramic shells. Ceramic shell and cores made by Three-Dimensional Printing have been used to cast parts in nickel superalloy at 1660°C.

The rate of fabrication for the next generation Three-Dimensional Printer will be about 2.4 vertical inches per hour over a bed of 12×24 inches. Dimensional control has been established by printing plates intended to be 1.500 inches wide; the standard deviation from part to part was 0.8 mils. The average shrinkage upon firing was 0.08 mils for 1.5 inch plates fired to 1000°C for one hour.

### **Development efforts**

I am in the Mechanical Engineering Department of MIT, and my colleagues, Michael Cima and James Cornie, are in Materials Science. We supervise a team of students, graduate and undergraduate, from both departments, and I am particularly proud of this project because it is an interdisciplinary effort that is functioning well. In a university setting, that is a major accomplishment.

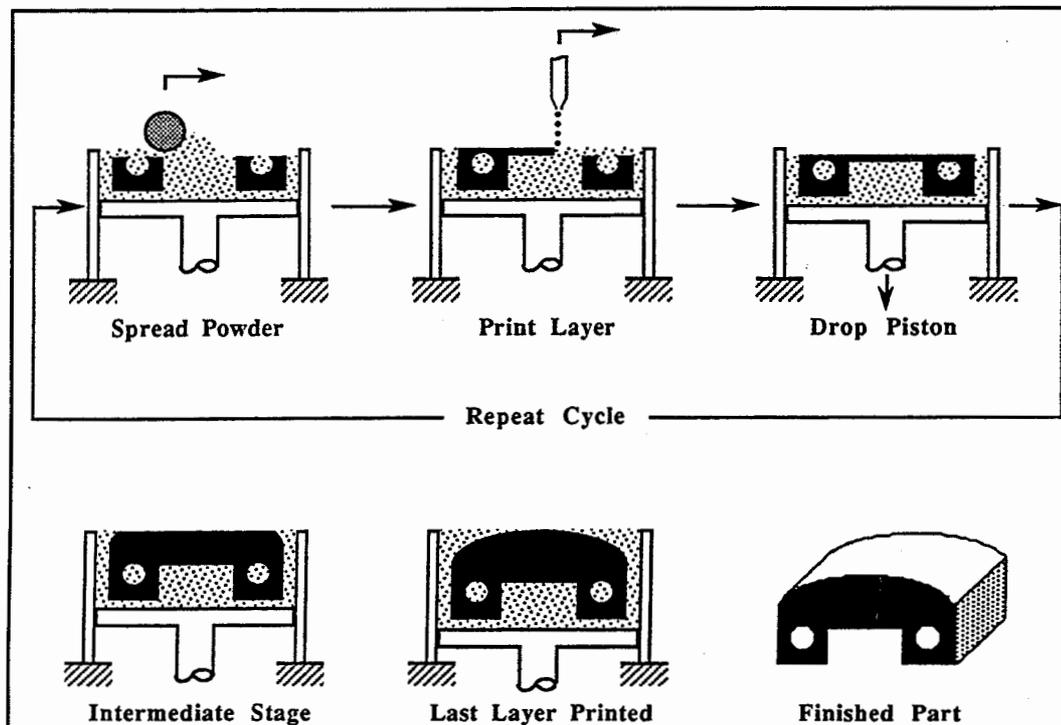
We set out against the background of the other rapid prototyping processes that were emerging, and we set the goal of creating functional prototypes and tooling directly from a CAD model. We thought that if we were going to succeed at that we would have to work directly in the materials of interest, that is, work directly by creating parts out of ceramics and out of metals. That was the genesis of Three-Dimensional Printing.

Our strategy for ongoing development of this technology has two parallel and complementary aspects. The first is to continue the investigative research work, described below, at

MIT. This work has three sources of funding, including MIT's *Leaders for Manufacturing* program, and an industrial *3-D Printing Consortium*, which currently has six member companies. The second aspect, which we are now starting to pursue, is to establish an off-campus company to build and sell equipment. These are complimentary because the Consortium consists of companies interested in *using* the technology, as opposed to companies interested in building the equipment.

### The Three-Dimensional Printing process

*Three-Dimensional Printing* is a manufacturing process for the rapid production of 3-dimensional parts directly from computer models.<sup>1</sup> This process creates a solid object by printing sequential 2-dimensional layers. Each layer begins with a thin distribution of powder spread over the surface of a powder bed. From a computer model of the desired part, a slicing algorithm draws detailed information for every layer. Using a technology similar to ink-jet printing<sup>2</sup>, selective application of a binder material joins particles where the object is to be formed. A piston that supports the powder bed and the part in progress lowers so that the next powder layer can be spread and selectively joined. This layer-by-layer process repeats until the part is completed. Following a heat treatment, unbound powder is removed, leaving the fabricated part. This sequence of operations is illustrated below:



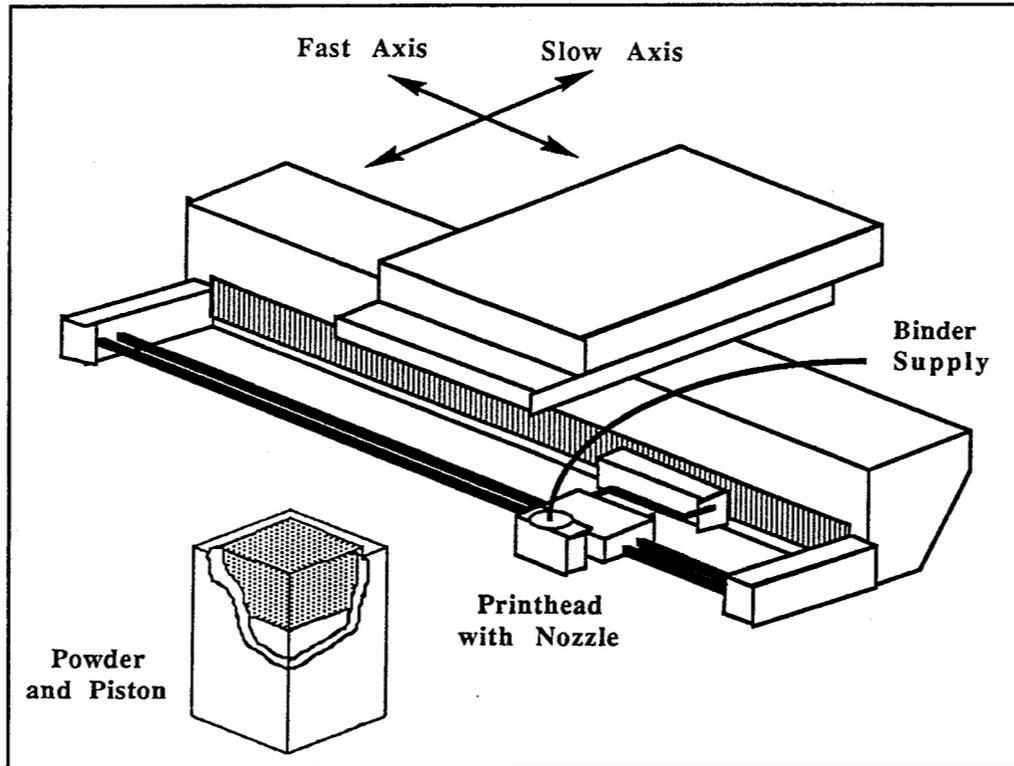
The Three-Dimensional Printing process cycle.

The motion of the printhead is controlled on two independent orthogonal axes. The overall dimensions of the working volume depend only on the translation mechanism and the

<sup>1</sup> E. Sachs, M. Cima, P. Williams and D. Brancazio, *Rapid Tooling and Prototyping by Three Dimensional Printing in '90 Trans. NAMRI/SME*, 41..5.

<sup>2</sup> There are two major classifications of ink-jet printing, continuous and drop-on-demand. Drop-on-demand is used in light duty applications such as the HP DeskJet Printer. Continuous jet printing is used industrially in higher volume applications and is the one we use for 3-D Printing.

powder-handling capabilities. The build rate of a part is dependent on the characteristics of the printhead; in particular, it is proportional to the number of jets running simultaneously. Because the part is supported in a powder bed, we can build parts that have overhangs, undercuts and internal volumes.

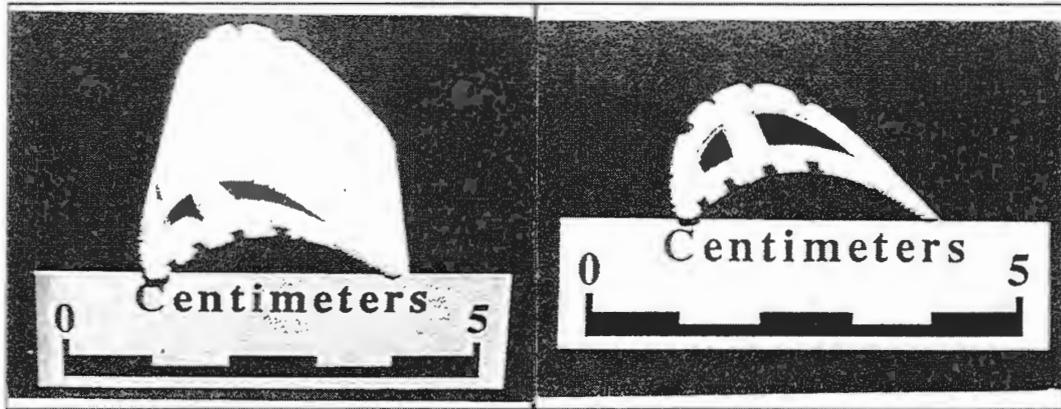


**Schematic of the Three-Dimensional Printing machine.** The part is built in a square piston, with a stepper motor that drops the piston between layers. The nozzle is raster-scanned over the surface of the powder. The fast axis is moved by a linear stepper motor, the slow axis by a stepper motor driving a lead screw. The binder is pumped from a pressurized reservoir through an in-line filter to the nozzle.

### *Parts made by 3-D Printing*

Ceramic shells and cores have been printed in silica-alumina ceramic from computer data files (.STL format) supplied by industrial sponsors. The materials used are Nyacol 830 colloidal silica binder (a suspension of 30 wt.%, 16 vol.%, SiO<sub>2</sub> in water) and Norton 320-mesh alumina powder (nominal particle size 1.8 mils). These have been chosen to duplicate the materials in a typical ceramic shell.

The following two photographs show an airfoil shape printed in this alumina-silica ceramic. This part was printed to demonstrate the ability to print hollow parts.



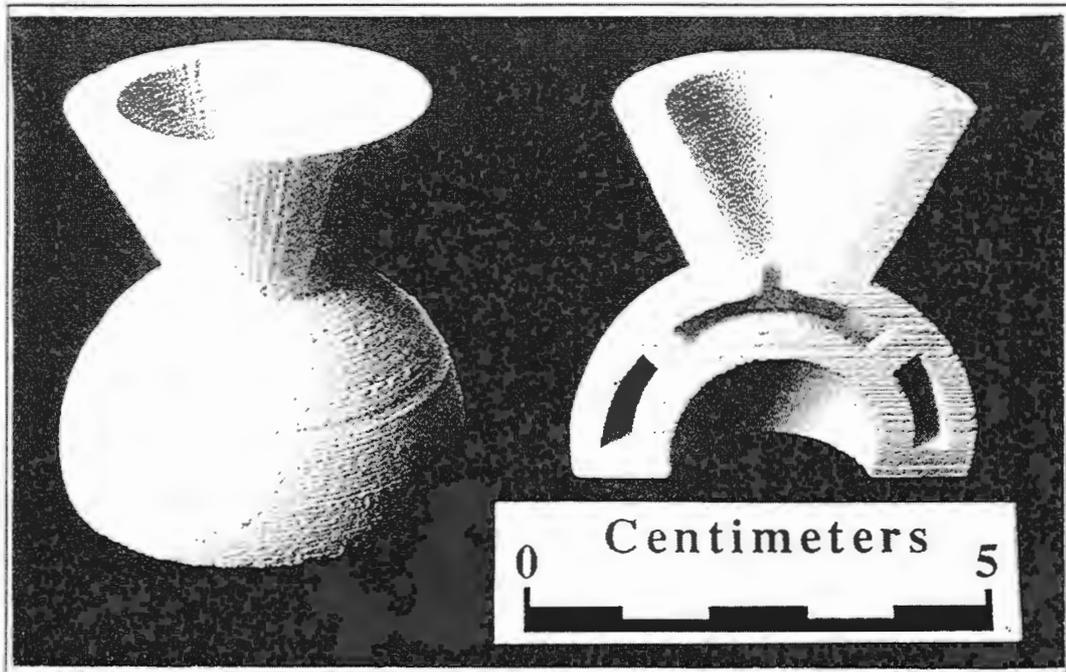
Turbine blade fabricated in alumina-silica ceramic by 3-D Printing process.

At right is shown a nickel superalloy casting using a core consisting of a solid airfoil similar in shape to that shown in the previous photographs. The core was coated with wax and invested in a conventional manner. The shell was fired to 1270°C and subsequently cast with PW 1455, a nickel-based superalloy, at 1660°C. After cooling, the core was leached out in a conventional molten caustic bath at 300°C.

A complete ceramic shell and a section of it are shown below. The 3-D Printed shell measured 2×2×2 inches, and was fabricated in 284 layers of 7 mils thickness. The shell was designed for a hemispherical stainless steel casting weighing about 2 oz, and the shell consists of a pouring funnel and a casting cavity.



Nickel superalloy casting. This was made with a 3-D Printed core in a shape similar to the airfoil in the previous pair of photographs.

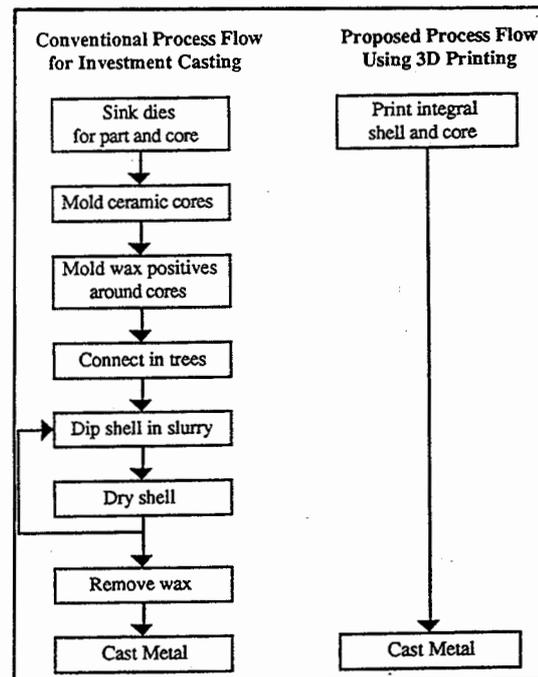


Ceramic shell fabricated by Three-Dimensional Printing. On the right is shown a cross section of the shell.

### Application to investment casting process

The fabrication of precision castings by the investment casting process<sup>3</sup> is a costly and time consuming process. The fabrication of tooling for the wax patterns and the ceramic cores dominates the manufacturing time and cost, thereby determining the minimum economic batch size for a given part. There are many steps involved in going from the master pattern to the final casting, and dimensional control is degraded in several steps along the way.

The Three-Dimensional Printing process can be used in the fabrication of ceramic shells with integral cores in a single-step operation directly from a CAD representation on a computer. The pair of flow diagrams at right contrast the conventional practice with the use of Three-Dimensional Printing. It shows that 3-D Printing eliminates the need for special tooling and greatly decreases the number of steps involved.



Comparison of process flows for conventional ceramic shell process and Three-Dimensional Printing of ceramic shells.

### The conventional investment casting process

In current investment casting practice, the master pattern of a part to be cast is rendered as a machined cavity in an aluminum tool which is used to transfer mold the wax positive. When cores are required to determine the internal geometry of a casting, an injection molding or transfer molding tool for the cores must be machined of hardened steel.<sup>4</sup> After the cores are molded, fired and finished, they are inset-molded in the wax patterns. The wax patterns are attached to a wax superstructure which forms a pattern for metal inlets (sprue, runners, and gates), gas outlets (vents) and specialized reservoirs for accommodating the shrinkage that accompanies solidification (risers). The design of this structure is special to a particular part, and there is often much hand labor involved in its construction.<sup>5</sup>

A ceramic shell mold is formed by dipping the wax pattern (with ceramic cores) into a slurry of ceramic powder in a liquid binder. Compositions vary, but the slurry is most typically composed of liquid colloidal silica with a suspension of powdered fused silica, alumina, zirconia, or alumino-silicate. The suspension must be continually agitated, and various

<sup>3</sup> Metals Handbook, 9th ed., (1988) 15 253..69.

<sup>4</sup> A very intricate part might contain several cores or acid-soluble inserts, each of which is molded in a separate tool.

<sup>5</sup> Wax patterns must be stored under very careful environmental control to prevent them from creeping (i.e., undergoing dimensional changes over time).

additives enhance the chemical stability of the binder and improve the wetting of the slurry onto the wax.<sup>6</sup>

To enhance the strength of the ceramic shell, the slurry coat is backed up with a layer of coarse ceramic stucco. This coat can be applied by sifting the material over the pattern or by immersing the pattern in a fluidized bed of the material. After coating, the shell must be dried, typically for one day, before being dipped again. This process is repeated several (typically seven) times until the shell has a thickness of ¼ to 0.4 inches. Shells are dried and cured for up to a few days before dewaxing. A great deal of this work is automated, with the dipping accomplished by robots and the drying taking place on a long conveyor.

Shells are initially dewaxed by heating them in an autoclave. The steam penetrates the porous shell and melts the wax from the outside surface before it can crack the shell.<sup>7</sup> Once the majority of the wax is removed from the shells, they are placed in a conventional kiln at atmospheric pressure and fired to burn out the last traces of wax and consolidate the ceramic.

Casting metal into the shell is usually accomplished immediately after the last firing step when the mold is still hot from the furnace. When vacuum casting is done, the molds must be introduced to the vacuum through an air lock. The ceramic shell is impervious to the thermal shock of the molten metal, but as the metal solidifies the shell cracks and crushes to accommodate the shrinkage.

After the casting cools, the shell is "knocked out" by vibration, impact and gritblasting. Cores are removed by chemical leaching in a molten caustic bath. The gates and runners are cut off with a saw and the various surface flaws such as stubs from gates and defects caused by poor control of the primary slurry coat, are cleaned off by grinding. Castings are inspected very carefully for shrinkage cracks and other flaws. Warped castings would be straightened by hammering. A cast part might be finished by subsequent milling, forging, joining, and hardening processes prior to assembly into a commercial product.

#### *Investment casting for prototypes and low-volume production*

The manufacturing cost for prototype quantities and small production volumes is largely determined by the cost of fabricating tooling for wax patterns and cores, and a small production run of a specialized part can be prohibitively expensive. The cost for any die set is dependent on the size and complexity of the part, but a typical range would be \$5,000 to \$100,000; lead times can range from 8 to 24 weeks. These two factors can have a serious impact on the commercial viability of a product, especially when prototypes are involved.

The fabrication of prototypes is an important step in bringing a new product to market. There are three broad classes of prototypes, distinguished by their functionality and destination.

- **Display prototype.** Used by a designer to evaluate the aesthetics or fit of a part.
- **Process prototype.** Used by the manufacturer as a test of metal flow and solidification in the shell, shrinkage, warping, and subsequent fixturing and finishing operations.

<sup>6</sup> The surface characteristics of wax are of crucial importance at this stage of the process. Surfactants are added to the slurry and the wax is scrupulously cleaned of oil and fingerprints. When the wax is dipped in the slurry for the first coat, there must not be any foam on the surface, and the slurry must form an even coat over the entire surface. Flaws introduced in this first coat are carried onto the metal casting and must be removed in the finishing.

<sup>7</sup> Removing the wax from ceramic shells is problematic. The ceramic shell is brittle and before it is fired it has relatively low strength. Wax is soft with about 100 times the thermal expansion of ceramic. If one were to place a shell in a conventional oven and warm it up gradually from ambient temperature, the wax would expand before melting and shatter the shell.

tions in order to have the later stages of manufacturing worked out while a die set is being machined.

- **Functional prototype.** Actually put into service in a complete assembly, or subjected to mechanical or endurance tests.

The dimensional tolerances, and therefore the expense, are different depending on the requirements, and a display prototype may not need to be rendered in the designer's specified material.

The processes for fabricating prototypes are extremely diverse. A prototype might be hand-fabricated in whatever material the model builder finds most convenient and reproduced in metal by a variety of techniques. If a part is of a suitable geometry, it might be machined in wax or some other material by a CNC machine tool. Sometimes a part to be cast in metal can be rendered in Styrofoam and subsequently cast by a lost foam process.<sup>8</sup> If a model of the part exists in some material such as wood, metal, or any combination of materials, and replicas in wax are desired, then a flexible mold might be made. Castable rubbers such as silicone, polyurethane and polysulfide are poured into a flask containing the model. Once the rubber is cured, the mold is peeled off the original and wax can be cast inside. If the part is complicated, the rubber mold might be made in many sections, with separate molds for cores and inserts. Rubber molds can withstand the temperatures associated with wax casting and can be reused up to about 100 times.

#### *Advantages of 3-D Printing in investment casting*

With 3-D Printing, the shell is printed with the cores in place. Then we simply remove the powder and cast in metal. There is a direct savings, in time and money, from eliminating the need to sink dyes for wax positives and ceramic cores. There is a further savings, again in both time and money, from eliminating the intermediate steps in the conventional process.

The elimination of part-specific tooling and the reduction in the number of process steps greatly reduces the time required to fabricate ceramic shells from a new design. This reduces the cost and time required to get a casting. The shortening of the cycle time can allow for more design iterations and thereby enable more aggressive designs. A new design can pass from CAD station to cast metal *in a single day* when previously it took weeks or months. Design iterations can be made by adjustments in software. Small modifications in the data file for a part can result in useful variations of the geometry of the printed part. A positive representation of a part can be printed, and the same data file can be manipulated to generate a shell. Scale models can be generated with equal ease.

Three-Dimensional Printing allows a part to be cast with a minimum of pattern transfers. This improves the dimensional tolerances that can be maintained on a casting. Since shells can be made with cores attached, the problems of core shift can be eliminated, thus further improving tolerances on castings.

Three-Dimensional Printing allows the designer greater control over all of the dimensions of a shell. Besides the external contour of the part and its core, the thickness of the mold wall can be specified. This allows one to control the heat transfer from the casting by varying the thickness of the mold wall. The density of the ceramic is a parameter that can be controlled in this process; some sections of a shell can be made very dense, while other sections can be allowed to "breathe."

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<sup>8</sup> Metals Handbook, 9th ed., (1988) 15 270..2.

## Application to metal matrix composites

A particularly attractive method for the manufacture of metal matrix composite parts is "pressure infiltration." The process begins with the manufacture of a porous ceramic preform of the desired final shape. The preform is then infiltrated by liquid metal under a pressure gradient to form the composite part. Compared to other composite fabrication techniques, pressure infiltration offers the advantage of good control over the uniformity and placement of the ceramic particles.

Metal matrix composites often offer superior cost and performance over materials used in many current applications. However, the difficulty of fabricating prototypes and small production runs often results in dismissal of composites, in spite of their favorable performance. A typical example is in the area of packages for electronic devices. Electronic packaging materials are required to allow thermal dissipation in order to minimize thermal geometric stresses, and to be lightweight (especially for avionic applications). Kovar, the traditional material of choice, is far from ideal because it has low thermal conductivity and high mass density. Metal matrix composites offer tremendous potential for this application. Aluminum/silicon carbide composites can be tailored to nearly match the coefficients of thermal expansion of gallium-arsenic and alumina substrates while having a higher thermal conductivity, lower density and lower material cost than Kovar.

Using Three-Dimensional Printing to fabricate metal matrix composite preforms, prototypes and small-scale production runs can be made with application-specific geometry and material properties, such as particle density and coefficient of thermal expansion. This flexibility should allow for metal matrix composites to displace inferior materials and to penetrate new markets.

## Technical details of process characteristics

### *Production rate*

In conventional ink-jet printers, jets are arrayed in groups of several dozen to several hundred.<sup>9</sup> This reduces the cost per jet of the process and boosts the production rate. In Three-Dimensional Printing, the production rate is expressed as a vertical build rate over a given operating area. In order to solidify material in the printed part, the printhead must dispense a certain fraction of the printed volume as liquid binder; the rest being composed of powder and porosity. The flow rate through a jet determines an optimum travel speed because it is necessary to deposit the required fraction (usually between 35% and 50% by volume) of liquid binder in a line. This is expressed by the relation

$$F_j = B_v v \delta y \delta z$$

where  $F_j$  is the flow rate per jet,  $B_v$  is the volume fraction binder,  $v$  is the traverse speed and  $\delta y$  and  $\delta z$  are the lateral and vertical line widths, respectively.

Given a fixed flow rate, it is possible to calculate an upper bound to the build rate. This is done by calculating the total cross-sectional area of the part to be printed, and dividing by the

<sup>9</sup> An example of a multijet printhead is made by Diconix, Inc., Dayton, Ohio. It has 1600 jets, spaced 120 to the inch. It prints on a paper web moving at 13 feet per second.

flow rate times the volume fraction of binder. This upper bound is 1 mil/sec or 3.7 inches per hour.<sup>10</sup>

This upper bound does not include the delays imposed by other machine operations that occur during the printing cycle. The two significant delays are the acceleration time of the printhead at the end of each raster line and the time to spread powder for each fresh layer. The time to fabricate any Three-Dimensional Printed part is equal to the time required for the printhead to make as many raster scans as necessary plus the time to spread as many layers as there are in the part.

$$\text{Time per layer} = N \left[ \frac{L}{v} + t_a \right] + t_s$$

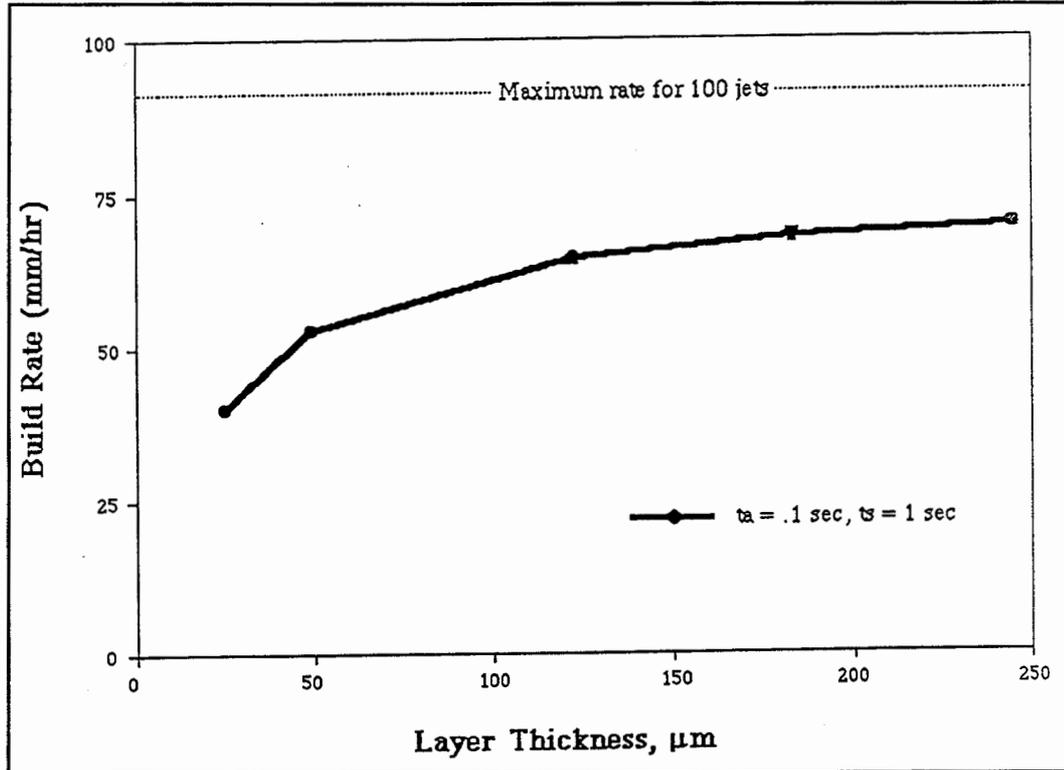
where  $N$  is the number of passes the printhead must make to define a complete layer,  $L$  is the length of the powder bed in the fast-axis direction,  $v$  is the travel speed of the fast-axis (determined by the flow rate),  $t_a$  is the time needed to reverse the motion of the printhead at the ends of the raster, and  $t_s$  is the time taken to spread powder for the subsequent layer.

The vertical build rate is equal to the layer thickness divided by the time per layer. The surface finish and feature size are also determined by the layer thickness, so it may sometimes be desirable to reduce the layer thickness below the maximum possible.

The following graph shows a calculation of the build rate for the next generation Three-Dimensional Printing machine with a 100 nozzle printhead. Calculations are based on a working volume of  $12 \times 12 \times 24$  inches which must be filled with 45% by volume liquid binder as before, with the same flow rate, and a traverse rate of 50 in/sec.

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<sup>10</sup> This assumes 100 jets operating at  $0.0013 \text{ in}^3/\text{sec}$  to cover an area of  $12 \times 24$  inches with 45% by volume of binder.



Build rate for next generation Three-Dimensional Printing machine.

### Feature size

The basic building block in Three-Dimensional Printing is a binder droplet combined with several particles of ceramic powder. The droplet size in the current embodiment of the printer is very close to the Rayleigh diameter of 3.3 mils.<sup>11</sup> Droplets impinge on the powder bed at about 30 ft/sec and form an aggregate about 8 mils in diameter. Capillarity tends to form a printed line into a cylindrical body 8 mils in diameter which overlaps other printed lines and bonds the part together into a solid network. Early experiments printing single walls showed that they were very uniform and could be built freestanding to a height limited only by the ability to handle the part after firing.

### Dimensional control

The widths of printed plates were measured with a micrometer with a spring-loaded anvil to maintain control over contact force. The plates had an intended width of 1.500 inches, a print line spacing of 7.5 mils and 50% by volume of binder.<sup>12</sup> Parts were measured in the "green" state, after curing at 120°C for three hours. They were measured a second time after firing to 1000°C for one hour, and a final time after firing to 1500°C for one hour. The results are shown in the following table:

<sup>11</sup> Sir Wm. Strutt (Lord Rayleigh), F.R.S. *On the Instability of Jets* in *Proc. London Math. Soc.*, 10 4 (1878) 4..13.

<sup>12</sup> C. Harris, *Characterization of Dimensional Variability and Part Bleeding Using the Three Dimensional Printing Process*, S.B. Thesis, Department of Mechanical Engineering, Massachusetts Institute of Technology, 1991.

Data from plates measured after firing at 1000°C			
	Green	1000°C	1500°C
Average width (inches)	1.501	1.501	1.480
Standard deviation, along a part (mils)	0.8	0.7	1.6
Standard deviation, part-to-part (mils)	0.8	0.6	9.1

The shrinkage above 1000°C is due almost entirely to the softening of amorphous silica deposited from the binder. If colloidal alumina or colloidal zirconia were used, these parts would be dimensionally stable to well over 1600°C.

Factorial experimentation was conducted to quantify the effects of relative binder volume content and printed line spacing on the properties of finished parts. Strength, flatness, surface finish, and dimensional control were characterized using second order regression models.<sup>13</sup> These models can be used to test process understanding, to design equipment and to design process parameters. Data points were collected at print line spacings of 5, 7.5 and 10 mils, and at relative binder volumes of 40%, 50% and 60%. The width of each part, intended to be 1.500 inches, was measured in the direction perpendicular to its print lines. The following is a contour plot of plate width against the binder volume percentage and print line spacing. Boldface numbers indicate the results from which the regression was derived. The key observation to be made is that over the entire range of process parameters, the change in dimension of the test part is small and further, the change is predictable (the regression model is a good fit to the data). Thus, the process is robust and predictable.

<sup>13</sup> M. Esterman, *Characterization of the Powder/Binder Interaction in the Three Dimensional Printing Process*, S.M. Thesis, Department of Mechanical Engineering, Massachusetts Institute of Technology, 1990.

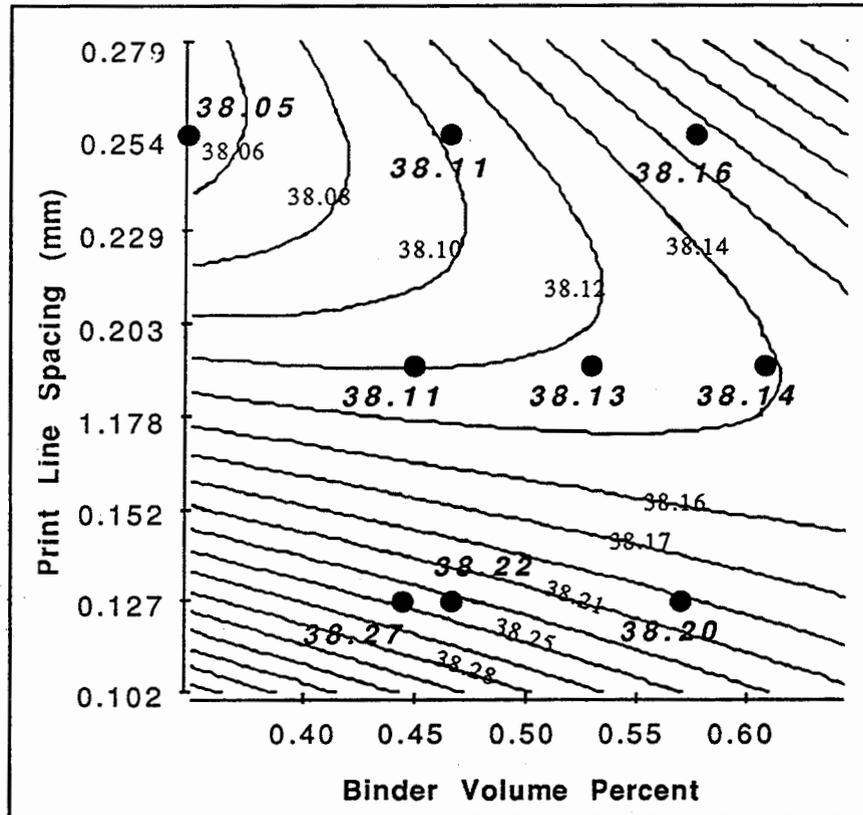


Plate width as a function of binder volume percentage and print line spacing.

### Strength

Four-point bending tests were applied to bars which were fired at 1500°C. Data points were collected at print line spacings of 5, 7.5 and 10 mils, and at relative binder volumes (with respect to overall part volume) of 40%, 50% and 60%. Four replicate measurements were made at each combination of process parameters. Strength varied from 12.3 to 18.7 MPa in all tests.

The strength is in the range required for investment casting (estimated at about 7 to 16 MPa, based on discussions with individuals in the casting industry).<sup>14</sup> It is also of interest to note that there is a peak in the strength as a function of the relative binder volume below which there is not enough material between powder particles and above which there is too much.

### Conclusion

Three-Dimensional Printing fabricates solid objects directly from a software representation. The process is extremely flexible, and can be applied to a wide variety of different materials. One application of Three-Dimensional Printing is the fabrication of ceramic shells with integral cores for investment casting.

<sup>14</sup> At proper strength levels, the mold and core are strong enough to avoid fracture during handling and pouring, but weak enough to fracture as the poured casting cools and contracts (thus avoiding hot tears in the casting).

The fabrication of ceramic investment molds by 3-D Printing has the potential to greatly affect the casting industry. As a prototyping method, it can be used to render a prototype from a computer model quickly and accurately, with no part-specific tooling. The materials used in the process are identical to those used in the casting industry, and the flexibility of the process allows for parts to be made in unusual materials as well. Ceramic shell slurries are specially formulated for long-term stability as a slurry. In 3-D Printing, ceramic compositions are not subject to that constraint.

The performance of the process has been demonstrated in a single-jet system. Ceramic shells and cores up to 2×2×2 inches have been produced, and castings have been made which show that the service temperature for 3-D Printed parts exceeds 1660°C. Work has already begun on a system with multiple jets, resembling conventional ink-jet printing technology. The build rate for this machine is expected to be roughly 2.4 inches per hour for a bed large enough to accommodate a tree of small castings, or a single shell up to 12×12×24 inches.

Ultimately, the process could be competitive as a production method. The ability to fabricate shells without any part-specific tooling would greatly reduce the cost-per-part for producing specialty castings, where the cost of dedicated tooling is prohibitive.

To summarize the advantages of 3-D Printing:

- Capability to deal with multiple materials: ceramics, metal matrix composites, metals.
- Ability to creating functional parts and tooling directly from the CAD model.
- Unlimited geometrical complexity (overhangs, undercuts, cavities) of parts built because the part is supported in a powder bed.
- High degree of dimensional control because we are working with very stable materials.
- Potential for high speed because of the relative ease of scaling up a print head to multiple nozzles. There is considerable development effort involved in creating a multiple-nozzle print head, but the unit to unit manufacturing cost for such a print head is quite reasonable.
- Potential for low to moderate cost of machines because of the simplicity of the ink-jet technology.

## Industry Panel

Dennis Medler	3D Systems
Haim Levi	Cubital
Kent Nutt	DTM
Scott and Lisa Crump	Stratasys
Emanuel Sachs	MIT/3-D Printing Consortium

After the vendors had made their presentations, all of the representatives formed a panel to take questions from the audience. The session was moderated by industry consultant Peter Marks.

**Question:** I would like to start this out by asking each of our speakers to indicate what one thing your process can do, one particular application, that none of the others can do. Your one unique capability or benefit.

**3D Systems:** The one unique capability that we have right now, aside from having systems in the field, is the largest capability as far as machine size. Our largest model goes up to 20×20×24 inches and lets you build very large models very rapidly.

**Cubital:** Besides accuracy, we are the only process that can build mechanisms with moving parts in one step without assembly.

**DTM:** Our unique advantage currently is our multiple materials approach with solid powders, with the potential for additional materials in the future.

**MIT:** Our unique capability is the creation of ceramic parts directly from a CAD model.

**Stratasys:** Our unique feature is the use of nontoxic materials in an office environment.

**Question:** Which of you folks actually used your rapid prototyping process in the development of your own equipment?

**3D Systems:** Actually, we did. In the development of the 190, our latest, entry-level, system, we used StereoLithography to model various components, such as the vat.

**Cubital:** Yes, we also do this. We are currently using our prototype machine in the design of our production machine. We found this quite helpful, made several changes in the design after we had the physical model in hand. It really is true that a 3d software model on a computer screen is not enough to understand your own design.

**Stratasys:** We did not use the process because it is too expensive. I think one of the things that we all need to do is get our costs down and our prices down.

**Question:** A question for Dennis Medler of 3D Systems. You listed some really interesting materials coming on line. When is the high impact LMB 5086 material going to be released and available to customers, and what will it cost?

3D Systems: LMB 5086 is a "high impact" resin that will make parts that can be machined, drilled, tapped, sanded and buffed. It should be going into beta in the next week or two, and that will probably take anywhere from a month to two months, so we are hoping it will be available in late summer. It will be in the same price range as the other resins, about \$300 a gallon.

**Question:** Every one of you has about the same presentation. The presentation starts with "Better, faster, cheaper concurrent engineering," and then moves on to conclude, "Buy our stuff." Could you point to some examples where one of your customers had not just shaved off a little bit of tooling time, but could actually point to something different in their product that was a result of using your machine, whether it was a cheaper product or a significant change that was made in the development.<sup>1</sup>

3D Systems: Texas Instruments has taken their parts in the missile group and gone directly to flight-ready cast parts. DePuy, with their medical parts, are able to go directly to metal from StereoLithography models using epoxy molds.

Different customers use our machines in different ways. They are used for form-fit-function applications, design verification, soft tooling, hard tooling, and other ways. You can justify the machine, not just from having a model quick, but in terms of some intangibles—and the fact that you can save \$30, 60, 100,000 in tooling costs. That is how you justify these machines.

MIT: If the question is, "Do these technologies enable you to do things that you could not otherwise do," then the answer is "Potentially, yes." An example is that we are printing cores that have holes going all the way through them, so for example if you have a long cooling passage in a casting, that core might be a quarter of an inch in diameter and two feet long, and it would be prohibitive to remove that by the conventional technology, but we can print it with a hole going all the way through it, and then it comes out in a couple of hours. So there is some design flexibility that you can get.

Another example would be, when we get to making tooling, like injection molding tooling, you can create tooling with cooling passages that go right near the surface so that you can make high thermal response tooling and actually get better properties on the final injection molded part. So I think there will be a lot of design flexibility that will open up, and that is exciting.

Don Roell, 3M: I might be able to offer a comment of value here. We have used StereoLithography in the service bureaus in some of our product development and we have been able to reduce the cycle time from gleam-in-your-eye to the store shelf by months, or even significant fractions of a year. That gets us into the market place faster, which brings us a bigger share of the market, and we make more money. We expect to be able to do the same thing with Stratasys' machine.

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<sup>1</sup> The best answer to this question is reported by Steven Ashley in *Rapid prototyping systems* in *Mechanical Engineering*, April, 1991, page 34. He retells the story given by Peter Sferro of Ford of how submitting a StereoLithography model to the machine shops along with the requests for quotes on a part resulted in one shop noticing a way to reduce the tooling costs by 49¢ per piece. Savings to Ford: \$10 million *annually* on one car model. — *Editor*.

**Question:** What software modeling systems are you using and what experiences have you had with them?<sup>2</sup>

**DTM:** At the DTM service bureaus, we are using SDRC primarily because we have had a lot of good experience with it. Also, their finite element analysis package lends itself well to our applications. And we also use ProEngineer from Parametric Technology Corporation.

**3D Systems:** I think we see the most use being made of CATIA and then SDRC. I also see a lot of ProEngineer and CADKey. It is a pretty good mix but if you rank the top three or four it would probably be CATIA, SDRC, Aries and Pro-Engineer.

We see people using both surface and solids packages. The solids seems to be the best in any of the packages that our users use. When you are working with a wire-frame surface package, getting closed surfaces or completely bounded surfaces seems to be a problem in some cases, although they all work.

**Cubital:** We have had good experience with SDRC and with UniGraphics. We have had some bad experiences with some others.

**Question:** What adhesive should be applied to a polycarbonate overlay so that it will stick to a urethane prototype?

**DTM:** Some type of epoxy adhesive. I do not work in the service bureau myself, but I know we have had good luck in the past using adhesives with our polycarbon materials.

**Cubital:** Crazy Glue.

**3D Systems:** Right. Crazy Glue works fine.

**Question:** In comparing SLA with solid ground carrying, are there any advantages to SLA?

**3D Systems:** We have got a lot of experience behind our technology and I think that is really our advantage right now.

**Question:** For Haim Levi of Cubital. You gave the advantages of your system. What are the costs, problems, and challenges associated with using the machine?

**Cubital:** As I said, our machine is more like a machine tool. You maintain it like you would maintain any other sensitive machine tool.

**Question:** A question for the audience. Has anybody with an SLA system ever have had to replace a laser tube?

[Several hands went up.]

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<sup>2</sup> See the paper by Bernie Battaglin (page 29) for a discussion of solid modeling software. —*Editor*.

3D Systems: That is only expensive if you are not on a maintenance contract. You can get several flavors of maintenance to cover yourself for that. Otherwise you can treat it as an expendable.

**Question:** Let's talk a little bit about some of the safety and ergonomic and human factors issues. In every case, we have a process that has something hot or a laser or a monomer or something that is going to be thrown away and disposed of. Any comments on that?

**Stratasys:** Well, I would say we have this one hands down. I mean, you can put your hand almost literally on the nozzle tip and it might be warm to touch and you would not keep it there. We use nontoxic, inert materials, and the process itself is safe.

**MIT:** We are recycling both the powder and the binder. The powder goes through a screening operation and the binder goes through some filtering, and they get reused. Even if you should decide not to recycle the binder, you can turn it, the colloidal silica, into basically a solid lump of rock just by squeezing a lemon into it. A little bit of acid will gel it and then you can throw it out. So it is a pretty good system from that point of view.

**DTM:** The SLS system runs in an inert nitrogen environment so there is no danger of explosion. The materials we use have MSDS sheets on them. They are nontoxic. The worst thing that could happen would be with PVC; it might dry your skin out a little bit if you come into contact with it. Basically, our materials are non-hazardous.

**Cubital:** The time that the operator is, if at all, exposed to a monomer is minimized because we spread, expose and suck it away. In any case, the machine is fully enclosed. The UV light is another potential source of problems, but again, it is completely enclosed. With respect to recycling, we do not recycle yet. The resin that is sucked off is cured and disposed of. We intend to introduce some new resins in the near future that will not contain V-pyrol,<sup>3</sup> probably the one most problematic ingredient of resins today. Once that is done, I think the machine will be fully safe.

3D Systems: There are some handling issues with the resins, but we build in a contained environment. As far as disposal, you polymerize it and dispose of it like any other plastic.

**Question:** To 3D Systems. How do your resins compare to Du Pont's new resin, especially in impact properties?

3D Systems: I cannot really answer that yet. I think they are probably comparable. We are evaluating Du Pont's resins for recognition. We hope that in the near future we can say they are usable in StereoLithography.

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<sup>3</sup> See page 37 in the paper by Myron Bezdicek, for a brief discussion of the problem with V-pyrol. —*Editor*.

**Question:** Would you indicate first what the cost of your process is, in terms of (a) the system, (b) installation, (c) maintenance, and (d) materials?

**Stratasys:** The 3D Modeler has a price of \$178,000. That comes with the workstation and a complete modeling software program. If you have your own workstation, we can provide a stand-alone unit for \$130,000. The installation is basically wheeling it up and plugging it in, so that is not an issue, and then for service it is the new software revision each year which is approximately \$4,000.

**MIT:** It would be premature for me to talk about cost. But I can suggest that, in terms of maintenance, you think about what the replacement cost is for an ink-jet cartridge on an HP DeskJet Printer. That is in the tens of dollars. Ours would be more than that, but still not a big sum of money. Another point is that the machine does not need any special enclosures or special atmospheres or anything like that, so the basic machine cost should be very reasonable as well.

**DTM:** Our machine is not for sale just yet, but we envision a price of between \$350,000 and \$400,000, for the production unit, available next year. For installation, I am not sure what that price is going to be. You have to provide your own nitrogen and external venting, nothing extraordinary. Service contracts will be in the range of 8 to 12% on a tiered basis. For materials we envision something on the order of \$20 to \$25 a pound, but again, those prices are not set just yet.

**Cubital:** Our system costs about \$490,000. This includes the installation, a 6-month warranty and a 3-week training program. The service contract is 10% per year for parts and labor. The raw material, the resin, costs about \$100 a gallon.

**3D Systems:** We have three machines. The entry-level SLA-190 is \$95,000, the 250 is \$185,000, and the 500 is \$385,000. Installation is 1%. The 190 and 250 run pretty much in an office environment. They take 110 Volts and have a charcoal filter so they do not require any special venting. The 500 does require water because it has a water-cooled laser. The maintenance is about 8 or 9% for the base coverage, or about 18% for full maintenance which includes unlimited laser replacement. Our resins are around \$300 to \$350 a gallon. There are other resin suppliers, such as DSM and Loctite, with prices in the range of \$200 to \$400 per gallon.

**Question:** Two questions about metals. First to Stratasys. I find it curious that you did not mention metals. It would seem that you could use metal filaments. Have you been working on that?

**Stratasys:** We did all of our early work in low temperature metals and hope to have that available, probably next year. But we do not have it commercially available yet.

**Question:** Second question on metals, to Elly Sachs. You mentioned that one of your underlying purposes of going into this particular technology was to work directly with particular materials, ceramics and metal. I wonder, if what you end up with is a metal powder with an interstitial binding material, how close to metallic properties do you get with such a composition?

**MIT:** There are a number of options for metal parts. One is to use a polymeric binder. In that case the system is a direct mirror to metal injection molding where you

mix metal powder with a polymeric binder and then you burn out the binder and you sinter the metal part. So that would be appropriate if you want to prototype parts that you will then make by metal injection molding.

Another option is the analog of the ceramic case. In the ceramic case we use ceramic powder and a binder which has ceramic in it. The beauty of that is that you do not sinter so you do not have shrink and you do not lose dimensions. We are looking at systems that can do that for metals as well.

So I think the answer is that the binder would change depending on what powder you were using. But the bottom line is that we do expect to fabricate metal parts with full metallic properties.

**Question:** To wrap up, would each of you give us just one or two guidelines for success in implementing this technology.

**Stratasys:** I would say that you should try to differentiate between whether the application is concept modeling or a finished prototype. Try to orientate the file such that you put the least amount of time in at the front end, in the initial design, and try to bring those files over to the modeler quickly. What I have found is that the .StL format is excellent for creating a final part, but it can take two or three days to use it to bring in a concept model and this kind of wipes out the whole idea of spontaneity in creating an idea. It can be better to use IGES to bring in concept drawings and use .StL or an equivalent later for the prototype designs.

**MIT:** I would say, do not look for one solution to all your prototyping problems. When you look at machining processes, you see vertical machining centers, horizontal, 3 axis, 5 axis, 4 axis, turning centers, etc. I do not see why this field should be any different. I think we will see many technologies blossom in the near future, each satisfying various prototyping needs.

**Cubital:** My advice would be to sit down, define your needs in prototyping applications, choose two or three of us that more or less cover your needs, and use the service bureaus to evaluate how well each process meets those needs. Then make your decision. On the other hand, do not wait too long for the ultimate solution to all your concurrent engineering problems, because that will take forever.

**3D Systems:** I think it is really dedication. If you are going to get into this, it has to be a dedicated effort. It is like any other technology. You can give the same CAD system to ten different groups and you are going to see varying degrees of success, depending on how committed they are to making the most of it.

The other key is multiple applications. Do not just buy for form-fit-function or concept modeling. Try to identify as many applications as you can to justify the investment. The payback is there.

And I agree that you should not wait too long. If you can pay for a machine in under a year then you might as well have it, even though the technology is changing rapidly. Then you will have had the advantage of getting into the technology early and exploiting it within your company. The bottom line is getting to market sooner and that is what these systems offer you.

## **USERS' CASE STUDIES**

# USERS' CASE STUDIES

Users of rapid prototyping systems come in two categories, independent service bureaus and "end users." Both categories of StereoLithography users are represented here. In addition, we have some comments from a Stratasy beta site.

## *Service bureaus*

David Tait of LaserForm in Detroit presents the results of a comparative cost analysis for prototypes produced by conventional methods and by StereoLithography. Eight cases were studied. The best results were for an intake duct for the Saab 2000: 83% reduction in project time (24 weeks to 4) and 65% reduction in overall cost. The worst results were for an automotive pillar seal: 42% time reduction (6 weeks to 3.5) and 30% cost savings. ...page 107.

An excellent breakdown of the steps involved in the StereoLithography process is given by Kevin Kennedy of ProtoTech Engineering in Chicago. Several factors are mentioned that should be kept in mind when designing objects to be built by this process. ... page 111.

## *End users*

The line between service bureaus and end users is not a definite one anymore, thanks to Baxter Healthcare, the world's first rapid prototyping customer, which has decided to capitalize on its experience by setting up a subsidiary service bureau, Technical Tools. Michael McEvoy, the vice president who brought StereoLithography into Baxter over three years ago, discusses the advantages and benefits realized at Baxter from using this new technology, the problems that arose in implementing it, and the variety of effects it had on the engineers given access to it. ... page 114.

Another major manufacturer of medical supplies and equipment, DePuy, is also a StereoLithography pioneer. A brief look at the organizational structure that was set up to best exploit this new capability, and a case study on a prosthesis designed using it, are given by David Trimmer. ... page 118.

At Digital Equipment Corporation, Steven Venditti uses StereoLithography as part of a program that also utilizes numerically controlled machining and shaping deposition. He describes how each of these processes contributed to various phases of the design cycle for several products at DEC. ... page 120.

Phillip Ulerich creates a concurrent engineering environment at Westinghouse using StereoLithography in conjunction with silicone rubber and spray metal molding. The result is model assemblies completed within a week after their initial design on a computer screen, without the use of paper drawings. Ulerich finds that the ironic challenge in introducing rapid prototyping to an engineering environment is in getting people to use it! ... page 128.

Until recently, users of desktop manufacturing were necessarily StereoLithography users. This is now beginning to change, and we are lucky to have a few comments from Don Roell on the reasons that 3M chose to become a beta site for Stratasy's 3D Modeler. ... page 136.

Another DEC engineer, and a long-time proponent of rapid prototyping, Al Cassista, explains the concurrent engineering philosophy in a historical perspective. He lays out the main elements of the concurrent engineering environment, people, machines and software, and discusses the fundamental technologies that make this new version of an old style of engineering possible. ... page 137.

# Cost Analysis: How Manufacturers are Profiting from Rapid Prototyping

David Tait, Managing Partner, LaserForm, Inc., Auburn Hills, Michigan

Davit Tait co-founded LaserForm in June, 1989. The StereoLithography service bureau did \$1.4 million in 1990 and employs 11 people. Previously, Mr. Tait was a manager of Advanced Technology Development for General Motors Corporation. He was part of the GM group that took delivery of the first production machine from 3D Systems in January, 1988. Mr. Tait received his B.S. in Business from Central Michigan University.

One of the common questions we hear from people that start to get interested in rapid prototyping is, "What does it cost and how much time do I save?" Other people ask, "Are there any other things that we can do with rapid prototyping beyond design verification? Can we do any physical testing with these parts?" In order to compile some answers for these questions, we did a survey of our customers who had quoted conventional prototyping against rapid prototyping. We are going to look at some results of this survey, eight case studies of the benefits of using rapid prototyping.

## Background

The customers we talked to thought of rapid prototyping as it fits into the total design program. In other words, they did not want to just dump us a file and have us build a model for them. What they wanted was to integrate the rapid modeling process into the design operations within their organizations.

Design changes were anticipated. That is the basic premise in using rapid prototyping, to use it as a catalyst, if you will, for promoting creative design and creative thinking. Sometimes this is difficult to get across. Some firms want to make sure that the design is perfected before it gets to the rapid prototyping process, and that is not at all necessary.

There was some uncertainty among the engineers as to how the rapid modeling process would be received by senior management. An engineer may spend a few thousand dollars on StereoLithography for a particular part, and then he may have additional copies made in either polyester or polyurethane. So he may be somewhat apprehensive about how his management will look upon his spending \$3,000 to \$5,000 on a model.

Another concern among the customers surveyed was the integrity of the initial CAD file, whether it was at a sufficient level to produce a good model, or required more development.

All of the customers participating agreed to provide detailed feedback on their overall perceived benefits from using rapid prototyping.

The projects included in our study satisfied the following criteria:

- The customer used both CAD and manual drafting in their design operation.
- They had used some form of rapid prototyping, whether SLA, Cubital, DTM or another technology, more than once before. We wanted to make sure that they had some kind of experience with rapid prototyping.
- Parts were required beyond the "rapid model." There had to be a need for parts that would be used in a molding process.
- The "rapid model" parts or parts molded from them had to undergo some type of physical testing.

- All the firms quoted our total service against conventional prototyping, so we would have something to compare to. We do not quote here the actual dollars, but we do give a cost comparison against conventional methods.
- The product required ASAP product release to begin hard tooling.
- The development had resulted in an engineering change at some phase of the rapid modeling cycle.

## Results

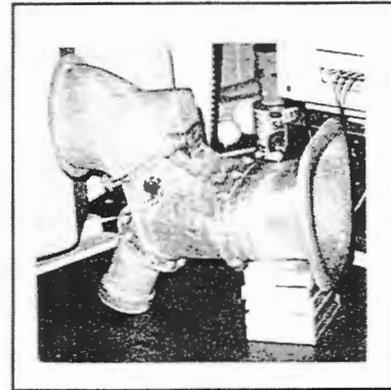
The following table shows the basic results of the survey. Column 2 gives the customers' estimates of how many weeks the project would have taken by conventional methods, and the actual project time using StereoLithography. In column 3 are shown the estimates of the number of hours that would have been taken to produce blueprints or other engineering drawings to be used by machine shops in making the conventional prototypes, and the actual number of hours taken to create the CAD files used in the SLA. Finally, column 4 gives the customers' estimates of their total dollar savings from using the rapid prototyping methods. In all cases there was a significant reduction in the time to complete the project, the time to convert the data, and the overall costs.

Time and dollar savings: Conventional → rapid prototyping			
Project	Total project time (weeks)	Data and design conversion (hours)	Overall cost savings
Air intake duct, 4/10 scale, for Saab 2000	24 → 4	(n/a) → 60	65%
Instrument panel air outlet for Jeep	20 → 4	600 → 60	45%
Instrument panel cluster lens	16 → 4	240 → 60	65%
Resonator bottle for GM	16 → 2.5	100 → 26	55%
Fog lamp bezel for Jeep	8 → 2.5	(n/a) → 24	60%
Automobile door seal for GM	6 → 3.5	120 → 40	30%
Instrument panel wiring harness	15 → 3.5	160 → 6	30%
Headliner bezel for Ford Aerostar	8 → 3	(n/a)	50%

There follow some specific comments on the individual projects:

**Air intake duct for Saab 2000 jetliner.** Because of its large size, even at 4/10 scale, this model was built in several sections. This turned out to have an advantage in that when the customer wanted to make changes, we only needed to rebuild the affected section. The part was mounted on a test fixture, holes were drilled for about 40 probes, and air was blown through it. They ran it up to Mach 3, without any kind of reinforcement, before it literally exploded into shrapnel. The tests resulted in design changes to the inlet section.

**Instrument panel air outlet for Chrysler Jeep.** We built the mold and cast 60 parts for the initial build. They did both cold weather and desert testing and made several packaging-related changes based on the results.



Air intake duct made by StereoLithography.

**Resonator bottle for GM.** This device creates white noise to overcome engine and transmission noise for a vehicle. We made a mold and cast 20 parts in polyurethane. They said the process showed great value for functional test parts. It accomplished exactly what they wanted even though the polyurethane was not the specified material for the final part.

**Fog lamp bezel for Jeep.** As Detroit moves over from steel to plastic fenders, there has to be a lot of consideration given to the materials and design of mating components. There were a lot of design changes for the surface and the mounting bosses for this part.

**Automobile door seal for GM.** The extruded and molded seals between the door and the main body of the car is always a problem. It has to function as a water manager and an air manager, and sometimes the sections are boxed, i.e., closed. We built an epoxy tool with an epoxy insert and molded the rights and lefts in a hybrid urethane so they could withstand wide temperature fluctuations. GM took the parts to the desert proving grounds and did physical testing of the vehicle with these parts. Door slam and air and water management tests were conducted.

**Headliner bezel for Ford Aerostar.** This was an eleventh-hour project, something that had simply fallen through the cracks in the regular design process. We built an SLA master, and from that a silicone rubber mold, from which 30 parts were made in three different colors.

### Concluding comments

The concept of time to market is one that I feel does not receive the attention it deserves. The rapid prototyping technologies are allowing us to compete better by accelerating product development. It is a very dynamic industry right now. The range of players is expanding and the current players are continuing to do excellent development. You who are deciding whether or not to use the technology, your biggest challenge is really to find the relevance for the processes in your organization. Where in your company could this best be applied? In making that evaluation, I suggest leaning heavily on current users of the systems, both end users and service bureaus. Pick our brains on where we found it easiest to integrate this into organizations like yours.

If there is an area where we really need help, it is on the CAD translators. How do we get these CAD systems to talk to each other a little easier? We use CATIA, I-DEAS, and Aries,

but only about 30% of our customers operate on those platforms. So we have to take in their CAD data, whether it is 2d or 3d, and convert it. This is very time-consuming, and it should not be necessary. There are a lot of software companies, including IBM, working on this problem.

Until recently, we were limited by the material properties, but the materials suppliers have done a superb job in developing new materials. So if you have heard that the material is brittle, or the accuracy is poor because of shrinkage, then please talk to us. Because this whole industry is very dynamic and there have been a lot of significant improvements in that area.

In summary, rapid prototyping has significant applications beyond design verification, as I have shown with the examples here. It can be used in actual testing of final part function, such as air flow and fluid flow. Furthermore, it can be used to make masters for duplication, where the copies are even more suitable for testing. With further development of the rapid prototyping processes, the list of applications will continue to grow.

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**Question:** We are just starting to use rapid prototyping and we are having some problems accounting for shrinkage. We find ourselves having to redimension our designs to account for it. What do you do? Is there some kind of software package to handle this? This is making it difficult for us to move from the simple form-fit-function applications into producing master patterns, as you have talked about here.

Ideally, what you want to create in your software model is an exact duplication of the final part. The process should then take care of shrinkage and other similar issues. There have been some developments in this direction; 3D has done a lot with the beam offset and other parameters. But unfortunately, as you are finding out, we are not quite there yet. In the meantime, there are a lot of skills you pick up over time from using the machine. There is not any simple solution to the problem; you do have to make the kinds of adjustments you are talking about.

# Part Design Considerations for StereoLithography Fabrication

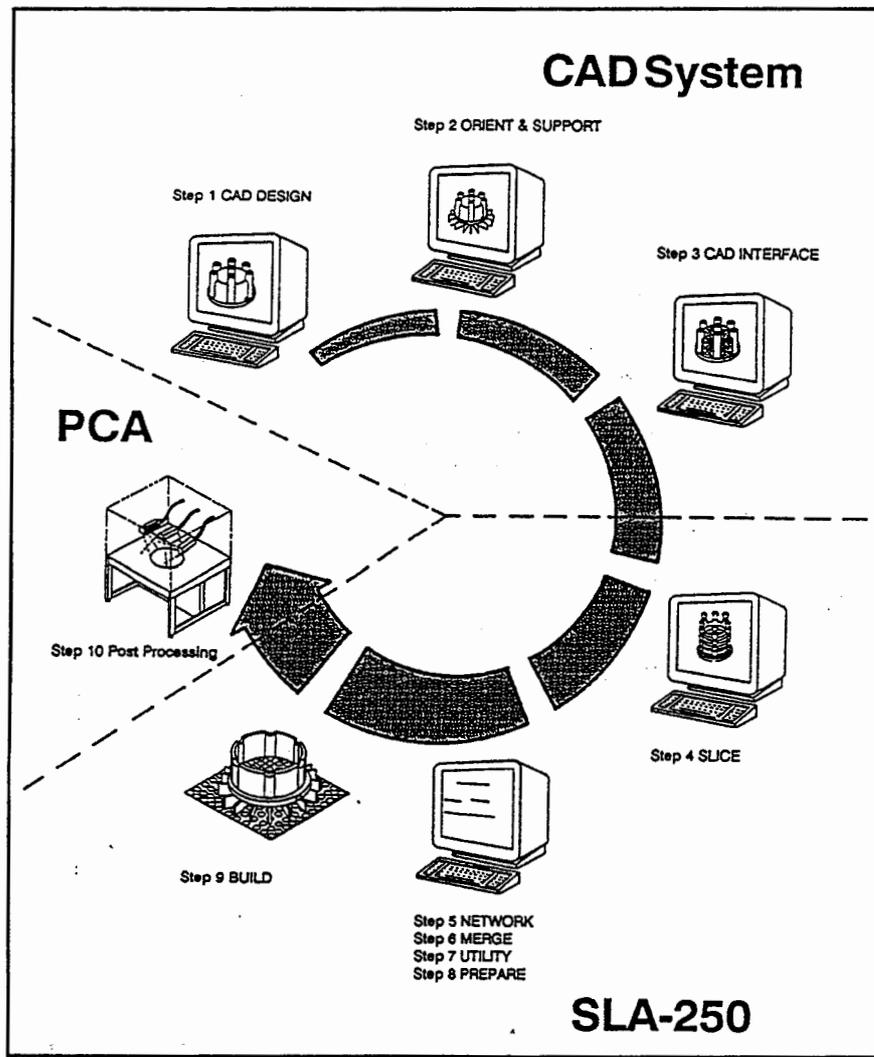
Kevin Kennedy, Co-owner, ProtoTech Engineering, Inc., Darien, Illinois

ProtoTech Engineering, Inc. is a service company combining StereoLithography with rubber molding and spray metal tooling in order to help customers shorten the time to develop new products. ProtoTech was started by Kevin Kennedy and Robert Zajeski in 1989. Prior to that Mr. Kennedy was National Sales Manager for Littelfuse, Inc.

Mr. Kennedy got his B.S. in Business Administration from Lewis University and a M.B.A. in Marketing from Illinois Benedictine College.

StereoLithography uses an ultraviolet laser to selectively harden a photosensitive liquid plastic in order to form 3-dimensional objects. Depending on complexity of the design, this process may produce a model in much less time than conventional methods would.

The StereoLithography process is composed of ten major steps. This paper addresses the parameters that must be considered in each step when fabricating models.



The StereoLithography Process.

**Step 1: CAD design.** The process begins with a design created using surfaces or solids generated by the CAD system.

If your software uses surfaces, then the model must represent a closed volume, with an inside, an outside and a boundary. Each surface normal must be facing out. And surface adjacency tolerance, the gap between two adjoining surfaces, should be less than 10 mils. Larger values will cause problems with the SLA cross-hatching algorithm.

Solid modeling software approximates a curved surface, such as a cylinder or sphere, by a large number of polygons or facets to reduce display time. The larger the number of polygons, the more closely the surface is approximated, which results in a smoother curve on the actual part as built by the SLA. But as the number of polygons increases, so does the slicing time and resultant file size. As a rule, a good CAD resolution to use is 1 to 3 mils. Another way to reduce slicing time and file size is to use simple primitives during the construction of the model. Extrusions work best, whereas revolutions generate the most complicated files. In solids modeling, perform unions (combining several shapes to compose a complex design) last. This keeps the software model from becoming difficult to manipulate.

The software model does not have to be in one piece. Two or more .StL files can be created and merged by the SLA. (See step 6.)

**Step 2: Orientation and supports.** The part must be oriented and supported so as to optimize the building process and integrity.

Each object must reside entirely in the positive octant of the CAD space. It should be oriented to:

- Minimize the distance between the part and the origin of the CAD space.
- Minimize the height of the object. This reduces the number of layers to be built, thereby reducing build time.
- Optimize part draining by reducing the number of entrapped volumes that can hold resin after the part is completed.
- Minimize the number of slanted or sloping surfaces. Such surfaces are constructed of overlapping layers, so they take on a staircase appearance, with the thickness of each layer being the height of the step.
- Maximize the number of smooth or esthetically important surfaces oriented either vertically or horizontally and facing up. Vertical and upward-facing horizontal surfaces are smoother than downward-facing surfaces.
- Maximize the number of curved cross sections drawn in the horizontal plane. Higher resolution can be achieved in the horizontal plane.
- Ensure that the part fits in the resin vat. If it is too large, it may be sectioned, built in several runs, and assembled after post-curing.

Obviously, several of these suggestions will conflict for any particular design. Their relative importance depends on your objectives in building the part.

Support structures are added to hold the part in place while it is constructed layer by layer. The supports help to maintain registration among the layers and structural integrity of the part. Supports are usually made of a cross-hatch of thin vertical surfaces or solids.

**Step 3: CAD interface.** The designed model and support data are converted to the .StL format. This format is similar to a finite element model consisting of triangular surface elements or patches. The user controls how accurately these triangles define original surfaces.

**Step 4: Slice.** Up until now, you have been working on your own. At this step the SLA takes over. Using a proprietary algorithm, the .StL file is sliced into cross sections, typically between 5 and 20 mils thick. The user can select the layer thickness and vary it throughout the part. In addition, the user controls the creation of an internal cross-hatch structure between inner and outer surface boundaries (vertical walls). This serves to support the vertical walls and entrap liquid which will later be solidified with a flood of ultraviolet light. Horizontal "skins" for top and bottom surfaces are also created. The output is a slice (.sli) file.

**Step 5: Network.** After slicing, the database is transferred to the control computer using a local area network. File size ranges from 3 kilobytes to 6 megabytes.

**Step 6: Merge.** Several objects to be built together, including supports, are combined into one build database. In this process, the data is reformatted into SLA machine code in four separate files: vector (.v), range (.r), layer (.l) and machine parameter (.prm) files.

**Step 7: Utility.** The laser power is measured and the SLA is initialized and set up to build parts. A platform is attached and lowered into the vat filled with liquid resin.

**Step 8: Prepare.** The user sets building parameters, including the amount of adhesion between layers and the number and location of parts to be built, as well as recoating parameters based on the model's geometry and end use. Each phase of the building process can be customized by varying building parameters within vertical ranges.

**Step 9: Build.** This step is the objective of the whole process. This is where the part actually gets built.

The resin level is adjusted by adding photopolymer and then the user activates the build software to start the building process. The laser draws the first layer, which adheres to the platform. When creating each cross section, the inside and exterior boundaries are solidified along with the internal cross-hatch. Resin is then trapped between the solid areas as the object is built up. The elevator dips below the surface, coating the cross section with resin, and a recoater system maintains the correct amount of liquid on top of the previous layer. Each successive layer becomes firmly attached to the previous as it is drawn. The process is repeated until all layers of the 3-dimensional object have been drawn. When the last layer has been printed, the completed part is raised out of the vat. Building times are then logged into a history file and the laser is automatically powered off.

**Step 10: Post-process.** The platform is raised out of the vat and excess resin is drained off. The platform and part are removed from the SLA and any excess resin is cleaned with solvents, ultrasonics or wicking. The platform and part are then placed into the post-curing apparatus to undergo several exposures. The part is then removed from the platform and the support structure is clipped from the part. Subparts of larger structures are assembled and finishing techniques, such as sanding, sandblasting, painting or dyeing, can then be applied.

### **SLA process limitations**

The process tolerance of the SLA is  $\pm 5$  mils per inch. There are no geometry constraints except for a 10 mil minimum wall thickness. (The laser beam diameter is 8 to 10 mils.) The maximum size of a single part is limited by the size of the vat, which varies from machine to machine, but multiple parts can be glued together to form larger pieces.

## Baxter Healthcare StereoLithography: Shortening Product Development

Michael McEvoy, Vice President for Advanced Engineering, Baxter Healthcare Corporation, Round Lake, Illinois

Baxter's Advanced Engineering Design Center is dedicated to reducing the engineering time to deliver a product to the marketplace through the use of advanced computer aided design tools. Mike McEvoy joined the company's machine design group in 1970 and has been responsible for the acquisition and implementation of computer aided design tools.

Mr. McEvoy has a B.S. in Mechanical Engineering from the Allied Institute of Technology.

The technology referred to as StereoLithography is quite new in the CAD/CAM business and represents the first technology of its type. The technology is unique for it interprets and fabricates CAD design information directly into 3-dimensional plastic models. The process runs in a device containing four major components.

- Ultraviolet laser,
- Computer controlled mirror system,
- Bath and elevator system, containing ultraviolet-sensitive liquid plastic, and
- CAD processing software.

The combination of these four components has generated a new technique for transferring an intelligent CAD model into an accurate 3-dimensional plastic part in literally a few hours. The process requires no special CAM-type preprocessing programming, but does require specific rules for preparation of the 3-dimensional CAD model.

StereoLithography allows a design engineer to take an existing 3-dimensional CAD database and directly transfer his or her model into the StereoLithography device for fabrication. The result of the process is a physical part representing the original CAD model (database) accurate to within 5 mils. Closer accuracies may be achieved depending on the geometrical shape and the type of liquid resin used in the process.

The suppliers of resins for the process continue to enhance the design characteristics of these resins. There have been continual improvements made in this area since this process was introduced 3½ years ago.

### **Why consider StereoLithography?**

The Advanced Engineering Center at Baxter has spent considerable time developing and implementing an integrated CAM (Computer Aided Machining) program. This has been achieved and provides full CAM resources to the product development groups.

However, in the process of evaluating a new product design it became apparent there was a need to evaluate the design in a 3-dimensional physical model. This changed our development pattern from

CAD → CAM tool

to

CAD → CAM model → CAM tool.

This allowed comprehensive change feedback from Marketing and Manufacturing before the final tooling was cut. Baxter focused on providing this expanded CAM service to its various design groups.

The first overview of StereoLithography came shortly after the new focus had been implemented. The need and fit of StereoLithography in our process was very obvious at the first review of the technology. The technology was ideal for reviewing a new product design prior to capital investment in tooling. The avoidance of extensive CAM programming and fabrication of prototypes or production tooling prior to final changes was extremely cost effective.

It was obvious at first sight that StereoLithography had the ability to transfer a new product design into physical reality, quickly (within hours) at an extremely low cost. The fact that the resulting part had limited attributes was insignificant. The design could be held, touched and evaluated by Marketing and Manufacturing, and by customers if desired. The limited functionality did not defeat the utility of the model in garnering an early commitment to a new product design.

This ability became invaluable to the design engineers for generating a consolidated agreement on what the final design should be like. In addition, the functionality of the part was always questioned, thus improving the functionality of the final design. The introduction of this process into our design cycle has substantially reduced errors and design changes. It has also generated a much higher confidence level when moving into prototype or production tooling.

### **Implementation**

The SLA (StereoLithography Apparatus) is not an office copying machine. The device requires special attention to environment and considerable planning to achieve integration into the engineering process. The device is best placed in an area closed to normal day-to-day office traffic. This area will require conventional temperature and humidity control.

Model post clean-up requires the greatest care. This is because of the sensitivity issues associated with the secondary curing process. The secondary process involves curing the part in an ultraviolet light bath. This is required to cure any encapsulated resin that was not cured by direct laser beam contact.

The post processing and part clean-up area should be maintained with strict rules and regulations. These procedures are provided by the vendors and should be followed closely. This is important because you may become sensitized to the material if this process is not controlled and isolated properly.

The integration of the process was achieved at Baxter by tying the device directly to our existing engineering Ethernet network. This enabled all engineering groups to have access to the technique via the conventional network services. Once the device was in place and a staff had been trained to generate parts, the human integration began.

### **Problems encountered**

The very first issue we had to contend with was how to leverage the existing installed CAD base into the process cost effectively. If you cannot offer the existing user a cost benefit to using the process you will have a difficult time succeeding. So our first task was to interface our existing CAD program, ComputerVision. Because we were the first user in the world, it

was difficult to interest the vendor in providing an interface, and we had to write our own. This would not be the case today, with interfaces available for most 3d CAD modeling products. This was one price we had to pay for being the first to use this new application.

The second area of concern was educating the CAD user as to what was required to prepare a CAD model for StereoLithography. The preparation required a different approach than conventional CAM toolpath modeling. The choice had to be made to interface through wire-frame CAD modelers or through solid surface modelers.

Baxter had a much larger installed base of wire-frame modelers, so our decision was obvious. The start-up operation would focus on converting wire-frame surface models to StereoLithography. The preparation of wire-frame surfaced models required a much higher attention to surfaces than normal. Not only did the exterior have to be surfaced but the interior as well. This required double the modeling time and developing techniques for this became a high priority.

The modeling for the first year and a half was all done by the wire-frame technique. The time that could be saved with software solid modeling became more apparent as time went on, and when we entered the service bureau business it became the software of choice.

The preferred method of interface is solid modeling, however, wire-frame from conventional systems can be transferred into solid modeling programs via IGES.

The last major problem we encountered was educating management, marketing and manufacturing about the value this technique could provide for a new design evaluation. We found that the best approach was to choose a relevant project, generate an SLA model, and put it in the hands of the project leader for his or her next project review meeting. This approach works every time because you generate much needed input prior to scheduling construction of costly prototyping or production tooling.

### **The user community**

The impact on your current CAD/CAM user group will be mixed. Most people are intrigued with the process but are not sure where it fits into their current procedure. There will be many views of the technology, from an expensive toy to a major design review breakthrough. One must be careful how the technology is promoted. People should be made aware this is not a device that builds fully functioning prototypes. The device should be promoted as a design evaluation tool that works from the original CAD database.

StereoLithography is not for everything, but it is a tool that will increase its influence across all product designs in the near future. The user community needs to understand where it fits and when to use it in the design process.

The use of a StereoLithography model can cut months off the process of gaining a universal design consensus before proceeding into production tooling. The user community must understand that this is only the beginning of utilizing the intelligent CAD database to drive their design into reality.

## **Benefits**

Baxter has realized several benefits from implementing StereoLithography. The core of our business is the generation of medical devices of all types. We currently market in excess of 120,000 products worldwide.

The use of StereoLithography has contributed to accelerating the product development process. The mere fact that we can generate a physical representation of a new concept in literally a few days or a few hours is a strategic advantage. The key thing to remember when dealing with StereoLithography is that it only solves part of the problem. The typical first impression is that the technology will get you to a finished product. This is a common misconception and needs to be addressed immediately with management or a prospective customer.

The process is powerful and certainly has its place in most CAD/CAM environments. Furthermore, it is only the beginning of processes that can be driven from an intelligent database.

I look forward to the future with great anticipation, for I feel we have only seen the beginning stages of the manipulation of the intelligent database.

# Concurrent Product Development with Rapid Prototyping

David G. Trimmer, Director, Engineering Services, DePuy, Warsaw, Indiana

DePuy (pronounced "di-PEW") is a division of Boehringer Mannheim Corp., a leading supplier of medical prostheses. David Trimmer is responsible for computer aided design, analytical engineering, prototype services, including StereoLithography, and the technical library. Engineering Services at DePuy reports directly to the Vice President for R&D.

Mr. Trimmer graduated from Purdue University with an Associate in Applied Science in Mechanical Engineering Technology and a Bachelor of Science.

Rapid prototyping is causing a sweeping revolution in the product development arena. The availability, in short time and at reasonable cost, of a physical model to those responsible for evaluating a new idea or concept has enhanced their ability to understand what it is they are evaluating, and to make better decisions. Companies striving to shorten the development cycle realize that they must capitalize on their greatest asset, the knowledge and imagination of their employees. DePuy has long worked towards concurrent product and process development, but not until the introduction of rapid prototyping did we achieve remarkable results. The most dramatic impact is on the time it takes to get a new product to market and the avoidance of costly engineering changes late in the design-production cycle. No amount of restructuring alone could have provided these benefits. We are now poised to expand our efforts into other areas of concurrent product development and just-in-time manufacturing.

DePuy is a leading manufacturer of orthopaedic implants and related instrumentation and supplies. While we are the world leader of hip implant units, we also make devices for nearly every joint in the body. These devices are metal and plastic parts that replace the articulating portion of the bone in a joint. Over 95% of all joint replacement surgeries use off-the-shelf products. Here the surgeon would select from a family of parts that may have from 5 to 12 sizes. In addition, he has a choice of different families of products for different surgical preferences and patient needs. Then there are custom implants. These are individually designed for a specific patient and are usually reserved for the most difficult or complicated cases involving severe bone loss due to cancer, trauma or secondary surgeries.

DePuy took delivery of an SLA-1 in September of 1988, and has since upgraded to an SLA-250. So we have over 2½ years of experience with rapid prototyping. There are many facets of rapid prototyping that I could discuss, but I will focus on the organizational structure that allows us to pursue concurrent product development and present a case study to show our results.

## Organizational structure

We chose a Senior Designer, Bart Huffman, to train for StereoLithography. It was essential to choose an individual who could work closely with the engineers in the concept stage of development, yet interact well with many other departments for their assistance. In addition, good CAD modeling skills are critical to achieving good models and prototypes. The six model makers in the prototype shop use CAD for basic 3-dimensional wire-frame geometry, but they do not have the necessary surface modeling skills to prepare a database for output to StereoLithography. Bart had these skills, as well as a good working relationship with the product development engineers. He also knew how to work in a concept mode where ideas are often quite vague, with few specific details.

The new StereoLithography operator moved his CAD station to the lab area near the SLA machine. This not only made it easier for him to monitor the machine, but also shielded him from daily design assignments and other interruptions. We also allowed other designers

who were good with surfacing techniques to submit for rapid prototyping software models of their projects. Bart reviews their software models and offers tips on achieving the best part resolution, then helps them troubleshoot the slice-and-build process. He helps them to understand the effect of part orientation on feature accuracy and helps them design supports for building and for controlling post-cure warpage. Bart has developed a level of expertise that now assures us of a satisfactory volume and quality of rapid prototypes. A second product designer has been assigned to work with him full-time.

### **A case study**

StereoLithography has been good for building models and prototypes, but the payoff has been even greater in new applications, such as soft tooling. Launching a new product three months ahead of the competition is good for establishing market share, and can impact the profit picture for an entire line. I will describe one example where this was the case.

A new hip implant system project was initiated at a meeting of a product development engineer, the Product Manager from Marketing, and two orthopaedic surgeons. The engineer returned with sketches for a proposed design, and each individual had his own mental image and expectations of what the system would be. The engineer teamed up with a designer, and they built a 3-dimensional fully-surfaced CAD model. This database was then reviewed and processed through StereoLithography. Within two weeks of the original meeting, each party had a plastic model in his hands for evaluation. This led to further product definition, and a second round of prototypes was produced. Now we had a very good idea of the definition, and a series of plastic models were made to use on cadaver bones for sizing considerations. At the same time, the models were shown to Manufacturing, Purchasing, Quality Control and Materials Research. They reviewed the project for ease of manufacturability, cost, quality considerations (inspection and gauging), and materials considerations (casting, forging, machining). Each department had a sure understanding of the design because they were holding it in their hands. And they felt free to suggest changes because we were still in the concept stage and no tooling had been cut. Their input allowed us to develop the implant system in a way that was most easily manufactured, used the optimal materials for casting and finishing and had the desired gaiting areas and bosses for fixturing.

Bart then built a new series of models for masters in the casting process. These included the necessary material shrink rates plus the features requested during the design review process. We made epoxy molds around these masters and used the molds for wax injection. The wax patterns were used in the investment casting process to get metal implants. We were able to supply metal implants to the surgeons within 16 weeks of the original meeting. But more important, the implants delivered met the expectations of the surgeons and our various departments, because each of them had seen and worked with the product in advance.

### **Conclusion**

Having a physical model can enhance the opportunities lying in a design project. This happens by the improvement of communication among the departments involved in the project, and the improvement of everyone's understanding of the product which is the goal of the project.

We are still finding new applications for rapid prototyping, as it is made available to non-R&D personnel. This is made possible by the freedom we gave our StereoLithography operator to experiment and interact with other departments.

# Rapid Prototyping: A Design Engineer's Perspective on Solid-to-Solid Modeling

Steven Venditti, Principal Mechanical Engineer, Video, Image and Printer Systems Group, Digital Equipment Corporation, Westford, Massachusetts

Steve Venditti has been at Digital for seven years. He is presently responsible for the complete mechanical design process, from concept to production, for desktop systems. This includes all conceptual and detailed design, as well as analysis and manufacturing applications.

Mr. Venditti has a B.S. in Mechanical Engineering from Worcester Polytechnic Institute and a B.A. in Mathematics from Assumption College. He is currently working on an M.S. in Mechanical Engineering from WPI.

## Executive summary

This paper describes methods for rapid development of conceptual, detailed and functional prototypes using a completely unambiguous solid model database. Computer numerically controlled (CNC) machining, StereoLithography (SLA) and shaping deposition processes have been utilized to create various parts, ultimately resulting in what can be termed "Solid to Solid" representation. More specifically, design geometry went from software solid model to solid part without the use of drawings. A critical portion of this effort was the integration and manipulation of design geometry to ensure effective transfer into the appropriate manufacturing process. This required some adjustment to the standard design approach, in terms of database development and manufacturing awareness. However, by using the concepts of design for manufacture (DFM) and concurrent engineering, and the tools of software solid modeling, this adjustment was minimized. The goal of this effort is to create a robust design and improve new product time-to-market by reducing the development cycle presently required for functional, production-intent parts. Some initial case studies have indicated the following:

- Industrial design conceptual models in 2-3 hours,
- Detailed design models in 24-48 hours, and
- Production-intent or seed units in 3-4 weeks.

## Introduction

Intense competition and aggressive product schedules have driven design engineers to continually enhance their tools, techniques and talents. Multiple iterations and verification tests to ensure design integrity are no longer acceptable. Today's diminishing time to market will only allow for one prototyping cycle prior to production. This dramatic change has created new challenge, responsibilities and insight, ultimately focusing on the rapid transition from product concept to production.

The software solid modeling tool combined with design for manufacturing techniques have enabled a concurrent approach to previously segmented and sequential engineering style. They have also instilled a manufacturing awareness in the design, resulting in a substantial reduction in development cost, time and improved product quality.

Use of integrated and sufficient database through a fully surfaced or solid software model was essential for expeditious design development and transfer into the appropriate manufacturing process or parallel applications. This 3-dimensional volumetric representation provided completely unambiguous geometry to facilitate visualization and manipulation. Instant cross-sectional data, complex surface displays and variational features, as well as a multitude of other capabilities, provided the design engineer with an effective tool for transforming

general ideas into quantified configurations. Of equal importance was the capability to selectively extract, simplify and prepare portions of the design database for applications such as CNC machining, StereoLithography and shaping deposition processes.

This paper describes the application of new techniques for conceptual modeling and prototyping from a design perspective at Digital Equipment Corporation. It addresses the underlying procedures for database development, preparation and rapid fabrication of models, prototypes and production-intent units. It also uses many examples and case studies of various products already benefiting from these new design developments.

### **Group background**

The Video, Image and Printer Systems (VIPS) group is part of the Personal Computer Systems and Peripherals (PCSP) business unit of Digital Equipment Corporation. The VIPS group is responsible for the development, coordination and marketing of products such as monitors, printer systems and input devices (i.e., keyboards, mice, etc.). Volume manufacturing is provided mainly by DEC-Taiwan, however, there are some additional internal and external manufacturing resources.

Most of the products developed by VIPS are low cost, high volume and relatively small in size. In addition, these products directly interface with the customer, so their aesthetics and ergonomics are very important. Therefore, most products are designed using plastic materials for exterior enclosures.

The Design for Manufacturing (DFM) group has been part of the VIPS organization for the past four years. The DFM group provides VIPS with electro-mechanical design services, from product concept to production. This includes expertise in:

- Plastics/sheet metal design,
- DFM/A (design for manufacturing and assembly) analysis,
- Finite element and thermal analysis,
- Numerically controlled (NC) machine programming,
- Rapid prototyping,
- Tolerance analysis, and
- Drafting.

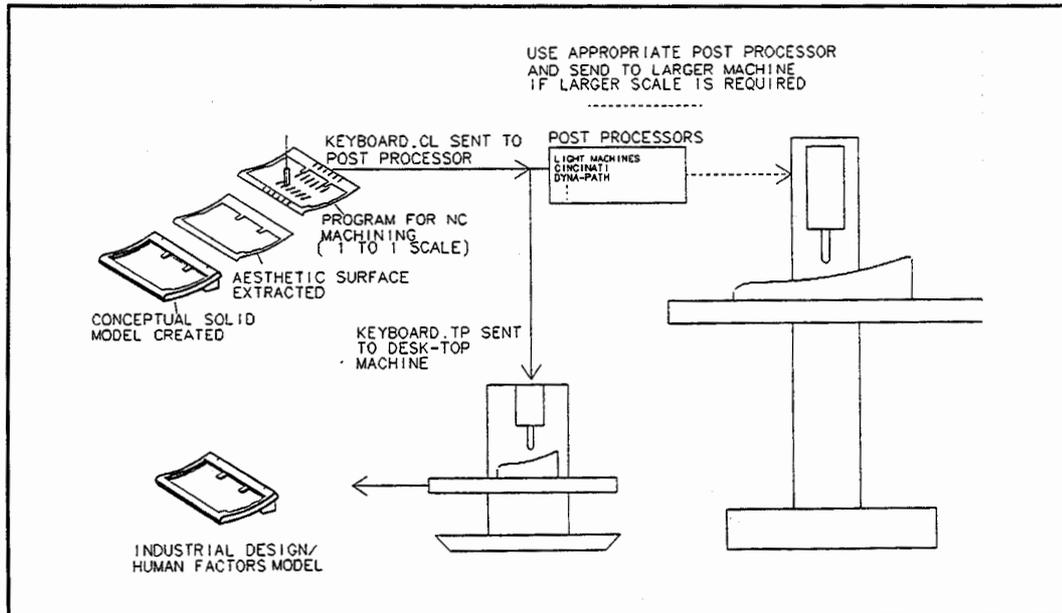
The VIPS group is capable of handling a variety of design problems. Products developed by the group range from the new corporate mouse to the VT1000 series system box. In addition, the VR300 series monitor, LK401 keyboard and various advanced development projects have benefited from these new rapid prototyping techniques. All of these products have been accomplished using SDRC's I-DEAS solid modeling software.

### **Conceptual modeling**

Production conception typically begins with input from a variety of groups including marketing, product management and engineering. All of the data from this input is channeled to a human factors and industrial design team, who develop the product's image in the most aesthetic and ergonomic fashion.

In the past, the design engineer would not be directly involved until the conceptual design was complete. This was indicated when a control drawing, hand-made Styrofoam model and preliminary human factors tests using this model were complete. This approach instigated many downstream problems all stemming from geometric integrity and ambiguity.

The new approach initially integrated the industrial design into a software solid model. It was rendered into shaded images and surface boundary displays for visual verification. Also, aesthetic surfaces were extracted for numerically controlled (NC) programming and immediate model creation using a desktop machining center. Size constraints and coordination were handled through geometry scaling and appropriate post processors. This capability enabled designing and programming at full size and scaling the model to fit into the desktop machining parameters. Once the program was proven on the scaled model, a full size version was created on a larger machining center. Models were created in hours instead of days and weeks. Most importantly, geometry was unambiguous, and industrial design and human factors input were received early in the development cycle.



Conceptual model process flow.

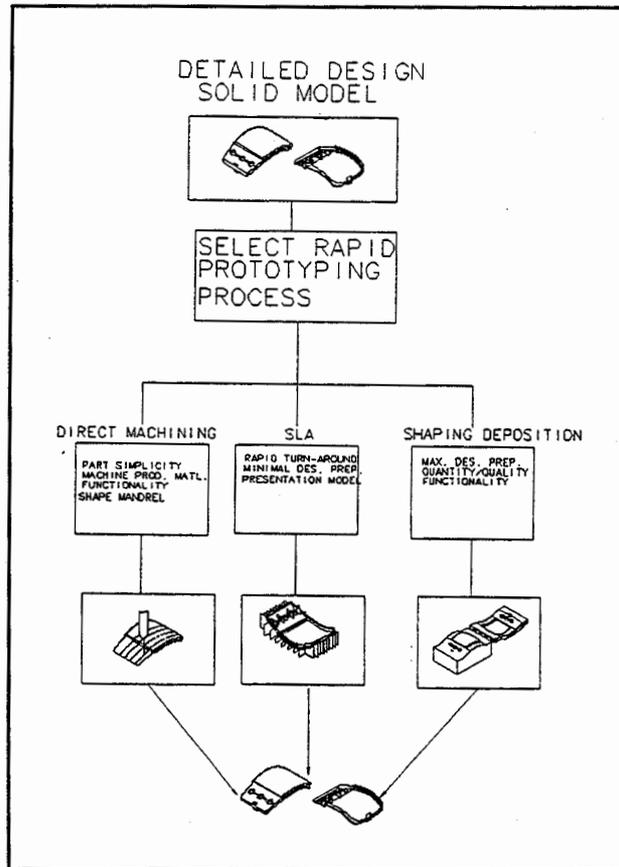
### Detailed design

Many engineering and manufacturing groups within DEC are seeking new methods and processes to reduce the time to acquire injection molded plastic parts. More specifically, a design engineer needs to have a completely functional, injection molded part in a time frame previously required for nonfunctional conceptual models. The key to accomplishing this is rapid prototyping.

Plastic part design details such as bosses, ribs, snaps and gussets, updated the conceptual model to comply with product specifications. Upon completion, prototypes were required for initial verification. Previously, preliminary prototypes were created from 2-dimensional drawings, by either "squashing" 3-dimensional geometry or starting with 2-dimensional data initially. The drawings were given to a skilled model maker who pieced together a master model. This model was used in a lengthy urethane casting process in which ten to twenty nonfunctional parts were developed. Again, a sequential approach combined with subjective data integrity led to inaccurate models and project delays.

Detailed prototypes were developed using several new techniques. Part complexity, tolerances and functionality were the determining factors for which method or combination of methods to select, as shown at right.

StereoLithography was available as a quick process to make plastic prototypes of various geometric shapes. Fabrication in 24 to 48 hours of unattended machine operation was not unusual. In some preliminary applications, SLA prototypes were created over a weekend and small part size enabled two adjacent models to be developed simultaneously. These were made available for industrial design, human factors, product management, and vendor quotation. In one particular case, parts were usable, although present resin shortcomings in tolerances and mechanical stability have limited functionality.



Detailed design process flow.

Simple geometry was directly programmed and machined into a block of appropriate material, for a close approximation of production units. As complexity increased, details were machined separately for simplification and fastened into machined pockets on the main body for exact placement. Depending upon the quantities required, this directly machined part could have also been used to create a master or mandrel for the shaping deposition processes.

Shaping deposition processes require a chemical, thermal or electrical catalyst to deposit incremental amounts of metal onto a mandrel surface. The mandrel or master part is divided into halves at a predetermined parting line. Some mold details such as shrinkage, side action, gating and cooling lines were incorporated into the mandrel. The extent of these details were dependent upon the desired quantity and quality of the part. Metal deposited on the mandrel surface was extracted and ultimately processed into a preliminary hard tool capable of producing up to 100,000 parts. Lead times of four weeks and costs of less than 50% of a conventional hard tool made this process extremely compatible with low-volume production and fast turnaround times.

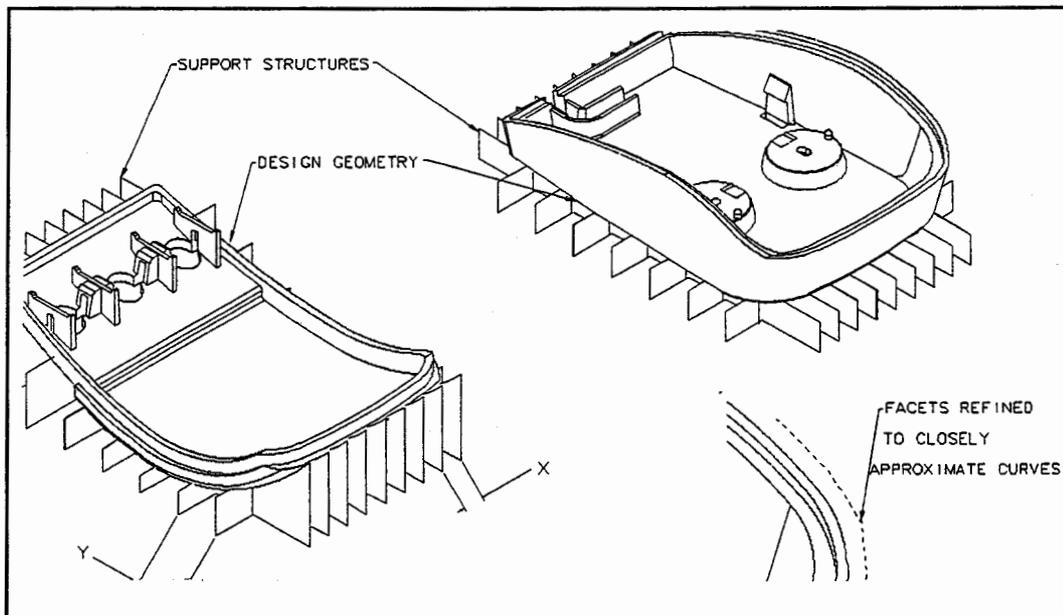
Some of the other benefits associated with this process are:

- Machining, polishing and texturing of the mandrel is done only once, regardless of how many cavities are subsequently required.
- An exact duplicate of the mandrel surface is made, capturing engravings, textures and optical quality surfaces.
- It supports many secondary processes such as injection, blow and rim molding.

## Design preparation

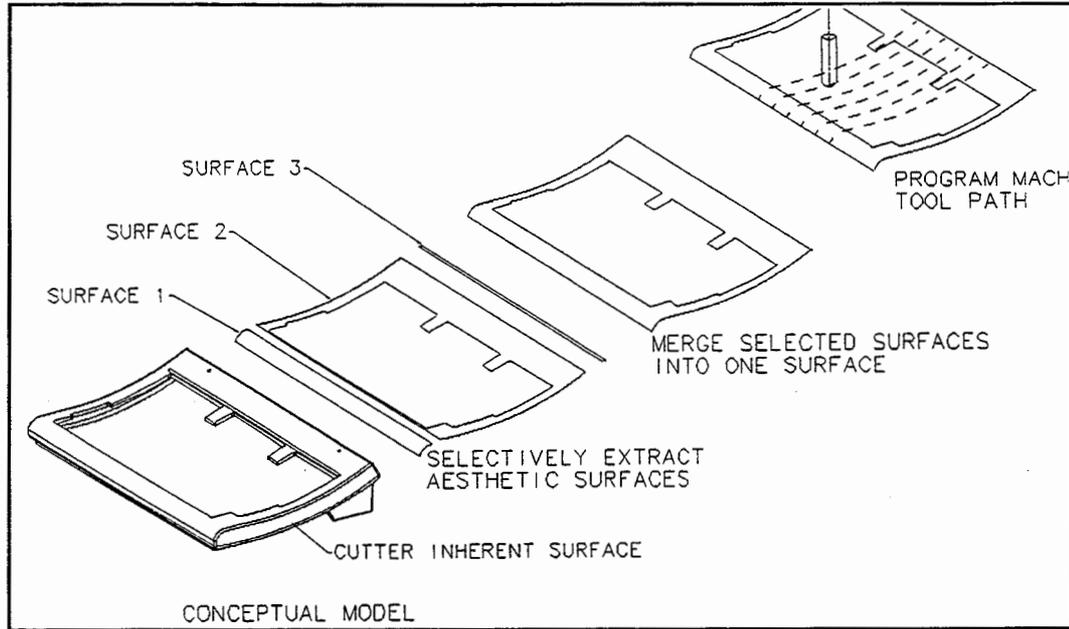
All of the new fast prototyping techniques required some adjustment to the standard design approach. Additional development of the database was necessary. Part design fulfilled form, fit and function for the production specifications. However, the conceptual and detailed design was prepared to incorporate features related to the appropriate manufacturing process or parallel application. Solid modeling software readily enabled any of the subsequent manipulations to the database and minimized the additional design effort.

During the conceptual phase, the software model was manipulated by simplifying the aesthetic surfaces and extracting only the necessary surfaces for direct NC machining. By eliminating machine cutter inherent surfaces, using drafted/radiused cutters and taking advantage of symmetry, the data transfer was minimized by 50% or more. This was a significant reduction in the time required to program the NC tool path for the particular geometry. In addition, design geometry was also simplified by merging several simple surfaces into one complex surface, reducing the time required to separately program each of the simple surfaces.



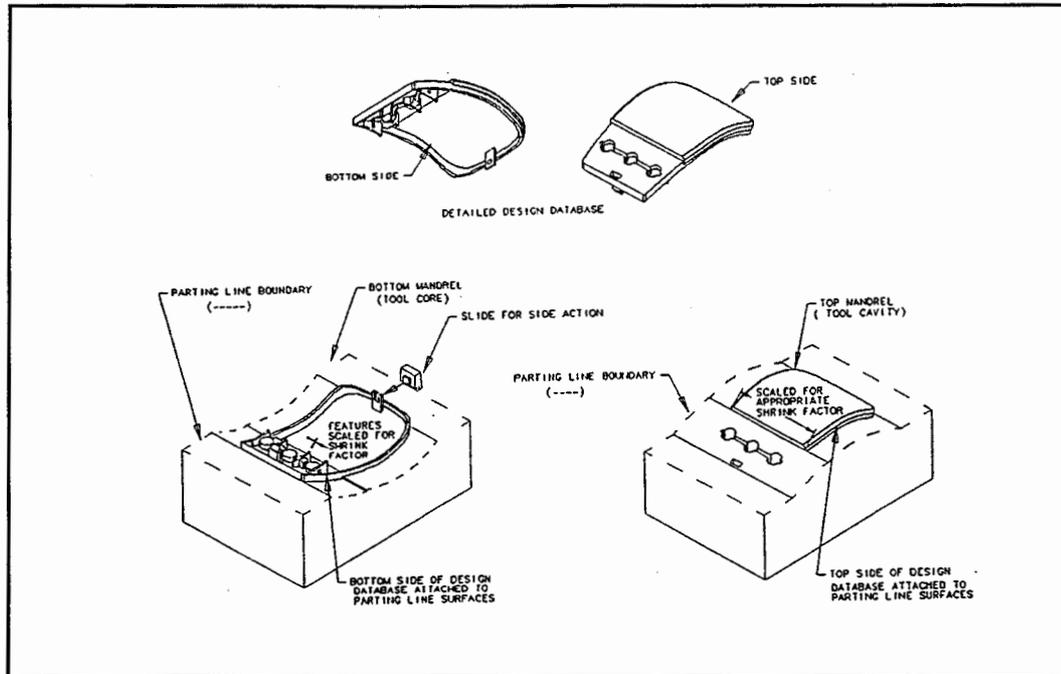
**Conceptual design preparation.**

The SLA preparation required considerable planning for process parameters to ensure accuracy and part quality. Support structures were created and appropriately attached for part development. Faceted geometry was refined to closely approximate analytical surfaces. Orientation of the part for effective and efficient build time also involved substantial evaluation. However, SLA required the least amount of effort with respect to the other prototyping techniques.



**Design preparation for SLA top/bottom enclosures.**

The shaping deposition processes required the most effort from, and provided the best results for, the design engineer. Effective mandrel creation was the key to the shaping deposition process as discussed previously. The mandrel development started with some additional manipulations to the design database. Parting line details which are usually inherent in the conceptual rendering were established as the boundary from which the mandrel was divided into halves. Appropriate geometry was oriented and attached to each side of the parting line surface and ultimately related to the core and cavity of the injection molded tool. The appropriate shrink factor was incorporated by selectively scaling features in the geometry. Any feature requiring side action had to include the corresponding feature that was a movable slide. In the first attempt at using this process, gate and core pin details were developed in post deposition modifications, but in future projects these details will be included in the mandrel. A final mandrel was programmed and machined directly from the database, as previously mentioned, and sent out for deposition.



Design preparation for shaping deposition and mandrel construction.

## Conclusion

Implementation of the tools and techniques discussed in this report truly enabled a concurrent approach to mechanical design. They significantly reduced time-to-market and product cost and improved the quality of many products.

Conceptual modeling was solidified early in the design cycle because the model was unambiguous and immediately available for evaluation. Detailed modeling required additional effort but parts were completely functional and minimized many iterations of design verification tests.

A key factor in all of the rapid prototyping processes was database preparation. They each required a varying degree of manipulation and development, which subsequently resulted in additional design work. A considerable amount of thought was given to product/part requirements and knowledge of the appropriate manufacturing process was essential.

These techniques have yielded significant savings for the Digital Equipment Corporation. For example, the material and assembly costs of the new corporate mouse are less than 42% of those of the previous model. The VT1000 Series system box provided a 70% savings compared to a benchmarked product and was mechanically completed two months ahead of schedule. It continues to be the most cost effective "box" for DEC. Both of these products have been praised by field service and human factors groups, confirming the design methodologies.

### **Acknowledgement**

I would like to express my sincere thanks to Ricardo Fernandez, Helen Connelly, Gordon Lewis, Daniel J.J. Velasco, Charles Patterson, Charles Kaberry, Venkat Subramaniam and Robert Faranda for their assistance with the development of this project and report.

# Rapid Prototyping: Cornerstone of the New Design Process

Phillip L. Ulerich, Senior Engineer, Westinghouse Science and Technology Center, Pittsburgh, Pennsylvania

Phil Ulerich has been at Westinghouse' Science and Technology Center for over 10 years. He has applied state-of-the-art computing techniques to a wide range of mechanical engineering problems and products ranging from escalators to "Star Wars" equipment, from gallium arsenide chips to the Sears Tower. For the last three years he has been designing circuit breakers on an engineering workstation and has established design procedures to shorten the time to market for these products.

Mr. Ulerich received both his Mechanical Engineering degrees from the University of Pittsburgh and is a registered Professional Engineer. He also teaches Mechanical Engineering at Penn State University's adult education centers in Pittsburgh.

American industry is being driven to greater efficiency by ever increasing world competition. Westinghouse' Low Voltage Breaker Division, where we design and manufacture a full family of circuit breakers, presents an example of this situation. Our products range from the 5 amp version you may have at home to the 2000 amp 3-phase breakers protecting stores and office buildings throughout the world. We face strong competition from European and Asian manufacturers, while looking to Europe and Asia as our greatest growth markets.

Part of our response to the drive for productivity is our use of concurrent engineering. The phases of the product development cycle are:

- **Design.** The general layout and detail of parts is created in an engineering database.
- **Mockup.** The first (nonfunctional) models are built.
- **Prototype.** Functioning prototypes are built and tested.
- **Product verification.** Permanent-tooled parts are used to build and test a salable product.

The objective of concurrent engineering is to get through all these phases as quickly as possible by getting them all started as soon as possible. All phases run concurrently, instead of sequentially, and revisions are generated as early in the process as possible.

In a conventional design environment, a drafting department creates the engineering database in the form of drawings. In our design environment, drafting is mostly an auxiliary function, documenting the design in drawings, much like a final report, after the designer creates the engineering database on a computer. Another function auxiliary to the design process is analysis, where the function of the product is simulated to check whether the proposed design will satisfy all requirements. At all phases of the process, revisions are introduced, sending us back to previous phases to repeat the cycle.

This paper recounts some experiences with four rapid prototyping technologies: StereoLithography, silicone rubber molding, spray metal molding and computer solid modeling. In concluding, I will suggest that the really big payoff comes from using all these technologies together and that the really big problem we face is motivating people to learn and use these proven techniques.

## StereoLithography

In December of 1988, we had a computer solid model of a part and needed to get model parts as soon as possible. Our standard model suppliers quoted \$3,600 with 6 weeks delivery. Although the part design was in the computer, it would still take four weeks for Drafting to get us a drawing to submit to the shop, so total delivery time was 10 weeks. The price was high and the delivery unacceptable. I had seen a StereoLithography demonstration at Autofact, so I called 3D Systems and got the name of two service bureaus, who both quoted

the part at about \$2,700 and 10 days. We knew enough about the SLA process to recognize that experience and magic were both critical to getting good parts, so we selected Micro-Cut Engineering, near Chicago, who had made more than 100 parts at that time.

Starting with a couple of faxed isometric views from our solid modelling software, a purchase request and an IGES file transmitted over the phone, Micro-Cut began creating our part while we continued to detail the part and make drawings. After a week I visited Micro-Cut to check on their progress and request a design revision. The revision was made in 5 minutes at no cost and with no lost effort or rework, certainly an improvement over what would have happened at a machine shop 70% through the delivery schedule. The first part was made on day 9, but was out of tolerance ( $\pm 62$  mils) due to an SLA machine calibration problem. After 3D Systems fixed the machine, a second attempt was made but the  $7\frac{1}{2}$  inch part was still about 40 mils oversized. This part was delivered to Westinghouse with the understanding that better parts would be made. The third try yielded two parts within 10 mils of the nominal dimensions on day 21. The draftsman found the parts very helpful while he completed the drawing. I try to maintain good-natured competition between Drafting and my SLA vendor to see who can complete the work first. So far, the SLA parts are winning.

We were very pleased with the part's accuracy, price, and delivery. We cut seven weeks off conventional delivery and saved hundreds of dollars on that first model, not to mention less tangible design costs. This job initiated an excellent relationship with Micro-Cut which has produced over 20 parts for us, to great mutual benefit. All the parts I have received have been very brittle and thus nonfunctional, but they glue nicely with Super Glue. These SLA models have been invaluable for checking part form and fit, and for discussions with mold makers and draftsmen. I find people need to fondle parts before they really understand them; drawings just don't do it.

A question I am always hearing is, "How accurate are these parts?" For me, the answer is, "Accurate enough!" Our drawing tolerances are typically  $\pm 5$  mils, so my design must accommodate that error on production parts. If model parts meet that criterion, I am happy. I have found that in cases where SLA cannot meet that criterion, a molded part from a permanent tool will likely have the same problem. I have found it more productive to adjust my design to accommodate the SLA inaccuracy than to throw rocks at SLA, and solve the problem later with permanent-tooled parts.

As an example of this, consider my colleague who received an SLA part with long, slender, cantilevered legs. The tolerance at the end of the leg, a critical location, was off by 15 mils. The engineer was unhappy with SLA, and the surface was corrected by hand. The model was used to make a spray metal mold from which prototype parts were produced using the final material, Vectra. When the same critical surface on the prototype parts was out of tolerance, the engineer was unhappy with the spray metal process. The parts had to be adjusted by hand in order to be usable. Five weeks later, the final parts came out of the permanent mold, and the same critical surface was out of tolerance. We are now doing the best we can with bad production parts while we try to fix the permanent tool. The fact is that StereoLithography had given us a very important signal that the design was unproducible. We ignored that message and criticized the "poor" models and prototypes, instead of re-evaluating our own design.

I have been very productive with the SLA system and there are several reasons why. First, I use a service bureau because of the large investment required to make the system work. Not just \$250,000 for a machine, but two people full-time, a CAD operator and an SLA machine operator. Both positions require highly skilled technicians who must have had the experience of making many parts before, in order to make new parts right the first time. Every step of the process is critical. You must make hundreds of parts a year to make a system truly productive.

Second, it is better to pay reasonable rates to use a service bureau's experience, letting them take the risks. Another Westinghouse division ordered a part from a bureau. That division created the slice file and the support structure themselves. In essence, they rented SLA machine time and the bureau simply ran the Westinghouse tape. The result was a disaster: the walls of the part collapsed during construction. I predict that, had that not happened, the tolerances would have been bad either because the slice thickness was wrong, the fill pattern was poorly chosen, or the bureau did not have enough exposure to the part to specify an adequate post-curing process.

I can summarize my experience with building parts by SLA as follows:

- Use a service bureau, at least initially, because of the big commitment required, \$250,000 plus two people full-time with years of related experience.
- SLA is not productive for all parts. Simple parts should be done in a machine shop.
- Accuracy is widely variable, depending on the experience of the operator.
- With an experienced SLA group, accuracy problems on an SLA part foreshadow accuracy problems on molded parts.

### Silicone rubber molds

Once we have our first part, the natural next step is getting multiple parts. We have used SLA parts as patterns for silicone-molded epoxy parts. This works, but I am not generally enthusiastic about it. The price of parts is high and the production rate is low. The tolerances are poor; I find each part from a mold tends to grow until the mold is scrapped. Finally, you still just have a model, the parts are not functional since they are not made from the correct material. We sometimes use these as prototype parts if the epoxy material they are made from is strong enough to function, but this is always risky. This is a valid method to make several visual models in a short period of time.

### Spray metal molds

I referred above to our "failed" spray metal part. Now let me elaborate on this process and our experience with it. A spray metal mold is a temporary tool which can be made quickly from a model part. It produces a number of molded prototype parts in the design material. This is a rather conventional mold with ejector pins, runners, gates, and draft. For this mold, the SLA part is mounted at the part line as a pattern for half the mold. Numerous layers of metal are sprayed onto the SLA part until it is covered with about a 1/2-inch thickness of metal. Now the other side is spray coated in the same manner. The two halves of the mold are separated and each half is backed in an aluminum box with a metallic-epoxy potting compound. Ejectors, gates, runners, alignment pins and (if needed) inserts are added to produce a short-run tool which is very similar in form and function to the permanent tool. In a typical case, the total cost for the SLA pattern, spray metal mold and 50 prototype parts is less than \$2,500. A useful procedure is to make two SLA models with tolerances as specified on the engineering drawings,  $\pm 5$  mils. One model is sent to Westinghouse for approval, checking form and fit, while the other is modified to be the pattern. The pattern is created by adding the required draft which is within the specified tolerance.

I will mention briefly two cases that highlight the value of these molds. The first case is a thermoplastic part which is molded flat and folded once at assembly. The hinge was the problem for this part. It is like a plastic hinge except it is folded only once or twice at assembly. The first sprayed metal parts of Valox, the material we specified, broke instead of folding. We tried about four different materials in the mold before we got an acceptable part. In five

weeks we evaluated molded parts from four different materials for less than \$4,000, then picked a material and built a correct permanent tool on the first try.

The second case is more critical. This was a push-to-trip button and was the last part to be designed for a particular breaker. It was very complex, probably because it was to fit into the space left over after everything else went in. The design was further complicated by the fact that it had to support significant load, deform elastically in use, and be installed in 50 functioning models within 30 days of the day it was designed. The day the computer model was complete it was sent on a floppy disk for StereoLithography. About a week later we got one of two SLA parts to check form and fit, and it fit properly in its space. We approved the sample with a couple of minor engineering changes. The changes and draft were added to the SLA pattern and a spray metal mold was made. Within three weeks of the day the design was done we had our 50 molded Valox parts. The flash was a little heavy and required hand cleaning, and some sharp corners were rounded slightly, but we had made our functional models with functional parts of the correct material!

Summarizing spray metal molds:

- They are the best way to get a quick, inexpensive, molded part in the correct material.
- Molds are good for 50 to 1000 parts, but the parts are not quite up to the quality of those from a permanent tool.
- We have had about six spray metal molds made by Micro-Cut. All the parts have been good, and there has been a noticeable improvement in the parts as their experience with the process has increased.
- Shrink and draft can be added to the pattern either in the SLA computer model or, as with our parts, by hand after the SLA master is created.

Finally remember, if accuracy is a problem, the permanent tool may well have the same problem.

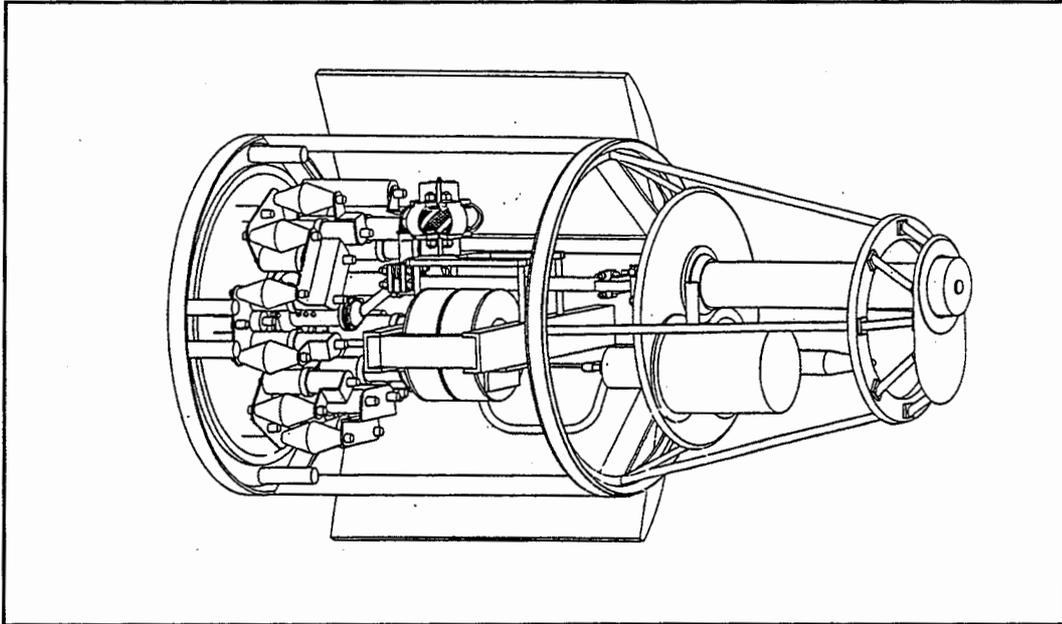
### **Solid modeling on the computer**

At the first Rapid Prototyping Conference I heard Bob Johnson refer to software solid modeling as a rapid prototyping method. This took me by surprise, but he is right. The designer sees the part take shape on the screen much the way a machinist sees a part take form. There are solid modeling programs available where the designer can create a new part within a layout of solid models and check fit, relative size, aesthetics, clearances and get an excellent visualization of function. The computer is a tool to help develop understanding of a design as it is conceived, and remind us of details and considerations we might have overlooked. Solid modeling software is not perfect, but available software is productive when used in an industrial environment. I will give three examples.

At Westinghouse' Science and Technology Center we have been using Euclid, Matra Datavision's solid modeling program, for ten years. Our group consists of consulting design engineers who work for many Westinghouse divisions. In every case we must be cost effective because there is no corporate incentive to use us. One of the most salable skills that we have developed is computer solid modeling. Our experience includes such diverse products as satellites, nuclear waste processing plants, circuit breakers, super conducting magnets, steam turbines, fuel cells, and many more. In fact, our rapid prototyping grew out of a desire to fully utilize the computer solid databases we had.

Below is shown a computer solid model, produced with Euclid, of the business end of a satellite. This particular piece of the Star Wars initiative was launched about a year ago and

contained an electric cannon that fires supersonic projectiles at ICBMs. It was a test device good for one shot in an experiment, not the real thing. We were contracted to design and build the cannon. We did this using software solid modeling and the government agency was so impressed by our design presentation, visualization, detail, and quality, that they inquired about computer solid modeling. Based on our demonstration of software solid modeling capability, they gave us the overall packaging responsibility for the satellite. This was a job we had never done before.



Euclid model with all the details. Euclid, by default, shows a hidden line picture on the screen. This model has sufficient detail to allow the engineer to zoom in and look at details of parts such as bolts and washers.

The second example is from our West Valley Plant in New York, where Westinghouse has been contracted by the government to clean up a nuclear waste site and a waste vitrification plant is under construction. Once it is operating, it may not be entered because of the high radiation levels. The plant design was well under way when we began, so our job is mostly in quality control. We used the existing drawings to create over 250 pieces of pipe, reactor vessels, tanks, and quick disconnects. The result: we found hundreds of errors before the costly jumpers were fabricated, helped designers locate cameras and windows so that all areas can be seen from outside the hot cell, and verified maintenance procedures by identifying inaccessible components. For this hot cell there isn't the classic room with an expensive and obsolete Plexiglas scale model. There is instead a GeoMod computer model on terminals in Pittsburgh, West Valley, and Oregon, where engineers can see a single, up to date model. GeoMod is SDRC's solid modeling product.

Finally, I am using a Bravo system at Westinghouse' Low Voltage Breaker Division. I have no training in Bravo's solids but I have learned at least four other solid modelers. I find Bravo's system incomprehensible but our draftpersons routinely create detailed parts in the solids program and then create the drawing from the software model. This works very well, eliminating numerous error and ambiguities. That is why our databases are directly usable by others. Any solid modeling program can do a demo. What separates the true work horses from the toys is "Can it do a real job?" It goes something like this: In every real job the database gets big. A big solid model database slows down the interactive process, the bigger the slower, until you lose all productivity. Industrial strength solid modeling programs handle real design problems fast enough to be productive. Even the best software solid modelers,

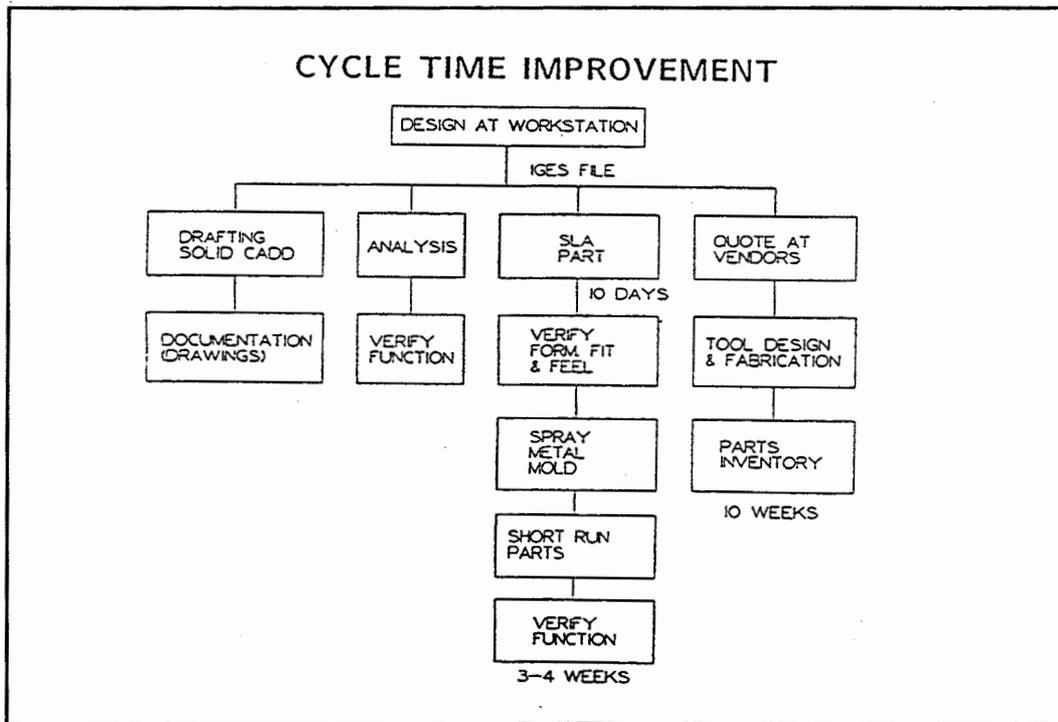
like Euclid, have limits to the practical size files they can handle, but experienced and inventive users can work around the limits and find ways to do the job. With the really "bullet proof" modelers, the only real limit is the creativity of the user.

It is best if the whole design process, for the whole assembly, is done with software solid modeling. Parts can then be separated and detailed as individual solids, so that drawing views are created by the computer, giving volumes, views, and dimensions without error.

In short, the solid modeling software helps us make fewer and less expensive changes during the development cycle.

**The prize**

The really big payoff comes from combining all of these technologies into a concurrent engineering environment. Below is shown the environment I work in. I design on an engineering workstation, a node on an Ethernet cluster, using Gem, Bravo's 3d wire-frame system. (I am using the software available at the LVB Division. As I said, Bravo solids are incomprehensible to me, so I am doing the best I can with the tools available.) I create parts in my assembled layout and then isolate each part in its own database for detailing. This is an inexact milestone; sometimes I have a very detailed part and sometimes I give it to drafting for them to develop most of the details. Productivity is the key: where will it be done quickest and most productively? Regardless of who completes the detail, data is passed back and forth between design and drafting. The critical concept is that the CAD model is the engineering database. A design exists as soon as the computer database is detailed and then the processes of modeling, tooling, and analysis begin. With a conventional approach, this point is represented by the completion of the first rough mockup, which is delayed for weeks or months while drawings are produced.

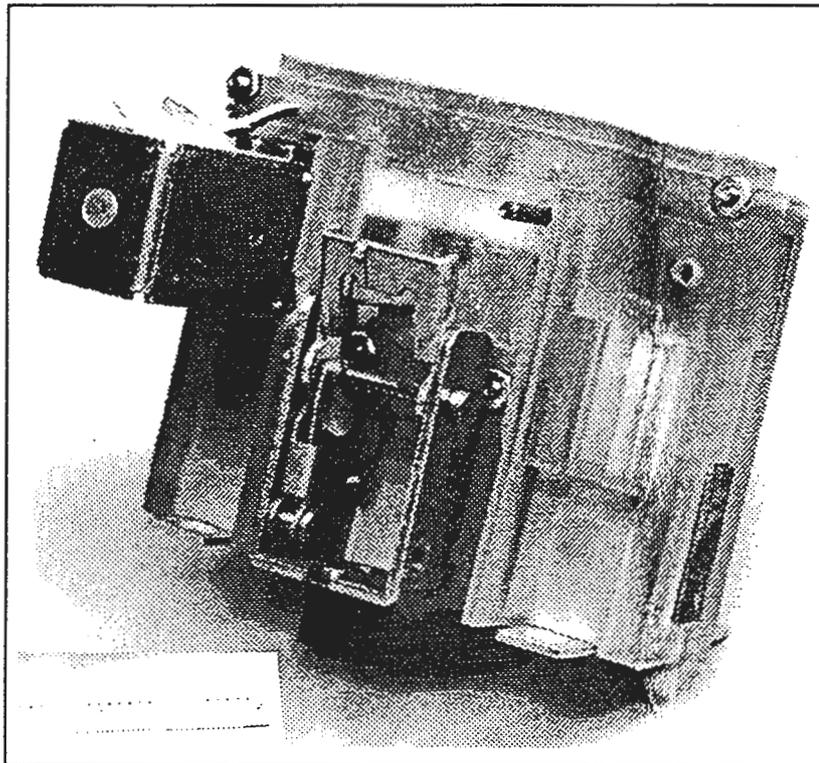


Concurrent engineering environment.

For years we have been sending CAD databases to Micro-Cut for SLA parts and to Patran, from PDA Engineering, for finite element analysis. Our shop is coming up to speed with interactive CNC, such that we are giving them CAD databases instead of paper drawings. I am currently developing relationships with molders and stampers so that Bravo's databases are compatible internally, but IGES files have been the workhorse of file transfers. AutoCAD has also been used at times to transfer parts to SLA or vendors for quoting. The whole point is to make a documented design (i.e., the computer model) available to as many functional groups as possible, as early as possible. This is the cornerstone of concurrent engineering and generates more of the revisions earlier in the design cycle when they can be done on the computer instead of in steel.

We are using these procedures. The technologies are here today and hold great promise, but the skills to use them are scarce within Westinghouse and very rare at the mold and tool shops that we deal with.

The reward is this: Today I am designing at the screen, the most rapid prototype, where I see what I imagine as soon as I conceive it. The computer database is the engineering control. It is electronically transferred to analysis for design verification, to SLA or the shop for prototyping, to spray metal or vendors for short-run tools, and to vendors for quotes and permanent tool design. As an example, the figure below shows an assembled model that was complete one week after the design. No drawings exist for these parts, just a complete computer model.



The prize: A model in a week.

At 10 days for an SLA part, it is a race to see if I get parts or drawings first, and I like to maintain that rivalry. For complex parts, I can be a month into permanent tool design before the drawing is done. Revisions due to the SLA models, drafting details, finite element or dynamic analysis, and manufacturing inputs can still be included without any steel changes.

## The challenge

I have worked every day in one of the most productive design environments in Westinghouse and demonstrated that these technologies and methods work to improve productivity and reduce cycle time and cost. I have taught computer aided engineering at three Westinghouse locations trying to encourage the use of these new methods.

The challenge now is getting designers to use these new techniques. Short of hiring a new staff, it seems nearly impossible. Ten years ago we said that software solid modeling would rule the roost in five years. We are still saying that today. The difference is that now we have 10 years of experience proving its value and we are less sure that five years is an attainable goal.

Everyone associated with the design function needs to learn how to look at a graphics screen and understand what the part will look like. Everyone needs to believe that a computer model can be the control document for design. People need to learn that when, for example, a fit problem arises, it is not a failure of the CAD system. It is a discrepancy between the part and the documentation which must be identified. Is the part out of spec? Are tolerances stacked up? Is this an error in the computer model, a shop assembly error, or a CAD assembly error?

I have found these tools to be lots of fun to use. They have unshackled me from 2d sketches and tedious tasks such as redrawing an assembly at 1×, 4× and 10×. They are different, however, from what most of us are comfortable with. "Mental inertia" is a very powerful force in human activity. Most people need lots of motivation to do something as different as I am suggesting.

Last spring we taught a course in these technologies to design and manufacturing engineers. Management created the course and paid for its development. They provided the CAD equipment and paid for half of the engineering hours to attend. Management support was there, although not unrestrained or unanimous. This 10-hour course was very applied and showed how CAD was essential for the design of a particular, highly important and successful product. Two-thirds of the time was spent actually working on a computer system, duplicating the processes used to design our breaker, the world's smallest 3-phase electronic circuit breaker. The class was well received and rated highly in the evaluations. Of about 50 students who attended, two engineers now use the system less than two hours a week. The rest have never touched it.

If you have any idea of how to recruit or create the new engineer, please let me know.

## A Beta-User's Perspective of the Stratasys System

Don Roell, Senior Design Engineer, 3M Corporation, Minneapolis, Minnesota

Don Roell runs a model fabrication unit for 3M. However, other 3M units are not required to come to him for their fabrication needs; he competes directly, on a price and time basis, with outside suppliers.

Let me start by admitting that I do not yet fully understand the *Fused Deposition* process, and we have not yet installed the machine. But I will tell you why we chose to go with Stratasys, and how we feel about the choice.

The main reason we picked Stratasys' machine is its relatively low cost.

Another reason, but one that will not be of much importance to other people, is that the company is, like 3M, from the Twin Cities.

From both a user's standpoint and a support standpoint, we see this system as an engineer's tool. We have looked at other companies who have prototype building tools and they have people with masters degrees in computer science running them and they have special craftspeople and special machinists and specially trained operators, and they have special environments. Our engineers do not have those things. We have people who moved up off the shop floor, spent a great deal of their lives learning the machine process, and then we sat them down in front of a CAM workstation and we have them NC our parts for us. These are the "engineers" we want to be able to use this tool, and eventually Stratasys is going to sell us a machine that we can plug in like a printer to every CAD station that we have. At least that is the direction we are going to push them. I do not know how far their genius will carry them in that direction. But that was one of the reasons we bought it. It was simple. We viewed it as a safe and an easy tool to use. We have a lot of enthusiasm for the potential to be able to directly drive the Stratasys machine from our CAD-CAM system.

As for the parts, I saw a part recently that holds tolerances to a thousandth of an inch. That is something we have been pushing them to do since we first met them. And they have been bragging about their ability to do it for quite some time. I finally saw a part that does it.

Last but not least, their beta site agreement is very favorable.

We like working with Stratasys. I think they like working with us, and we have a lot of hope for the process.

# Concurrent Engineering Tools and Systems— Concepts and Experiences

Al Cassista, Manager, Computer Integrated Manufacturing Lab, Digital Equipment Corporation, Maynard, Massachusetts

Al Cassista is responsible for process analysis for design-for-manufacture and assembly development, verification of rapid prototyping and concurrent engineering concepts, test and evaluation of software applications, and evaluation of new technology in computer integrated manufacturing. His most recent responsibilities include support of DCC/ACT, customer visits, strategic partnerships, and enterprise integration services activities.

Mr. Cassista attended the U.S. Coast Guard Academy, Lowell University and MIT.

## Historical perspective

When America was young, our forefathers were practicing what we would now call "concurrent engineering," long before we identified it as a work style. For the most part, we had a work force comprised of craftspeople who had learned their respective crafts or trades through a long and in some cases difficult apprenticeship program. These people took a great deal of pride in the work they produced. The work was generally organized in such a way that a number of these craftspeople would work together toward a common goal. All the principals with any influence on or responsibility for the project were assembled and worked together.

Ship building is a good example. The shipwright and naval architect, as well as the iron workers and carpenters would be assembled in a common area. As work would progress, any problems with geometry or materials would be dealt with by decision makers. All the principals understood clearly what the common goal was and they all had ownership in the final product.

Over the years this system began to break down. Skilled craftspeople were gradually replaced by people with limited skill sets. In many instances these people were charged with performing the same repetitive tasks over and over again. The process of redefining the work tasks into subunits, or "stovepipes," is generally credited to one Frederick W. Taylor (1891-1915). Taylor was a pioneer in the automation of work in the style of the assembly line. Although he worked for Bethlehem Steel, he is often credited with the co-development of the automobile assembly line. His work with Henry Ford was soon identified as the "Taylor System."

The problem with this solution was that it dehumanized the work place. The simplicity of individual repetitive tasks fosters boredom, and with boredom comes poor quality and lack of ownership in the final product by the individual contributors. Assembly line manufacturing tends to be expensive to retool and the nature of the process makes it relatively inflexible and difficult to respond to new market demands.

With product life rapidly diminishing and consumer demand for new products ever increasing, we have had to respond to the challenge.

Industry and the academic community, working in partnership, have spent long hours evaluating the way we conduct business. There has been a gradual shift "back to basics" where engineers are encouraged to become more "generalists" than "specialists." What we mean by that is that emphasis should be placed on broad-based education. Usually this type of training fosters innovation and a new way of looking at work assignments. With technology advancing

in leaps and bounds, it is the generalist that tends to look at a new product with an open mind. This phenomena will be discussed in depth later in this paper.

## **Concurrent engineering tools**

### *People*

This paper is focused on concurrent engineering tools and systems, but no discussion of this topic is complete without considering the "people" element.

In many areas, educators are beginning to re-evaluate the way we teach our young people. Encouragement to "be your own man" or "be an individual" is being slowly replaced by early training in team dynamics. The ability to work effectively with type "A" and type "B" personalities in a team environment is looked at with increased importance. Universities are restructuring their basic curricula to reflect this style of interaction. The leading universities are now implementing programs that reflect broad skills as a basis for excellence.

For example, MIT's College of Engineering in cooperation with the Sloan School of Business will be offering a double Master's Program for Business and Engineering students. Graduates of this program will be awarded two Master's degrees. The intent of this program is to cross train the brightest and the best students in the principles of both engineering and business. These graduates will be entering the work force with unique skills that foster concurrent engineering. It is hoped that similar programs will be instituted by other leading engineering colleges.

### *Machines*

Computers have been in the workplace for several years now, but it is a relatively new practice to incorporate workstations and PCs on the shop floor. In many areas, the dispersal of computing power from central facilities to a more distributed base has radically changed this picture, and now more people than ever are taking advantage of this new resource. Data management has taken on a new meaning.

Computer architecture is constantly evolving. Not so long ago machines incorporating CISC (Complex Instruction Set Computing) were all that was readily available. Now we have several high speed workstations available that use RISC (Reduced Instruction Set Computing) chip sets. These machines tend to work considerably faster than the older CISC architecture machines, although some new compilers are closing the speed gap.

Operating systems are taking on a new importance. Until recently, most major computer hardware vendors had developed their own proprietary operating systems. DEC had VMS, IBM had MVS, etc. With a growing trend toward open architectures, operating systems are taking on a new importance. UNIX and UNIX-derived operating systems have been favored by many CAD vendors. This operating system is common in the workstation environment and lends itself well to portability. CAD vendors find it easy to port code developed on one system to another.

Several prototyping processes have been developed recently that are now robust enough to provide samples for evaluation in manufacturing. An excellent example is StereoLithography. This process incorporates the latest developments in polymer chemistry, lasers, and computers.

StereoLithography works by translating CAD data directly into instructions that scan a laser beam across the surface of a liquid resin. The laser literally "paints" individual layers of the CAD geometry on the surface of the resin. A chemical reaction takes place at the point of irradiation, changing the liquid to a solid only where the laser light hits the resin. This layer is submerged and the process is repeated until the entire geometry has been fabricated. The result is a plastic replication of the data in the CAD file. This process is especially useful where complex geometry is involved. A prototype can be produced in hours where conventional methods would take days to produce the same part.

StereoLithography is only one of a growing family of new processes that are finding their way from the research laboratory into the manufacturing environment.

### *Software*

CAD systems have been around for several years now in many facilities. They have been extensively used to replace the drafting table.

It was with the arrival of 3d wire-frame systems that manufacturers really began to get a payback from CAD. These early systems generated CAM (Computer Assisted Manufacturing) machine tool files from the CAD data. Then the introduction of software solid modeling brought further major reductions in product development cost and reduced the time to bring a product to market. The unambiguous volumetric information provided by solid modeling software makes it one of the enabling technologies of true concurrent engineering as we know it today.

When discussing concurrent engineering, and specifically CAD environments, the question of monolithic versus mixed environments is rarely omitted and in fact is usually a hotly debated subject. The truth of the matter is that we can make a strong case for both scenarios.

Monolithic systems, such as ComputerVision, allow many users to pass CAD data generated by the system to a captive CAM module with little or no data translation required. In some cases data management is much easier with this type of approach. Hardware compatibility is, however, an issue. Many of these systems require dedicated workstations that in some cases will not work in a mixed environment containing personal computers. Our feeling is that no one vendor is best at everything. Some excel in the CAD arena while others are better at CAM.

We favor a mixed environment. We think that it is most important that the engineer choose the CAD package that he or she is most comfortable with. With few exceptions, major CAD packages available today are fully functional. The difference is in the interface. Some vendors take great pains to mimic the human interface to match a work environment. A draftsman would feel very comfortable with several CAD systems that relate to points, lines and arcs, where a machinist may feel more comfortable with a package with an interface that utilized holes, slots and chamfers.

Determining the "best CAD system" is a nearly impossible task. One only has to understand how CAD packages are developed to fully appreciate how difficult it can be. Most CAD vendors enter the marketplace, and if they are lucky, will find a group of special interest users. This group may be, for example, into plastics design or sheet metal fabrication. Once the CAD vendor has found its niche it will strive to service that group with any and all enhancements that are pertinent to their specific problems. The natural result of this process is that some CAD systems are better suited at certain tasks than others. So when one asks the question "Which is the best CAD system?" the answer has to be "Best at what?"

Operating system and hardware configurations can complicate the equation. Not all CAD packages will work on all platforms.

Another interesting software development has been the maturing of CAE (Computer Aided Engineering) tools. These tools were once relegated to the world of the scientist and the mathematician. Many of these programs now are quite user friendly and are taking on an increasingly important role in the concurrent engineering workplace. They facilitate computer modeling of various physical, thermal and fluid dynamic processes. Computer simulation and modeling can have a dramatic impact on time to market and product reliability.

CAM systems have evolved to the point that CAD data can now be automatically translated into code to operate NC (Numerically Controlled) machine tools. In addition, many CAM systems can now drive sophisticated machinery such as the StereoLithography apparatus.

## **Fundamental enabling technologies**

### *Adherence to standards*

Close adherence to standards is fundamental to concurrent engineering. Imagine walking into a library and finding that all the books were written in different languages. Standards, as defined by international groups and government agencies, provide the common languages for data translation and manipulation.

### *Communication across different platforms and environments*

The NAS (Network Application Services) and the LANworks architecture give us the flexibility to communicate and pass data freely from one computer environment to another, without regard for the data structure.

### *Software solid modeling*

By providing complete volumetric information, software solids modeling has opened up entire new technologies and manufacturing practices unknown only a few years ago. This concept has had a profound impact on the way we manufacture products. The increasing use of technologies like this will allow processes like StereoLithography to become commonplace.

### *Downstream applications*

Technology is moving so quickly in the CAD/CAE/CAM arena that several processes that are now only in the laboratory will soon be commonplace on the manufacturing floor.

An interesting process, being developed by Professor Emanuel Sachs at MIT, involves the conversion of CAD data directly into a mold to create hard tooling. This type of process is truly data driven manufacturing. In addition, the national laboratories are developing processes and technologies that will revolutionize the way we manufacture and assemble products. And other programs are underway that will use CAD data to drive milling machines and robots directly without any human intervention. These technologies will free up

people to do what we do best, innovate, while the machines take care of the more mundane manufacturing tasks.

The future in manufacturing is limited only by our imaginations.

### **Summary**

We have seen that we have come full circle in our approach to manufacturing. Concurrent engineering was in full bloom when America was young. Somehow we managed to temporarily lose that style of manufacturing, but we have learned some valuable lessons from our forefathers. What they were practicing in a physical sense face-to-face, we can achieve through modern computing not only in the same room or building but on a global scale. With the help of our major universities and colleges, we are now training our young people to be more effective team players.

Concurrent engineering, utilizing state of the art networking and solid modeling software in an NAS environment, will make us far more competitive and allow for manufacturing flexibility unparalleled in our history. With Computer Aided Engineering, we now have the freedom to be creative and play "what if" games with our geometry. We are truly limited only by our imagination.

## RESOURCES

# RESOURCES

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- Journals dedicated to desktop manufacturing and rapid prototyping
- Articles on desktop manufacturing and rapid prototyping in general
- Technical papers on photopolymers
- Articles on *StereoLithography* and 3D Systems
- Articles on Quadrax
- Articles on *Light Sculpting* and Light Sculpting, Inc.
- Articles on *SOMOS* and Du Pont
- Articles on *Selective Laser Sintering* and DTM Corp.
- Articles on *Fused Deposition Modeling* and Statasys
- Articles on *Laminated Object Manufacturing* and Helisys
- Articles on subtractive processes (NC machining)

## Industry directory

- Vendors of desktop manufacturing systems
- Developers (including former developers) of desktop manufacturing systems
- Vendors of photopolymer resins
- Partial listing of independent StereoLithography service bureaus
- Research centers
- Consultants
- Partial list of owners of *StereoLithography Apparatus* from 3D Systems

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36 West 35th Street, Suite 3C, New York, New York 10001; 212-268-1690

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# Industry Directory

## Vendors of desktop manufacturing systems

**3D Systems, Inc.**  
26081 Avenue Hall, Valencia, California 91355  
805-295-5600

**Cubital Ltd.**  
Post Office Box 330, Herzlia 46103, Israel  
971-52-529415.  
or  
23647 Ryan Road, Warren, Michigan 48091  
313-754-7557

**DTM Corporation**  
1611 Headway Circle, Building 2, Austin, Texas 78754  
512-339-2922

**Eos GmbH**  
D-8033 Planegg/Munchen, Pasingenstr. 2, Germany  
089-89-91310

**Helisys, Inc.**  
2301 205th Street, Suite 107, Torrance, California 90501  
213-782-1949

**Light Sculpting, Inc.**  
4815 North Marlborough Drive, Milwaukee, WI 53217  
414-964-9860

**Mitsubishi Machinery Division**  
1201 Third Avenue, Seattle, Washington 98101  
206-682-0744

**Quadrax Laser Technologies, Inc.**  
300 High Point Avenue, Portsmouth, Rhode Island 02871  
401-683-6600

**Sony Corporation**  
6-7-35, Kita Shinagawa, Shinagawa-ku, Tokyo, Japan  
03-448-2797

**Stratasys™, Inc.**  
7411 Washington Avenue South, Minneapolis, MN 55439  
612-941-5607

**Developers (including former developers) of desktop manufacturing systems**

**Babcock & Wilcox**  
Alliance, Ohio

**Battelle Memorial Institute**  
Battelle: 505 King Avenue, Columbus, Ohio 43201-2693  
614-424-5637

**Carnegie Mellon University**  
The Robotics Institute, Pittsburgh, Pennsylvania 15213  
412-268-7657

**Chem-Form, Inc.**  
18 West Windermere Terrace, Lansdowne, PA 19050  
215-259-7576

**Du Pont SOMOS Venture**  
Two Penns Way, Suite 401, New Castle, Delaware 19720  
302-328-5435

**Formigraphic Engine Company**  
P.O. Box 4995, Berkeley, California 94704  
415-868-1283

**Incremental Fabrication Technologies**  
1233 NW Lewisburg Avenue, Corvallis, Oregon 97330  
503-745-7739

**Landfoam Topographics**  
45 Brentwood Circle, Needham, Massachusetts 02192  
617-444-6910

**Laser Fare Ltd Inc.**  
1 Industrial Drive South, Smithfield, Rhode Island 02917  
401-231-4400

**MIT/3-D Printing Consortium**  
77 Massachusetts Avenue, Room 35-229, Cambridge, Massachusetts 02139  
617-253-5381

**Perception Systems, Inc.**  
1110 Powdersville Road, Easley, South Carolina 29640  
803-859-7518

**Vendors of photopolymer resins**

**Allied-Signal Aerospace Co.**  
Kansas City

**Ciba-Geigy Ltd.**  
Marly Research Center, Marly, Switzerland

**DSM Desotech Inc.**  
1700 South Mount Prospect Road, Box 5030, Des Plaines, Illinois 60017  
708-931-9358

**Du Pont SOMOS Venture**  
Two Penns Way, Suite 401, New Castle, Delaware 19720  
302-328-5435

**Loctite Corporation**  
705 North Mountain Road, Newington, Connecticut 06111  
203-278-1280

**Partial listing of independent StereoLithography service bureaus**

**Alpha Mold Inc.**

3488 Stop Eight Road, Dayton, Ohio 45414  
513-890-8636

**Astro Model Development**

35280 Lakeland Boulevard, Eastlake, Ohio 44095  
216-946-8171

**LaserForm, Inc.**

1091 Centre Road, Suite 270, Auburn Hills, Michigan 48326  
313-373-4400

**Laser Prototypes Inc.**

3155 Route 10, Denville, New Jersey 07834  
201-361-7666

**Magna Engineering Inc.**

85 Hill Avenue, Fort Walton Beach, Florida 32549  
904-243-6406

**Marathon Manufacturing Services**

9155 North Pennsylvania, Winter Park, Florida 32789  
407-644-3158

**Micro-Cut Engineering**

1534 Burgundy Parkway, Streamwood, Illinois 60107  
708-837-7001

**Plynetics Corporation**

1442-A Beach Street, Emeryville, California 94608

**ProtoTech Engineering**

8145 South Cass Avenue, Darien, Illinois 60559-1999  
708-971-3663

**Prototype Express**

415 West Golf Road, Suite 25, Arlington Heights, Illinois 60005  
708-640-6444

**Scicon Technologies Corporation**

26,027 Huntington Lane, Unit D, Valencia, California 91355  
805-295-8630

**SiCAM Corporation**

One Harvard Way, Suite One, Somerville, New Jersey 08876  
908-685-2211

**Technical Tools Group, Baxter Healthcare Corporation**

Route 120 & Wilson Road, Round Lake, Illinois 60073-0490  
708-270-4050

**J.H. Young Company, Inc.**

8 Symington Place, Rochester, New York 14611  
716-235-7698

**Research centers**

**Carnegie Mellon University** (Fritz Prince, Lee Weiss)  
The Robotics Institute, Pittsburgh, Pennsylvania 15213  
412-268-7657

**Massachusetts Institute of Technology** (Emanuel Sachs, Michael Cima, James Cornie)  
Laboratory for Manufacturing and Productivity, Room 35-229, 77 Massachusetts Avenue,  
Cambridge, Massachusetts 02139  
617-253-5381

**University of Dayton** (Allan J. Lightman, Richard P. Chartoff)  
Rapid Prototype Development Laboratory, 300 College Park, KL-465, Dayton, Ohio 45469  
513-229-2966

**University of Louisville** (Tim Gornet)  
Louisville, Kentucky

**University of Texas at Austin** (Joseph J. Beaman, Harris L. Marcus, Joel W. Barlow)  
Mechanical Engineering Department, ETC 5.160, Austin, Texas 78712-1063  
512-471-3089

**Consultants**

**Albert Consulting Group**

Post Office Box 2085, Saratoga, California 95070  
408-464-0600

**Design Insight (Peter Marks)**

336 Village Lane, Post Office Box 37, Los Gatos, California 95031-0037  
408-395-4001

**Ennex Technology Marketing, Inc. (Marshall Burns)**

825 West Eleventh Street, Suite One, Austin, Texas 78701  
512-860-2220

**F Cubed (Adam Lloyd Cohen)**

10,717 Wilshire Boulevard, Suite 802, Los Angeles, California 90024  
213-470-0955

**KMR Engineering (Keith M. Rudofsky)**

3868 Carson Street, Suite 300-1, Torrance, California 90503  
213-543-1162

**Wohlers Associates (Terry T. Wohlers)**

1511 River Oak Drive, Fort Collins, Colorado 80525  
303-225-0086

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