SOLID FREEFORM FABRICATION

a new manufacturing paradigm
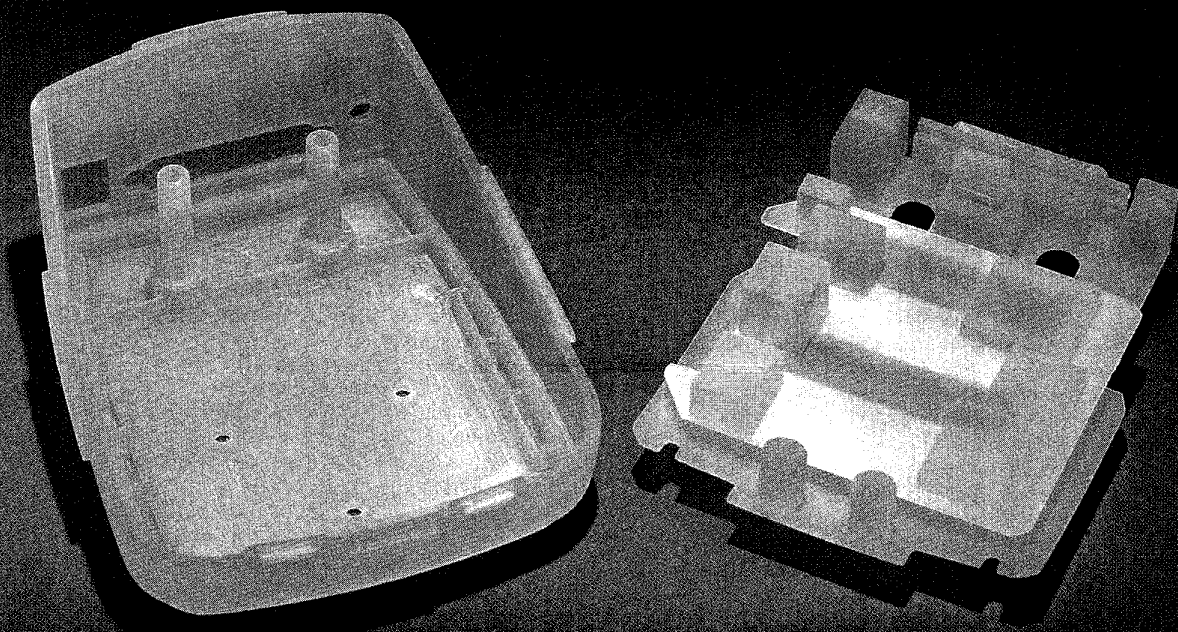
[1] A physical mockup of a hand-held laser scanning system was produced by stereolithography, one of several solid freeform fabrication (SFF) technologies. The model includes a a plastic housing [left] and printed-circuit board with electronic components [right].

SITTING AT A COMPUTER, a designer has just completed a rendition of an exotic shape for an equally exotic application or artistic object. It is now time to create the real thing. She clicks on the hard copy command, and minutes later the object materializes beside her desk. Is this the manufacturing environment of the future?

This dream portrays an ideal method of manufacturing, one in which a part, component, or entire subsystem would be designed electronically, relying on the power of present computer-aided design (CAD) systems and then output immediately at a push of a button. Though it may seem fanciful, the method is reminiscent of a well-established concept, desktop publishing, in which print and graphics are laid out on a computer and automatically printed by dot matrix, ink jet, or laser printers.

In many ways, printing is a good two-dimensional analogy of three-dimensional manufacturing. Lettering or drawing by hand is analogous to low-volume manual manufacturing methods using standard machines and tools. Offset printing is analogous to high-volume automated manufacturing using specialized machines. Desktop printing, however, lacks an analogy in present manufacturing. While it does not compete with offset printing for large numbers of copies, it is eminently practical for small numbers. Its analogy is with an up-and-coming area of manufacturing under development for several years at the Massachusetts Institute of Technology, Carnegie Mellon University, and The University of Texas at Austin, among other places. Researchers here in Austin have been working on technologies termed solid freeform fabrication (SFF) or, as reported in the popular press, desktop manufacturing, rapid prototyping, and layered manufacturing.

Such processes have the potential to produce accurate, structurally sound 3-D renditions of objects designed with computers and manufactured directly from a CAD database, without part-specific tooling or human intervention, and to make them available to the user in minutes or hours [Figs. 1 and 2]. The benefits include greatly reduced prototyping cost and design time and the ability to achieve, in one operation, shapes that would otherwise require multiple operations or in some cases be impossible to produce with standard techniques.

Automated manufacturing technologies in general are well suited to large production numbers, but ill suited to low-volume runs. In the latter case, the components are too few to adequately amortize the cost of part-specific tooling; instead, they are typically made by hand at much greater unit cost and longer completion times. Nor is it a completely desirable low-volume option to interface CAD systems with numerically controlled (NC) machining centers—in essence, computer-controlled material removal systems—because so much human intervention is involved in producing NC programs and setting up and supervising NC systems. In fact, the low-volume production arena is exactly where SFF slashes cost and time to completion. Obviously,

too, these new manufacturing technologies fit well into computer-integrated manufacturing environments.

Development cycles for complex systems can be dramatically shortened by desktop manufacturing, which breaks the bottleneck between model-making and prototyping. In addition, the geometric information about a part's shape that can be captured digitally in a CAD database can alternatively be transmitted over telephone lines, radio signals, and by satellite. Coupling this information with an SFF machine may make large inventories a thing of the past by enabling parts to be produced on demand in remote locations or allowing replacement parts to be produced on the spot. Again, couple this solid freeform fabrication technology with modern 3-D digitizing techniques in which geometric information on existing parts can be scanned with lasers or X-rays and captured, and the means to create 3-D copy or fax machines is at hand. In fact, a 3-D fax was implemented for the first time in August 1991 in Austin, Texas, when a part was digitized at Scientific Measurement Systems Inc., an Austin-based technology company that manufactures high-power X-ray scanning systems. The data was then sent over telephone lines to the Laboratory for Freeform Fabrication at The University of Texas, in Austin, where a selective laser-sintering system was used to recreate the part.

Different processes

Today, about 30 technologies address the rapid creation of models, prototypes, patterns, and limited manufacturing runs. Many SFF methods are based upon layered manufacturing. In this approach, a computer representation of an object's geometry is decomposed into slices of 2-1/2 dimensional information. A slice is a planar cross-section of an object with an associated small, but finite, thickness. During processing, each slice is physically deposited and its interior is fused to the previous layer to create an object sequentially. While a slice's interior region demarcates the geometry of the object, its exterior also serves an important function in SFF technologies. In most processes, it becomes a structure that serves as an implicit fixture for the part as well as a supporting matrix upon which regions that occur in overhangs can be constructed. The overhangs require this support since they are not joined with the main body until subsequent layers are deposited.

A layer's support areas are handled in distinctly different ways by many of the process methods. In some,

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Defining terms

Fused deposition modeling (FDM): a solid freeform fabrication (SFF) process in which a thermoplastic precursor material is heated and extruded from a head carried on an XYZ table to produce a three-dimensional part.

Laminated object manufacturing (LOM): an SFF process in which one sheet after another of precursor material are made to adhere to each other, forming the layers of a part. Areas of a layer not included in the part contour are cross hatched with a laser for eventual removal.

PCMCIA card: a credit-card-sized memory or I/O device that fits into a PC, usually a notebook or laptop computer. A common example is a modem for notebook computers.

Selective laser sintering (SLS): an SFF process in which powder is deposited in a thin layer and scanned with a laser, so that powder particles adhere to one another and harden in selected regions of the layer. The layering process is repeated until the part is completed.

Shape deposition modeling (SDM): an SFF process that combines additive and subtractive processes. First, a layer of material is deposited as molten droplets, as in laser welding, and is then milled using a numerically controlled milling machine, to ensure dimensional accuracy. The part is built up in a series of these two-step operations.

Solid freeform fabrication (SFF): any method of manufacturing solid mechanical parts without part-specific tooling or human intervention. The version called layered manufacturing is based on additive processes that build parts in layers. Rapid prototyping (RP) emphasizes speed and the initial applications of the technology, while the newer rapid prototyping and manufacturing (RP&M) stresses applications that result in functional parts, rather than models.

Stereolithography: an SFF process in which an ultraviolet laser selectively radiates a vat of photopolymer, which then hardens in a thin layer in desired areas. The part is built on a platform that is lowered in the vat sequentiallly, to make successive layers. A workstation based on this process is referred to as a stereolithography apparatus, or SLA.

STL format: a data format first created for stereolithography.

3-D printing: a powder-based SFF process in which layers are selectively scanned by a head that deposits a binder in the powder bed. Subsequently, the surplus binder is removed and the part made denser.

Tooling: the jigs, fixtures, dies, and molds used to shape mechanical parts. Most conventional manufacturing processes require special tooling based on the shape of the part to be manufactured, hence the term "part-specific tooling."

Two and one-half dimensional, or 2-1/2 D: a two-dimensional planar contour extruded in the third dimension to produce a solid.

explicit support structures use the same material as the object being formed, but are deposited in such a way as to be easily removed, usually manually. In others, the entire exterior of the slice becomes a sacrificial portion of the layer that is subsequently removed and discarded or recycled; often, the support material is different from the part material and can be can selectively removed by dissolution, melting, or etching. Still other process methods use base materials that are the same as the part but are in a powder form that intrinsically supports the part while remaining removable.

Solid freeform fabrication technologies use a computer graphic representation and simple stock material (powder, liquid, gas, sheets, and so on) to fabricate complex parts. Photopolymer systems build shapes using light to selectively solidify liquid photocurable resins. A number of other systems prefer powders as their stock material. Some examples of powder-based techniques are selective laser sintering [Fig. 3], 3-D printing, and 3-D laser cladding. Lamination systems operate with a variety of feedstock from paper sheets to metal plates. SFF deposition techniques include extrusion, ink-jets, 3-D welding, gas, and plasma spray [Table 1].

The capabilities and costs of SFF processes are rapidly changing. Currently, SFF workstations cost between US $50 000 and $500 000. Workstations such as those from Z-Corp and Stratasys are on the low end of that spectrum, while larger workstations from 3D Systems and DTM Corp. tend toward the high end of the range. Parts made by service bureaus average $1000 to $2000, depending on part size, material, and process. The average build volume for SFF workstations is a cube of about 250 mm on a side. Accuracy and surface roughness vary widely, depending on the particular SFF technology and precursor material. Typical numbers for dimensional errors are 25 μm to 380 μm. Surface roughness varies with the orientation of the part for layer-based techniques. The best reported surface roughness is about 100 nm on a top surface, and about 170 nm on a side surface (assuming a vertical build).

Contrast this with computer numerically controlled (CNC) milling, which can easily produce parts with dimensional errors in the range of 13 μm and surface roughness of 400 to 800 nm. While CNC offers an order of magnitude improvement in the accuracy of the part, the required accuracy of the part

must be weighed against the time savings offered by SFF. Many examples are reported in the literature that document six- to eight-week savings in lead time compared to conventional manufacturing processes. This leads to thousands of dollars in savings over the design cycle of a product.

Many applications

If it is true that a picture is worth a thousand words, then a physical model is worth a thousand pictures. When designers employ the latest 3-D CAD systems, they see and understand the physical nature of their work-in-progress in ways unimaginable in the world of orthographically projected 2-D drawings. Yet these 3-D CAD objects remain only abstractions, virtual representations of yet-to-be-realized artifacts, because their world is without gravity, friction, or relational scale. The virtual models viewed within this environment routinely defy the laws of physics, require interpretation, and can engender a false sense of certainty in the design team.

In contrast, by using the rapid capabilities of solid freeform fabrication, people of all disciplines can use their senses of sight and touch to thoroughly communicate and understand the basic mechanical implications of numerous design solutions. Many product development companies are realizing the benefits of solid freeform fabrication prototypes, as the following case studies show.
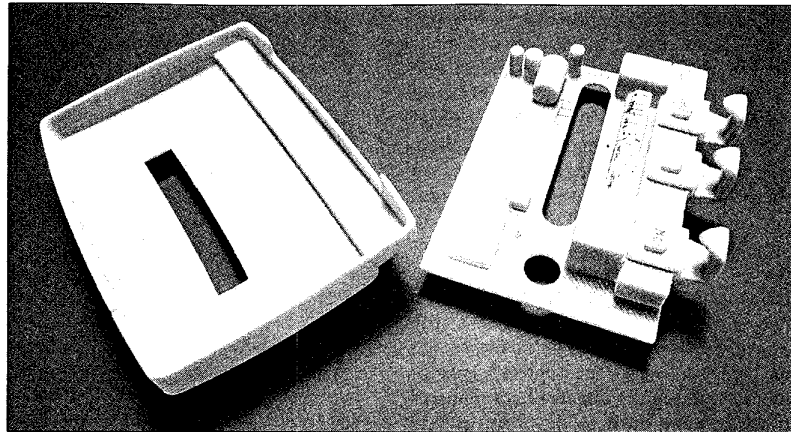
Integrating electronic and mechanical design

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ne of the hardest-to-communicate aspects of a product development effort is the integration of electronic components into a mechanical system. Design Edge Inc., a product development firm in Austin, Texas, employs solid freeform fabrication to help bridge the gap between electrical engineers, who use 2-D CAD, and mechanical engineers and industrial designers, who use 3-D CAD. The CAD tools of these disciplines differ not only in the number of dimensional axes (3-D vs. 2-D) but also often cross computer platforms. Complicating things further, the

design activity of these two disciplines can be located far apart, even when the groups are within the same organization.

A 2-D board outline drawing, provided by a mechanical engineer, is the formal mode of communication with the electrical engineers responsible for the layout and component selection of printed-circuit boards. The drawing describes the dimensions of the board and provides a sort of map of it, to dictate the allowable physical dimensions of an electronic component's location. The creation of this outline drawing is a give-and-take exchange between the board designers and the mechanical designers. In the process, an electrical engineer, in an effort to meet electromagnetic interference or thermal goals, may wish to position connectors or other components on the circuit board in a location the mechanical design team has deemed off limits. Conversely, the mechanical team may be trying to reduce the package size or to meet a stylistic goal that might require moving electrical components from their electronically desired locations. In either case, it is difficult for a team stuck with the traditional 2-D or 3-D CAD tools to see if a compromise may be reached.

Solid freeform fabrication can vastly improve design communication between disciplines with conflicting design goals. The physical model, or perhaps multiple models in far-flung locations, is excellent as a common tool with which to discuss and mediate a design concept's potential

[2] Selective laser sintering was used to create these mockups of a thermostat's housing [left] and printed-circuit board [right]. The models help designers identify and resolve potential mechanical, and even electrical, interference problems early in the design cycle.

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1. Some solid freeform fabrication methods

Paper, plastic, or ceramic sheet	Laminated object manufacturing (LOM)	Helisys Inc., Torrance, Calif.	Uses a laser to cut cross sections out of sheets of paper, plastic, or ceramic.
Metal or silicon powder	Selective area laser deposition (SALD)	University of Connecticut	Uses a laser to excite a gas precursor material to deposit solid material. (At research stage)
Semi-fluid thermoplastic	Fused deposition modeling	Stratasys Inc.,[1] Eden Prairie, Minn.	Extrudes a semi-fluid thermoplastic through a nozzle, which scans cross sections of a part to form a model.
Weld-based metals	Shape deposition manufacturing (SDM)	Carnegie Mellon University, Pittsburgh; Stanford University, Palo Alto, Calif.	Deposits "weld-based" metals or other materials to form layers, then uses numerically controlled machining to level layers and finish outer surfaces. Supports are created out of sacrificial materials. (At research stage)
Photoreactive polymer resin	Stereolithography apparatus (SLA)	3D Systems, Valencia, Calif.	Uses a laser to selectively cure photoreactive polymer resin in a vat. The part is created layer by layer on a platform that is lowered into the vat after each layer is cured, so the next layer can be cured.
	Solid ground curing	Cubital Ltd., Raanana, Israel	Selectively cures a layer of photoreactive polymer resin with a mask and ultraviolet lamp, then removes uncured resin from the layer and adds wax to fill in gaps in the cross section. The wax is milled level and resin is introduced into the chamber for the next layer.
		Formigraphics Engine Corp., Berkeley, Calif.; Battelle Institute, Columbus, Ohio	Cures a photoreactive resin at a point by means of two intersecting lasers
Powder	3-D printing	Z Corp.,[2] Somerville, Mass.	Selectively applies binder material through an ink-jet print head to a layer of powder, so as to glue it together into a cross section.
	Selective laser sintering (SLS)	DTM Corp.,[3] Austin, Texas	Melts powder particles together with a laser to form part cross sections.

[1] Developed under NASA Rapid Prototyping program.
[2] Technology licensed from the Massachusetts Institute of Technology.
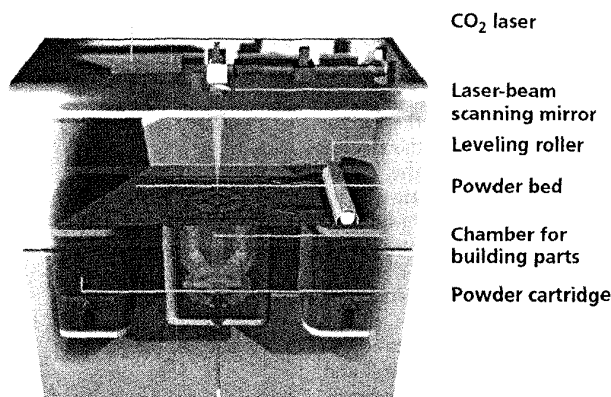[3] Technology licensed from the University of Texas at Austin.

mechanical and electromagnetic interference issues. Physical models of circuit boards, with the significant electronic components represented, help to visualize design challenges. A physical model assists all the parties in exploring, feeling, and seeing their mechanical impact on the system in a way that electrical designers working in 2-D CAD may find hard to visualize. SFF enables mechanical designers to create more accurate volumetric criteria in the board outline drawing because it lets them test their designs in a true physical space. Also, beyond the design of the circuit board, the approach is helpful in exploring the effects of components that are very hard to describe in 3-D CAD, such as flexible cables and wire harnesses. This is done by having the designers mock up flat designs of flexible cables or by routing actual wire assemblies into the freeform physical model with their own hands.

Thanks to the rapid modeling techniques available today for solid freeform fabrication, modifications to these designs can be made quickly and assessed in the most effective manner. The models are often created overnight. Design Edge

CO$_2$ laser

Laser-beam scanning mirror

Leveling roller

Powder bed

Chamber for building parts

Powder cartridge

DTM CORP.

[3] In a typical selective laser sintering process, a laser beam fuses particles of powdered plastic, metal, or ceramic to build a three-dimensional object, layer by layer, in a chamber. The beam is activated in accordance with 3-D computer-aided design data of the object's geometry.

uses prototype services, which can quickly provide models from its 3-D computer files of component parts. These prototyping services supply physical prototypes made with selective laser sintering (SLS) or stereolithography apparatus (SLA), and employ fast Internet file-

transfer protocol (FTP) file exchange methods to speed the communication process. The cost of these services varies with the quality of finish desired and with turnaround times. In a time crunch, it is not uncommon for Design Edge to have the prototypes created overnight

NIST 's support of rapid prototyping standards

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Recent activities and interactions with industry have suggested to the National Institute of Standards and Technology (NIST) that formal standards for rapid prototyping could stimulate the growth and advancement of the technologies involved. Standards could provide common methods for measuring the benefits and limits of rapid prototyping. They could also hasten the transfer of rapid manufacturing capabilities still in the research laboratory to commercial products.

Existing standards related to rapid prototyping (RP) are primarily informal or "industry" standards. For example, the STL format—the data format originally created just for the stereolithography process—has become a de facto industry standard for the interface between computer-aided design (CAD) systems and all RP processes.

In addition, what came to be known as benchmark parts were created by organizations wishing to evaluate various RP processes—companies like DuPont and Kodak, as well as the National Center for Manufacturing Sciences. These benchmark parts are viewed as informal standards for the rapid prototyping industry.

Some formal standards also exist. In the

United States, the first organization to initiate them for this field was the American Society for Testing and Materials (ASTM), headquartered in West Conshohocken, Pa. The ASTM Subcommittee E28.16 on Rapid Prototyping has addressed mechanical testing standards for evaluating the tensile strength of RP parts.

Then in October 1997, the NIST Manufacturing Engineering Laboratory hosted a workshop in Gaithersburg, Md., to assess industry needs for RP standards. The workshop participants proposed four areas of standards development: a methodology for evaluating RP system performance; a methodology for measuring RP parts; improvements in the STL-based data interface between computer-aided design and rapid prototyping; and development of an alternative to that data interface, for future use, to be known as the Solid Interchange Format (SIF).

Existing benchmark parts are typically process-specific, user-specific, or not comprehensive enough to provide meaningful comparison across multiple RP systems or applications. Participants in the NIST workshop therefore proposed a new approach to evaluating RP system performance, one based upon a standard library of three-dimensional part features—spheres, cylinders, prisms, and

cones, for example. The part features would be built and measured in a standard way, in a variety of sizes and orientations. Selected "real-world" parts (possibly from existing benchmark parts) would supplement this approach.

Current techniques for measuring parts produced by RP processes are no different from those for measuring machined parts. But measurement issues specific to rapid prototyping, due mainly to the parts' layered nature, are typically ignored. Issues such as contact versus non-contact inspection methods, the types and sizes of inspection probes, and the number of measurements needed for an acceptable confidence level would be addressed in a standard methodology for RP part measurement.

As for the STL data format, it defines an approximation of the desired part shape through a collection of triangular planar surfaces, called facets. Due to its simplicity and support by all major CAD vendors, the STL data format will continue to serve as the de facto standard CAD/RP data interface for years to come. The limitations of STL, however, are substantial. The format specifies redundant data; contains no knowledge of topology, critical features, or materials information; and limits the accuracy of resulting parts.

and delivered the next morning, counter to counter, by an airline package service. Although it may seem expensive to the uninitiated, the numerous iterations of physical models cost far less than do the mistakes, missed opportunities, and under-optimized designs that can be avoided by physical model reviews.

When Honeywell Inc., Minneapolis, Minn., asked Design Edge to develop a huge volume of thermostat devices for the Asian market, the design had above all to be refined and optimized to meet: the small package size required, production volumes of approximately 100 000 units per month, very low component costs, and a long production life. These requirements led to a very close integration of the mechanical and electrical teams. Both SLA and SLS physical models were used to review and explore early design concepts [again, Figs. 1 and 2]. Printed-circuit boards and their electronic components were modeled into the CAD assemblies and refined to help meet assembly, electrical design, and board panelization goals. Without the aid of physical models early on and regularly through the design process, the communication and verifica-
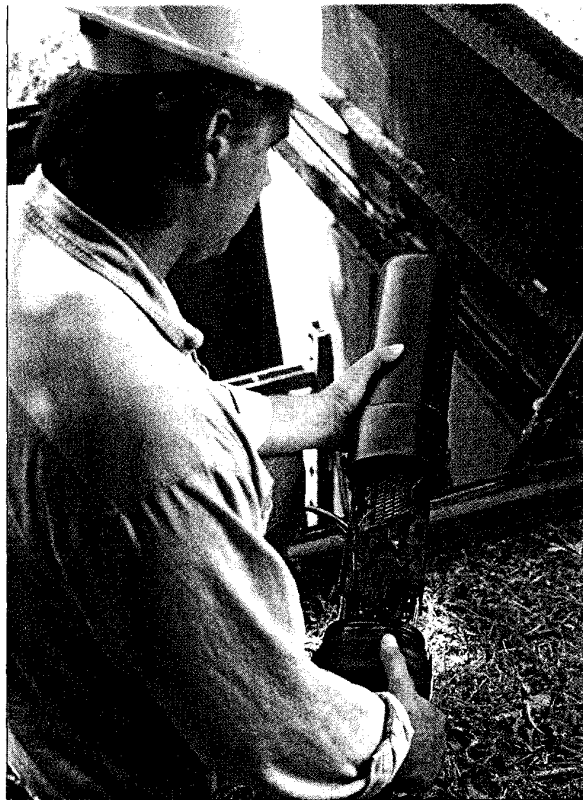
[4] After evaluating several prototypes using solid freeform fabrication technology, engineers with 3M Telecom Systems Division, in Austin, Texas, developed this protective housing—the FibrDome—for optical-fiber cables.

3M

Also, its use commonly results in data truncation errors, gaps between adjacent facets, and incorrect facet intersections. Participants in the NIST workshop made specific suggestions for improved use of the format and proposed that an industry-based group work with RP and CAD vendors and RP users to provide a mechanism to modify and extend the format.

Given the shortcomings of STL and recent advances in RP capabilities, several organizations have been pursuing an alternative format, called the Solid Interchange Format (SIF), to serve as a CAD-to-RP data interface in the future. Contributors from the University of Michigan, the University of California at Berkeley, Rensselaer Polytechnic Institute, and others have proposed various SIF requirements, content, and structures for consideration by the RP research community.

So far, the format remains a research topic, with no consensus solution or commercial availability. It will be based upon a precise, mathematical representation of the part geometry. Moreover, it will accommodate capabilities expected of future layered manufacturing systems, including the use of multiple materials, gradient material properties, nonplanar build layers, explicit fiber directions for composite materials, color specifications for the parts, and embedded foreign components.

Those at the NIST workshop favored continued development and prototypes of SIF and requested NIST's assistance in facilitating coordination and collaboration among the efforts.

NIST activities in the area of RP standards include: serving as standards "advocate" to encourage further industry discussion and interaction; facilitating the development of and industry consensus on specific needs and requirements; and collaborating with industry partners to develop proposed technical solutions for identified standards needs. One research effort at NIST is an evaluation of the Standard for the Exchange of Product Model Data (STEP, formally known as ISO 10303) for possible applicability to the upcoming Solid Interchange Format.

Meanwhile, there is pressure to move forward. The need for formal rapid prototyping standards is growing even more pronounced as new applications and system improvements, as well as companies entering the industry, are announced with seemingly increasing frequency.

Typical electronics applications include prototyping mechanical housings for components, creating conformal cooling channels within the complex surface of a structural material to meet heat transfer requirements, and integrating embedded electrical components while a product is being fabricated.

In addition, the Defense Advanced

Research Projects Agency recently announced some efforts in the area of Mesoscopic Integrated Conformal Electronics (MICE). The agency proposes to use RP technologies to develop rugged, miniature electronics in the so-called mesoscopic or "middle" regime of millimeter-to-submillimeter part sizes as well as assemblies that integrate both passive and active components.

Obviously, the recommendations and proposed standards activities that arose from the NIST workshop of October 1997 represent only a small sample of the rapid prototyping community's thinking. Further discussion and consensus is required to move these efforts forward.

After all, strong industry participation is vital to the success of any standards effort. *IEEE Spectrum* readers may submit their views and provide feedback to help guide future efforts for RP standards.

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tion of concepts would not have been as effective. The product is now successfully up and running in full production in the People's Republic of China.

Symbol Technologies Inc., Holtsville, N.Y., gave Design Edge a contract to create a hand-held laser scanning system with strict ergonomic, functional, and cost requirements. Because of the organic form of these highly integrated components, it was all but impossible to visualize the implications of component placement strategies without a physical model review. Design Edge tested various electronic layouts in physical model form in order to develop and optimize flexible circuits, connector placements, and switch locations. The speed of obtaining solid freeform models enabled the team to refine the design many times over without holding up the extremely aggressive schedule.

When modeling electronic components and circuit boards in 3-D CAD, mechanical designers can either represent the topographic boundaries indicated in the board outline drawing, or they can create libraries of key electronic components and actually place them on the board in the desired locations. The electrical and mechanical teams must work together closely to be sure that the 3-D CAD mechanical representation of the electrical layout is accurate.

A new method of ensuring accuracy is the mechanical design package that can read the data from an electrical layout program and automatically create a 3-D CAD file as the electrical engineer has designed it. This can now be undertaken by an E-CAD software module called Pro/Engineer, from Parametric Technology Corp., Waltham, Mass., which works with electrical layout programs such as Allegro. To profit from this capability, a 3-C CAD library, tied in with both the 3-D CAD program and the electrical layout design program, must be created and maintained. With CAD tools like these in place, organizations can exploit solid freeform fabrication further, to represent their current design thinking in a faster and more accurate fashion.

Reduced time-to-market and higher quality

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With the growth of the Internet, the demand for bandwidth from the home has soared. To handle the demand quickly, local telephone companies and various other communication providers need to upgrade much of their networks from copper wire to glass fiber. One of the elements vital to this development is a low-cost housing to protect the optical-fiber cable splices from the outside environment. The 3M Telecom Systems Division, Austin, Texas, responded by starting the FibrDome project. From the beginning, the project team understood that a short product development cycle was critical for success. They determined that the best way to reduce cycle time was to use solid freeform fabrication to quickly generate prototypes for design evaluation.

The FibrDome Closure system consists of a sealed, external housing to protect the fiber splices, plus a fiber management system that organizes the fibers without damage [Fig. 4,]. As the external housing had already been developed, the team focused on the fiber management system, which had to store up to 96 splices in four separate trays, and had to include a spare tray for slack fiber storage. However, the most challenging requirements were that the fiber could not be bent with a radius less than 38 mm at any time, and any fiber splice must be accessible without disturbing the other fibers.

Once the design process started, SFF prototypes were used for five purposes: customer presentations, design form and fit tests, functional tests, product installation tests, and supplier communication. For customer presentations, a 3-D representation communicates better than a design on paper and is a good way to impress customers with responsiveness. For example, after one FibrDome presentation, the customer concerned requested several design changes that other processes would take weeks to prototype. The team quickly made the changes on the 3-D computer model, generated a new SFF prototype, and showed the delighted customer the updated model just a few days after the initial request.

Solid freeform fabrication prototypes are an excellent means of checking for interference problems with mechanical designs. In an earlier design, interference occurred at the hinge when two of the splice trays were pivoted. A feature on one tray was flexing more than expected and it was hitting the other tray. To identify the exact interference, the hinge area was modeled at four times actual size [Fig. 5]. These prototypes helped the team identify the exact nature of the problem, and it was rectified easily and quickly.

For most of the prototypes for this project, the stereolithography process was used because of its finish, dimensional accuracy, and cost. Nonetheless, in one instance the part needed to be tested functionally, to determine whether it conformed around an optical-fiber cable. As luck would have it, the strength and flexi-

bility of the SLA polymer were inadequate. For this reason, the selective laser sintering process was employed because it could create the part using a structural polymer, such as polycarbonate. In this case, the prototype showed the design was not feasible and it was dropped, obviating much wasted time and effort.

SFF parts were invaluable for testing the fiber installation procedure [Fig. 6]. With standard techniques, the prototypes would have been impossible to create. Approximations would have been made and in all likelihood mistakes would have occurred. With accurate representations, problems with fiber splice installation were quickly caught and rectified. The benefit that is usually overlooked is the improved communication between designer and supplier. Before the supplier started the design of the production injection molds, the FibrDome team delivered prototypes of the product design. With a visual representation, the supplier eliminated the mistakes common with misinterpretation of the computer files. In this case, the injection molds worked the first time.

The use of solid freeform prototypes was truly a tremendous success for the FibrDome project. The team estimates that the product development cycle time was decreased by at least 25 percent because of these prototypes, which are now standard for all 3M Telecomm Systems Division projects.

Medical and prosthetic applications

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Engineers were the first group to embrace solid freeform fabrication, in their case to increase productivity. Now the SFF technology is finding its way into other disciplines where 3-D models offer advantages. Many examples of the use of solid freeform models as surgical planning tools have been reported, particularly in the last two years or so. Surgeons planning difficult operations have many of the same problems that design engineers face.

Medical imaging, including computed tomography (CT) scanning and magnetic resonance imaging (MRI), is commonly used to help physicians visualize problem areas in patients. But the technologies suffer from many of the same shortcomings as the 3-D graphics used in CAD: the projection of 3-D objects on a 2-D

screen, requiring abstract interpretation. Worse yet, noise is present in the data, as medical imaging relies on processing sensor signals rather than the relatively noise-free input from a keyboard and a mouse that CAD designers use.

Even so, many doctors find that 3-D models of CT or MRI data allow them to study subtle features that are difficult to detect otherwise. The result is better pre-operation planning. The models are also useful in explaining procedures to patients, for training physicians, and for practicing difficult techniques. The results are that surgeons carry out operations more accurately, with more confidence, and in less time, all of which benefit the patient tremendously.

Solid freeform biological parts

While the applications described above produce models, much ongoing research into this technology focuses on searching for new processes and material systems that will allow the creation of functional parts. One promising area of application is fabrication of replacement biological parts, whose complex shapes are well served by solid freeform technologies. Research at The University of Texas at Austin is focused on the selective laser sintering (SLS) process and the development of biocompatible material systems that can be processed with SLS. In particular, a new material system has been created for fabricating bone implants.

The process for developing bone implants uses a calcium phosphate powder that is coated with poly-methylmethacrylate (PMMA) in a spray dryer. The PMMA acts as a binder. During the SLS process, the PMMA coating is melted by the laser and binds the calcium phosphate particles to form a "green" part—a part that has not reached its full strength or density. (The term derives from the color of ceramic parts prior to their firing in a kiln.) Laser power, scan speed, scan spacing, and powder bed temperature are carefully controlled to optimize green part strength. The SLS-fabricated green parts are subsequently infiltrated with a calcium phosphate solution, fired in a furnace to remove the PMMA binder, and then fired at higher temperature to sinter the calcium phosphate powder.

Preliminary studies in animals have been carried out at BioMedical Enterprises Inc., San Antonio, Texas. One set of studies involved oral implants in dogs. Radiograph images taken four weeks after implantation showed a high degree of biocompatibility and bone ingrowth. The results suggest that, in time, the specimens would be completely filled with mineralized bone.

Embedded electronics

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Shape deposition manufacturing (SDM) is a solid freeform fabrication process originally intended to unite the advantages of geometry decomposition and material addition with the advantages of processes for removing materials [Table 1]. In this method, individual segments of a part and of support material structure are deposited as near net-shapes (nominal shapes as designed) and then machined to net-shape before further material is deposited and shaped.

The rapid prototyping of complex shapes is clearly possible and, so, too, are the use of selective additive material processing to fabricate structures from several materials and the embedding of prefabricated components within the growing shapes. For example, an embedded electronic device can be fabricated by building up a nonconductive housing package and simultaneously embedding and interconnecting electronic components within the housing.

The approach lends itself to producing compact, rugged, customized computer modules in small lots. In particular, it suits such military and industrial applications as manufacturing mission-specific, conformally shaped "smart" devices—wearable computers are an example. These last might store maps or equipment descriptions, help to log data, or provide communication links.

The Frogman is a waterproof computer built with SDM that can store maps for navigational aids or detailed assembly drawings for service, maintenance, or field operations. The graphical information, which is stored on PCMCIA cards [see Defining Terms, p. 36], is displayed on a heads-up display. A conformally shaped rear surface is also required so that the unit can be comfortably strapped to a diver's leg.

The unit is built up in layers of polyurethane and sacrificial wax. The former is deposited as a two-part thermoset. The wax can be extruded with a conventional hot-glue gun, or thick layers can be poured from a hot-melt pot. The important points are that custom tooling is not required to manufacture the Frogman and that embedding facilitates waterproofing.
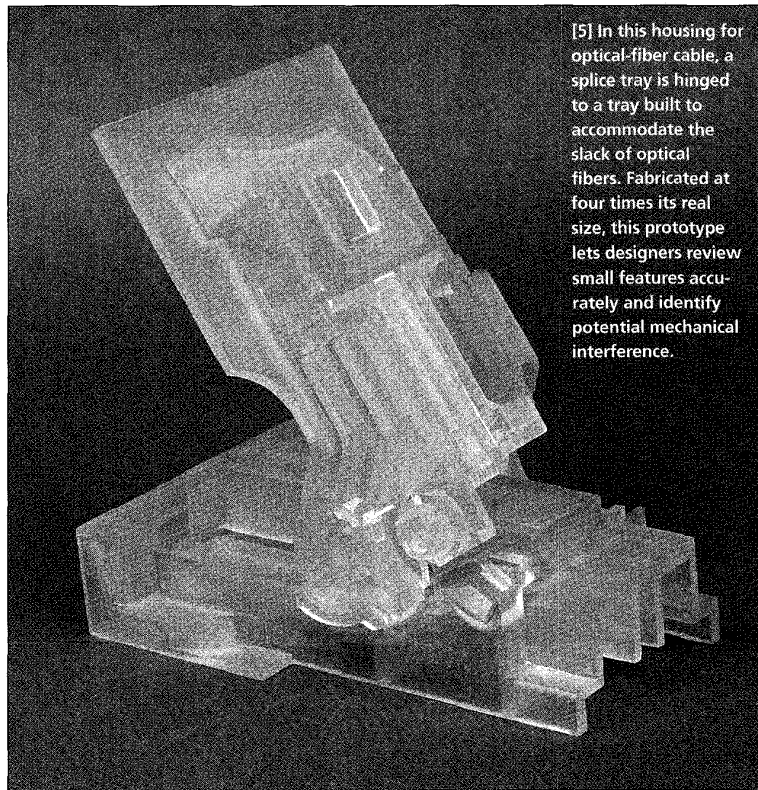
[5] In this housing for optical-fiber cable, a splice tray is hinged to a tray built to accommodate the slack of optical fibers. Fabricated at four times its real size, this prototype lets designers review small features accurately and identify potential mechanical interference.

The company is developing this material in the hope that it will one day be approved for use in humans. Imagine a scenario in which, say, a patient suffers an injury to the left jaw. Today, oral surgeons sculpt a replacement implant by hand out of a bone replacement material. The implant serves as a scaffold upon which the body rebuilds the original bone. Soon, however, it may be possible to scan the right jaw, reflect it, and create a custom implant automatically.

Customized prosthetics

Medical researchers are also developing methods for applying solid freeform fabrication to prosthetics. At the Department of Rehabilitation Medicine at The University of Texas Health Science Center in San Antonio, a process has been developed for manufacturing custom prosthetic sockets for below-the-knee amputees. The residual limb is first digitized with a high-speed laser scanner. An interactive CAD system then processes the data and allows a skilled prosthetist to modify the geometry to improve its fit, its comfort, and the stability of the socket. The CAD data are then transmitted to a CNC milling machine, which mills a plaster mold. Finally, the plastic socket is vacuum formed using the mold.

The current process is faster than the standard manual approach of making a plaster cast of the residual limb. Still, researchers hope that, using solid freeform technologies, prosthetic sockets can be produced directly from the CAD data, eliminating the mold fabrication step. The San Antonio group has collaborated with DTM Corp. in Austin, Texas, to fabricate a nylon socket using the SLS process.

One advantage of using SLS is that the fitting for attaching the leg pylon to the socket can be built as part of the socket. Currently, fittings are attached mechanically to sockets, and they require extensive alignment for each patient. The integral socket fitting can potentially include the patient's specific alignment characteristics, resulting in a better product.

The San Antonio group is now collaborating with researchers from The University of Texas at Austin to develop sockets with locally variable mechanical properties. Such a socket would have areas of relative compliance to increase comfort near pressure points, and other areas of relative stiffness to improve the socket's load-bearing capability and stability. The goal is to allow prosthetists to design and fabricate sockets completely from computer data, with manual intervention.
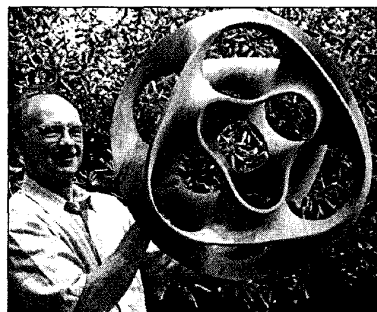
[7] Intricate 3-D geometrical shapes can be generated using solid freeform fabrication technology. Artist Brent Collins is shown with the first wood sculpture he made jointly with Carlos Séquin and the special program Séquin developed.

Rapid prototyping of geometric sculptures

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t is hard to make a sculpture that looks good from every side. Conceptual flaws often cannot be corrected when discovered during the actual sculpting. Even an artist excellent at 3-D visualization will make a 3-D mockup to judge the look of the intended shape from all possible angles and to ensure that potential weaknesses in presentation from a particular side have not been overlooked. The creation of the final physical artifact demands a firm commitment in time and energy, and the dedicated artist wants to make sure that it is expended toward a promising goal.

For more than a decade, artist Brent Collins of Gower, Mo., has been creating abstract geometrical wood sculptures. Many are highly organized assemblies of saddle shapes that seem to flow into one another and terminate in rims that form intriguing patterns and complicated knotted space curves. The internal saddle shapes often are close to minimal surfaces—the kind formed by soap films spanning a curved wire frame—even though Collins heard of that concept several years after his first sculpture of this type.

To construct this complicated shape, Collins first devises a skeleton of the basic topology using polyvinylchloride

pipe sections and embroidery hoops. This he covers with wire meshing and beeswax, which in turn he molds smoothly to the most desirable shape. The prototyping can take several weeks, and often several attempts have to be made before a shape is found worth executing in wood—a process that will take another few months.

In 1995, after many conceptual exchanges over the phone, author Séquin started to develop a custom program to generate shapes that hewed to the particular flavor of Collins' recent artwork. The idea was to greatly extend this family of shapes to a level of complexity that Collins' prototyping process simply could not handle. The parameterized sculpture-generator program was fine-tuned for producing and displaying virtual prototypes for this special class of geometric sculptures. The shapes are displayed fast enough for enjoyable interactive exploration, but realistically enough that the viewer can properly judge the quality of the resulting geometry. From a menu, the designer selects the basic shape (tower or ring) and then adjusts a variety of parameters interactively to obtain an artistically interesting and pleasing configuration. With this medium it is easy to explore a vast space of possible shapes, to concentrate on promising topologies, and then to fine-tune a particular shape to perfection—all in a matter of minutes! Figure 7 shows an example generated by the program.

The author's program can also output the boundary representation of these shapes in STL format, the standard data exchange format for solid freeform machines. The STL files output by the

sculpture generator program were transmitted over the Internet to Metalcast Engineering, Plynetics, Malmberg Engineering, Z-Corp., 3D Systems, Stratasys, and The University of Texas at Austin. Small models ranging from 75 to 300 mm in diameter were fabricated with stereolithography, selective laser sintering, fused deposition modeling, or 3-D printing. With turnaround times as short as a few days, a robust 3-D artifact was obtained for inspection and to be shown to friends and visitors.

In some instances, the solid freeform model served as more than an early demonstration of a future sculpture or as the final proof of concept before Collins committed to months of toil. It also demonstrated that a complex structure was physically realizable when even an inspection on the computer left some doubt as to its freedom from self-intersections.

A final word

Evidently, a variety of uses have already emerged for solid freeform fabrication. Many examples of improved time-to-market and lower-cost product development have been reported. And users are finding ways to use the method for more than just generating models. For instance, the industry is developing the technology for rapid tool making, in which either patterns for making molds, or the molds themselves, are fabricated by layer-based manufacturing. Researchers are also advancing the technology to the point where functional parts can be fabricated rapidly with these technologies.

While solid freeform fabrication will probably never replace conventional

manufacturing for mass production, it can easily be imagined in use at remote sites where spare parts are needed but are difficult to stockpile. One day soon, solid freeform workstations may be installed on aircraft carriers, the space station, or even a Mars base.

Also worth noting is that the technology can manufacture products in materials or shapes that otherwise cannot be manufactured. For instance, since most forms of solid freeform fabrication are additive processes, it is possible to control the material composition at every point in a part. Consequently, functionally gradient materials, in which the material properties vary spatially, are on the horizon, allowing truly optimized structures to be fabricated.

It is worth noting, too, that a growing number of researchers and industry practitioners have spotted similarities between solid freeform fabrication and the VLSI industry. The interest here is in standardizing the data exchange formats and in developing and codifying design rules to allow engineers to develop designs and ship them off to fabrication houses, confident that they will work as planned. [See "NIST's support of rapid prototyping standards," pp. 38–39]. Many analogies can be drawn between events that allowed VLSI manufacture to develop along these lines, and what is needed for similar development for the newer technology. Through this effort, the SFF industry may one day do for mechanical design and manufacture what the VLSI industry has succeeded in doing for electronics. ◆

Virtual Conference, MCB University Press, 30 June–30 September 1998; Web, www. mcb.co.uk/services/conferen/jun98/forp/.
The same Jurrens was editor of "Rapid Prototyping's Second Decade," *Rapid Prototyping*, Rapid Prototyping Association of the Society of Manufacturing Engineers, Vol. 4, no. 1, first quarter 1998, pp. 1–4. See also Richard L. Rhorer, Jurrens, and Bradley N. Damazo on "Evaluating the Performance of Rapid Prototyping/Rapid Manufacturing Systems," *Proceedings of the 31st CIRP International Seminar on Manufacturing Systems, Networked Manufacturing-Integrated Design, Prototyping, and Rapid Fabrication*, University of California, Berkeley, 26–28 May 1998.
And finally, Jurrens and Richard L. Rhorer authored "*Workshop Proceedings: Measurement and Standards Issues in Rapid Prototyping,*" 16–17 October 1997, National Institute of Standards and Technology, 1998 (to be released).

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