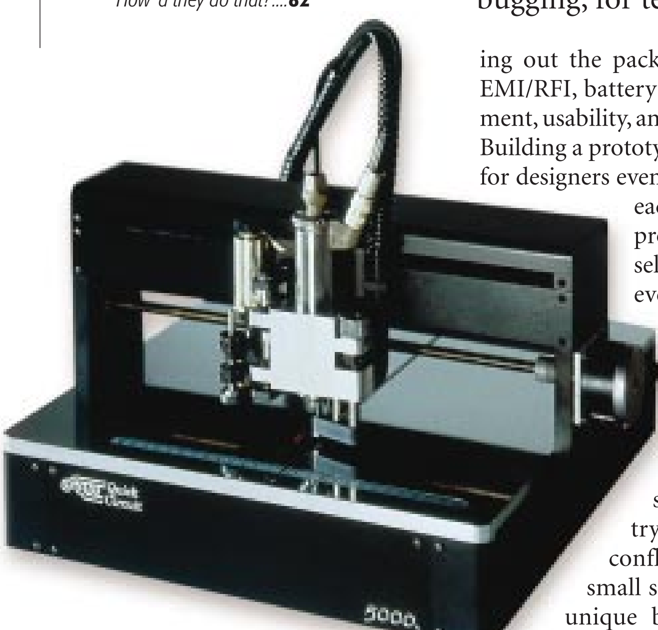
 By Bill Schweber, Technical Editor

WHEN YOU'VE GOT TO PRODUCE A PC BOARD AND ENCLOSURE, THE RIGHT CAD-DRIVEN EQUIPMENT CAN ACCELERATE YOUR DESIGN CYCLE AND REDUCE FRUSTRATION.

Prototyping tools TRANSFORM design dreams into reality

If your engineering team could deliver just the netlist for your fully modeled and simulated circuit, along with the system's operating-software code, your design life would be much easier. Reality, however, is that you need to build a working prototype for debugging, for testing your software in the real world, and for working out the packaging issues, such as EMI/RFI, battery and connector placement, usability, and overall look and feel. Building a prototype was not as difficult for designers even a few years ago when each aspect of the design process—the product itself, its components, and even your team's development schedule—had more room and flexibility. To aggravate your situation, many products now have custom-designed enclosures that try to meet the many conflicting constraints of small size, user convenience, unique batteries, and special user interfaces while looking distinctive to the market and meeting demanding RF requirements. The basic rectangular, standard-sized plastic or metal enclosure that you can get from a convenient electronics-supply catalog can't meet your stringent needs.



Fabrication of pc boards gets personal with a desktop milling, drilling, and routing machine, such as the T-Tech Quick Circuit 5000, under the control of your PC.

Fortunately, the same CAD and EDA technologies that drive today's increases in system functionality, up-front modeling and simulation, and circuit density also provide you with the tools to meet these design objectives. With PC-driven electromechanical systems, you can make detailed, ready-to-load circuit boards in a few hours, which you can then fit into the board's unique enclosure, along with the ancillary components and connectors, for a meaningful test fitting.

THE BOARD COMES FIRST

Layout demands on your pc board for component placement, connectors, and high-frequency performance—plus your need to debug software on a "real" system—mean that you normally want to confirm your pc-board design before you commit to an enclosure design. In the "Middle Ages" of the solid-state era when circuits had many larger discrete components and DIPs, you could make the board in-house using basic photographic techniques, chemical etching, and a drill press (see **sidebar** "You still want to be in pictures?"). For today's high-density designs, these relatively crude techniques are insufficient.

But an attractive alternative offers you the benefits of short cycles and layout flexibility and gives you that near-total control of pc-board fabrication that most design teams doing prototype work really need: benchtop milling machines. Such benchtop board fabrication is the prototyping analogy to desktop publishing as far as the direct contact and control you have over the final product.

LPKF Laser and Electronics (www.lpkfcadcam.com) and T-Tech Inc (www.t-tech.com) offer these units; systems from these vendors are roughly comparable in features and performance. For a starting cost of around $8000 to $10,000 (but usually somewhat more, depending on the options you choose), you can make those prototype boards as you need them, with minimal mess and frustration. Your payback—measured only in dollars—is typically a year or two compared with the cost of going outside; this payback doesn't include your productivity and time-to-market improvements because you can now do your board right away. Thus, you can proceed to the next step in the design and debugging cycle.

These systems mill selected areas of the conducting copper layer from a nonconducting base layer, such as a standard glass-epoxy circuit board; drill any holes for component leads, mounting, or support hardware; and route the final board shape or any large interior open areas. They perform these functions with precision commensurate with today's high-density designs. The machines use X-Y control of an 8000- to 60,000-rpm, (depending on model), spindle coupled with Z-axis depth control. The motion of the spindle is based on commands from software on your PC to transform 2-D PC laminate or other material—for example, FR3, FR4, G10, PTFE, Teflon, or Duroid—into a 3-D pc board. When you see the combination of sophisticated CAD software and precision motion control in action, it's easy to admire what such a combination can do.

AT A GLANCE

- With PC-controlled machines, you can quickly and reliably produce your own multilayer pc boards with minimum frustration, so you can begin your debugging cycle sooner.
- The precision of these machines is similar to PC-based photofabrication and matches today's high-density designs and high-pin-count packages.
- To accelerate your mechanical and physical integration cycle, use solid freeform fabrication to produce accurate prototypes of your enclosure and any other mechanical parts in your design.

The process begins with your standard CAD-layout and drilling files in Gerber, HP-GL, Excellon, or one of several other formats. You import these files to your Windows-based PC, which runs the prototyping machine, and use vendor-supplied software, which has two roles. First, it converts the CAD file to a milling file, which guides the spindle head's X-, Y-, and Z-axis motion. Second, it lets you specify some factors that the initial plot does not. After all, a physical layout is more than just a simple interpretation of the connected points of a schematic diagram. Nearly every physical-board layout needs some intervention in which you include rules for insulation spacing, ground and isolation paths, and the amount of copper that you must remove from certain areas (**Figure 1**). Additionally, many RF and wireless designs now use the pc board's copper as an antenna, a filter, or a stripline element, which requires complex shapes or carefully sized and shaped traces and spaces.

Once you adjust the board's layout and set some parameters, you're almost ready to go. You set your blank board on the machine's work surface and register it in place via pins that project from the surface. These pins not only define the board's location for the top-surface pass, but also ensure either front-to-back alignment when you turn the board over for a two-sided board or layer-to-layer alignment for a multilayer board.

The high-speed spindle mills away undesired copper. Unfortunately, a single milling, drilling, or routing tool in most

YOU STILL WANT TO BE IN PICTURES?

Today's proliferation of tiny ICs, such as SO, SOT-23, and SC70, coupled with high-pin-count, tight-pitch components, such as PLCCs, increases the challenge of photoregistration and drilling through-holes. Until a few years ago, you could get a kit at Radio Shack consisting of chemical etchant, a pen with special ink that would resist the etch, and some etch-resistant decals representing standard DIPs.

To identify where the etch should not remove copper, you would hand-draw your desired connecting circuit traces on copper-clad pc-board material. Alternatively, you could get a Mylar sheet and make a full-scale negative of your layout, clamp the negative to a clad pc board that you coat with photosensitive resist, and expose the negative to bright light for about 20 minutes. The light would transform and harden the resist so it wouldn't etch away. Times have certainly changed: Radio Shack no longer sells do-it-yourself pc-etching kits, although some specialty electronics-supply companies still do.

You also have to consider the environmental aspects of this operation; pouring used etchant down the drain is probably a violation of state pollution laws. Many smaller pc-board-fabrication shops, especially the ones that specialized in fast turnaround for prototypes, have closed in the last 10 years. The closings resulted from a combination of the lack of money these companies needed to deliver fine-pitch, high-density boards and the increased environmental regulation of chemicals. Another once-popular prototyping technique, wire wrapping, has also virtually disappeared. Its demise resulted from a combination of the introduction of tight-pitch ICs with high pin counts and wire wrapping's unsuitability for high-speed circuits that are common today.

For these reasons, the no-chemical mill, drill, and route machines are attractive. They take about an hour or two to set up the first time, need just a standard ac line and PC, and consume only about 200W.

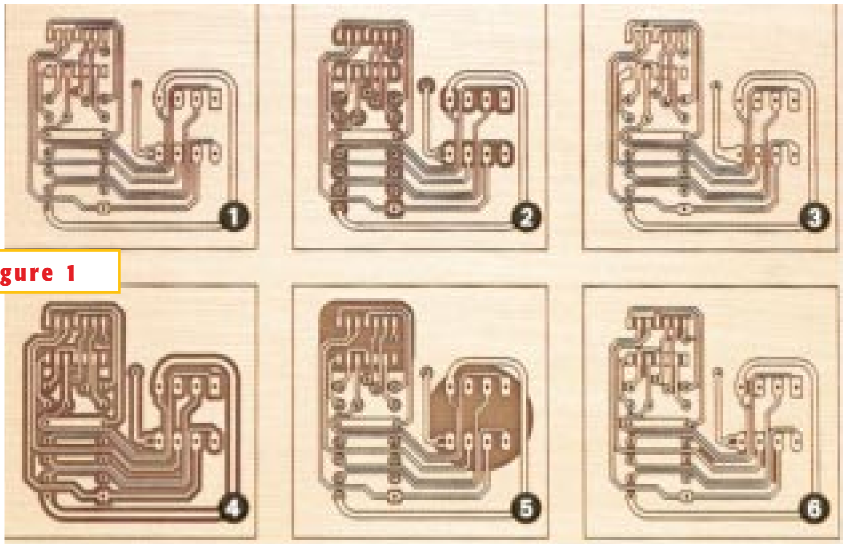


Figure 1

The software that vendors provide between your EDA/CAD software and their machine-control software lets you modify the layout to meet the electrical and mechanical requirements of your design. LPKF's software, for example, offers standard isolation for fast production (1); pad-clearance isolation (2), which eases soldering of surface-mount-technology components; a 0.1-mm cutter for tight-area isolation and smoothing (3); wider spacing, with two milled channels around the conducting track for high-voltage areas (4); "rubout"–the removal of small, leftover smudges and areas–for removal of residual, unneeded copper (5); and spike removal to eliminate any stray copper whiskers that may cause short circuits later (6).

cases cannot handle every aspect of your board (**Figure 2**). The machine signals that you need to change tool bits, which takes a few seconds; the good news is that the software that drives the machine optimizes its routine so that you usually need to change each bit only once per board. Some of the more expensive machine models even eliminate this human intervention by interfacing with optional multistation tool holders and changers so that you can walk away during the entire operation.

Typical double-sided boards take about one to two hours to complete. These machines are precise and repeatable and can produce pc layouts compatible with today's requirements: 0.1- to 0.2-mm (4- to 8-mil) minimum track width and track spacing and holes as small as 0.2 to 0.3 mm (8 to 12 mil), depending on the model. Don't worry that you can fabricate only small boards, either. Depending on the model, you can load a blank board as large as 42×38 cm (16.5×15 in.) in the LPKF unit and 40×61 cm (16×24 in.) in the larger of the T-Tech units, and you can mill to within a few centimeters of the edge.

When you finish the circuit milling and drilling, the spindle head and appropriate tool finishes the job by routing any internal cutouts you have and then routing the board outline so you can remove your finished board. (This outline does not have to be rectangular; it can have curves and card edges.) As a nice touch, if your pc board is small, you can specify—via the software—that you want several boards laid out and fabricated side by side, so you have more than one bare board. You can then load one board with components and use the unloaded one for signal tracing or as a debugging guide.

Most pc boards have plated through-holes to conduct signals, power, or heat either from the top layer to other layers or between inner layers. With these pc-prototyping systems, you can achieve through-hole conductivity in several ways, depending on the number of holes you have to plate through. You can press small eyelets into the holes (the open eyelet can also accept a component lead); insert "via" pins that completely fill the hole; automatically dispense a conductive, solderable paste that bonds to the layers; or use a completely closed chemical plating system that vendors offer, which emulates conventional plating but with minimal chemical hazard.

WHO HAS THE PARTS?

When you have that pc board in hand, you're well on your way to having a prototype to debug and demonstrate. But there's one serious obstacle you still have to overcome: You need to put the electronic components on the board. You can do this step in one of several ways. You can send it to an assembly house, but then you have to provide the necessary documentation, plus all your components on reels or in carefully bagged and labeled packages. This preparation is time-consuming and again puts you at the mercy of an outside vendor (see **sidebar** "Can I go out now?"). Furthermore, checking your documentation and resolving placement issues become more difficult.

Alternatively, you can use a pick-and-place machine that targets low volumes, such as the Expert 5000 from Manncorp

CAN I GO OUT NOW?

The conventional method of fabricating a blank, ready-to-load pc board is to generate a file of the board layout and send it to a pc-fabrication house or use an in-house fabrication operation if your company has one. Typical leadtime for such fabrication is at least 24 to 48 hours, depending on the other jobs in line at the fabrication operation, what price you are willing to pay, and the relationship you have with that vendor or in-house department.

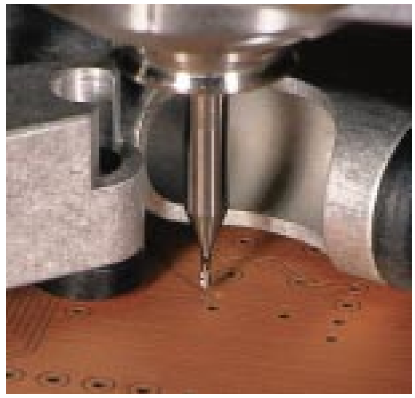
The pc-fabrication house (or your internal department) charges you based on several primary factors: the number of layers, the size of the board, and the number of holes to drill. In addition, your minimum line width and spacing, as well as any special cutouts or routing, affect the price. Plan on paying $200 to $1000 for a 4×6-in. (10×15-cm), two-sided board with about 100 plated through- holes. In many cases, you are less concerned about cost than you are about the time in which you need to get your hands on that pc board. You may also need to use special substrates for RF designs, such as ceramic or Duroid, which a conventional fabrication operation cannot handle.

(www.manncorp-smt.com). This $8000 semiautomatic unit guides the operator via mapping software and a magnified screen image; the device shows where each part should go with placement accuracy of 0.6 mm (25 mils) as standard and 0.4 mm (16 mils) with an optional fine-pitch package. A motorized parts-supply tray holds your components, and you can also use tape or stick feeders for components that you are using in quantity.

Don't rule out the old-fashioned hand-load method, either. Using vacuum tweezers, a foot-operated solder-paste dispenser, and a wide-view 3 or 4× magnifier with sufficient lighting, a careful operator can load a pc board one component at a time and can then solder the board in a regular production setup. Yes, it's laborious, and you don't want to do it for more than a few boards, but it takes virtually no setup time, and your costs are just a few hours of labor and some basic equipment that you probably need anyway.

HAVE IT YOUR WAY

These board-producing machines offer options in addition to higher speed spindles for smaller dimensional work and automatic tool changing. These options include a vacuum unit that sucks up the debris that the cutter tool generates, a sound-reduction box that cuts the typical 80-dB sound level at 3 ft by about 10 dB, and a high-power magnifier—typically 50×—for visually checking your fine-pitch design. Consider this last item more of a necessity than a luxury, because you probably need to inspect the board and its design in a few critical areas.



A milling bit, such as the one on this T-Tech machine, strips the copper cladding of the pc-board laminate with precision and following a software-specified path and depth.

Don't think that cladding removal is the only way to go, either. In some applications, such as those in which you need special claddings other than copper or those that need a circuit built on a substrate that is unavailable with copper cladding, you may want to consider a precision writing system (see **sidebar** "Don't forget to write").

MAKE A CASE FOR YOUR PRODUCT

When I first saw a stereolithography-apparatus (SLA) system in action at a trade show, my initial thought was how it functionally paralleled the handy "replicator" of the *Star Trek* series (in which the crew used the device to create—on the spot—replacement parts, food, or whatever it needed). The SLA I watched magically produced a detailed, 3-D part that matched solid-modeling engineering figures on a nearby screen. To add to the science-fiction aura, this solid rendition of the image I saw on the screen rose from a pool of liquid polymer and emerged ready to use (see **sidebar** "How'd they do that?"). As the finished part rose from the pool, I had a distinct *Terminator 2* flashback: The sight reminded me of the ultra-advanced, metallic, morphing cyborg who comes after Arnold Schwarzenegger in the movie.

But SLA is not science fiction. SLA and the broader area of rapid prototyping and solid freeform fabrication (SFF) are significantly changing the way that manufacturers are making mechanical parts for both prototyping and short production runs. A design team can plan its enclosure on a PC or workstation using solid-modeling software tools supplemented by special SFF application software; can see whether and how the board, connectors, power source, antenna, and other pieces fit; and can then have an exact prototype of the enclosure or housing in hand—complete with mounting ears, tabs, and openings for a display and keyboard.

You gain several benefits from a tangible 3-D enclosure. First, just as you have to debug a simulated circuit and its soft-

DON'T FORGET TO WRITE

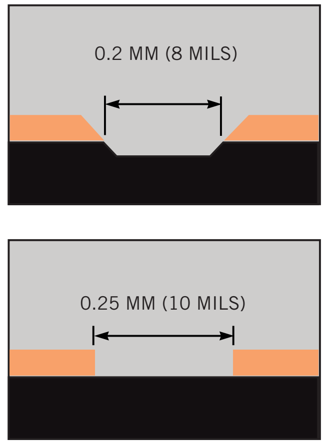
When you fabricate pc boards made with these mill, drill, and route machines, you are using a subtractive process, which mechanically grinds away the substrate's plating to create the design. Fabricators and manufacturers make most commercial pc boards with a subtractive process, except this process is chemical rather than mechanical. The industry has tried, at times, to instead use additive plating, but this method generally is uncompetitive with the specifications, convenience, and costs of the copper-removal-based technique.

A way exists, however, to produce circuit lines as well as actual components without electroplating. Direct-writing technology uses a sophisticated closed-loop pump and control system to dispense fluid through a precision orifice. Ohmcraft (www.ohmcraft.com) developed the Micropen system in 1985 to allow the US Navy to create replacement parts for thick-film or RF electronic parts that were no longer available with a just-in-time, no-retooling technique. The $150,000 machine, driven by Autocad or electronic CAD software that the vendor's custom software supplements, writes your specified patterns. The machine in one pass produces 2- to 100-mil-wide lines with 0.1-mil accuracy. Line thickness in the Z dimension ranges from 0.25 to 10 mils, and you can get a thicker line by using multiple passes.

The most interesting thing about this system is that you are not limited solely to using conducting inks, such as a copper suspension for pc-board tracks, for writing. Instead, you can use fluids ranging in viscosity from water to tar; they can be resistive, conductive, or dielectric inks. Copper; aluminum; precious metals, such as gold or silver; polymer sealants; colored inks; and other thick-film inks are among the fluids you can apply with the precise-pen system. After writing the pattern, you fire the substrate to cure and harden the ink if necessary. Using precise writing, you can even build your own thick- and thin-film resistors; by running some test patterns, you can "write" resistors with 5% tolerance and with a depth that yields a predictable temperature coefficient of resistance that can be as low as zero if you're willing to experiment.

ware, you have to assess the enclosure to make sure that the internal parts fit properly and with correct clearance and that you can assemble the whole product without physical interference or poor access to mounting screws and tabs. Second, such an enclosure lets you assess your RFI/EMI situation and see what steps to take to reduce circuit emissions or sensitivity; these steps can include adding filters, gaskets, or shielding; moving components and pc-board traces; or spraying metallic coatings on the inside of the enclosure. Third, a real enclosure makes it much easier for you to demonstrate to man-

Figure 2



(a)

(b)

The tool you use in the spindle is critical. A basic milling tool provides single-pass depth of 0.005 to 0.07 mm (0.2 to 2.8 mils) with a V-sided insulating channel as narrow as 0.2 mm (8 mils) wide and lets you put two pc tracks through 1/10-in. IC grid spacing; the less rugged microcutter tool cuts a 0.1-mm (4-mil) path and can place five tracks in that same grid spacing or two on 1/20-in. surface-mount-technology grid spacing (a). For defining RF structures on the pc board, you would use an end mill tool that cuts straight-sided channels from 0.25- to 0.4-mm (10- to 15.7-mil)-wide in one pass (b) (adapted from LPKF Laser & Electronics).

HOW'D THEY DO THAT?

The technology of rapid prototyping and solid freeform fabrication (SFF), in which stereolithography-apparatus (SLA) machines are the most common implementation, is about 10 years old. In that relatively short period, this technology has spawned variations in the type of material it can use to produce parts, the underlying technology, and the disparate vendors (**Table A**).

At the core of each technique is sophisticated 3-D CAD software. Most SFF systems work by looking at the complete 3-D object you wish to create and then producing it one thin slice at a time; the system creates these slices one on top of the other, so that the complete object is built up layer by layer. Designers often call these slices 2½-D renderings.

Most SFF systems work by controlling lasers, which build the object's shape by changing the physical characteristics of a raw stock material. In the most common type of SLA, for example, the lasers trace the object's 2½-D slice on the surface of a pool of photosensitive polymer resin, which cures (hardens) where the laser beam hits it. This top-surface layer rests on a slightly submerged elevator platform, which then drops so that the laser can trace the next layer right on top of the first one. The process then repeats until the laser traces all the layers and the object is complete, at which point the elevator raises the object from the polymer pool.

Because the system builds up these objects layer rather than by removing unwanted pieces from a solid starting block, SFF machines can create more than simple boxlike enclosures. For example, the machines can produce the numerous internal details, cutouts, mounting bosses, tabs, indents, and other small but critical features that you want in a modern enclosure that combines physical protection with ease of assembly. The time it takes to produce a simpler geometry solid object is comparable with the time it takes to machine it. However, the relative speed advantage of SFF increases as the object's geometrical complexity increases, whereas the machining process would have to make many small steps or change cutting tools.

Different resins are available with various hardness, clarity, strength, and other mechanical characteristics, giving you a selection of trade-offs, such as material hardness versus the smoothness of the surface finish. Besides the polymer resins, some systems use metal powders that the laser sinters, or fuses, to create the layers. Other systems use the laser to cut out thin layers of paper, plastic, metal, or even ceramic, which the machine then laminates to create the complete complex 3-D object. Finally, in a sophisticated variation of the conventional laser printer, some SFF systems place a layer of starch or cellulose powder on a flat surface, "print" a binder material on this powder in the shape of the object's cross-section at that layer, and then repeat the cycle by spreading a new layer of powder on top of the now-formed layer. For added strength, you can impregnate the finished object with wax or epoxy.

Reference A provides a discussion of the technology's status, as well as of some technologies that are not yet in commercial production.

TABLE A—SOLID-FREEFORM-FABRICATION VENDORS

Vendor	Web address	Technology
Cubital Ltd Circle No. 305	www.cubital.com	Ultraviolet curing of photopolymer or resin wax
DTM Circle No. 306	www.dtm-corp.com	Sintering of copper and steel powders; nylons and polymers
Sanders Prototype Circle No. 307	www.sanders-prototype.com	Thermoplastics or wax
Stratasys Circle No. 308	www.stratasys.com	Extrusion through a nozzle for ABS plastic, polyesters, wax
Z Corp Circle No. 309	www.zcorp.com	Powder and binder printing for starch and cellulose with impregnation for strength

REFERENCES

A. Crawford, Richard H, and Joseph J Beaman, "Solid Freeform Fabrication—a new manufacturing paradigm," IEEE Spectrum, February 1999, pg 34.

B. Lerner, Eric J, "How industrial concepts become prototypes fast," Laser Focus World, April 1999.

A semiautomatic pick-and-place system, such as the Expert 5000 from Manncorp, guides the operator to correct and precise component placement using a component tray as a parts source in addition to conventional tape and stick feeders.

agement and target customers the product, its operation, and even your progress. It even inspires your design team!

The benefits of SFF go beyond having the tangible enclosure. You can also use it to make fittings, connectors, mounting brackets—anything you need to further verify your mechanical design and how it integrates with your circuitry. If you're thinking about a sliding door to protect your product's display, you can make one and try it.

Note that you don't have to go to SFF directly from your solid-modeling design and simulation for the individual part by itself; you can get advanced-system solid-modeling packages that let you "assemble" your product on screen, so you can check for clearances, fit, balance, and the correctness of the sequence of assembly steps. But, like any simulation, the real product in hand often reveals things that you missed, which is especially important when you consider the cost and leadtime of final production tooling for an enclosure or an internal part.

The tolerance specifications of SFF machines are impressive. Depending on the technology you choose, you can expect dimensional errors from 0.025 to 0.4 mm (1 to 16 mil). In contrast, a typical computer-controlled milling machine in today's machine shop can produce parts with errors of less than half the 0.025-mm value. But the SFF specifications are often tight enough for a thorough first-pass analysis and may be sufficient for your final product as well.

The sizes of the parts that SFF machines make encompass most solid-part sizes you need in product development. You can make parts as long as about 300 mm (12 in.) on each side, though most parts made today with SFF are about half that size on each side. Completion time for parts ranges from 20 minutes to a few hours, depending on the technology of the SFF machine and the part's size; the completion time is somewhat independent of the complexity of each layer the SFF builds.

The biggest down side to SFF is probably the cost. Even though prices of the controlling electronics and PCs are dropping, the machines still have a lot of complex, precise, and relatively costly parts. Prices range from $50,000 to 10 times that, depending on the underlying technology the SFF uses, the materials it forms, and other factors. These factors make it too expensive for all but the largest companies.

However, local service bureaus fill the gap. You send them your file in suitable CAD format, and they deliver your part the next day for $1000 to $2000 for a representative part. This process is still much cheaper and faster than having a machine shop fabricate one part for you. Some of these service bureaus have more than one type of on-site SFF machine, so you are not restricted to one type of SFF technology or capability but can select the one that matches your part and application. Because SFF is a rapidly changing area and because many of the vendors and service bureaus are probably unfamiliar to electronic-design engineers, for additional information you should check the Web site of a publication with a strong mechanical-design focus, such as *Design News* (www.designnews.com) or check out **Reference 1**.

SFF is affecting design and preproduction verification in other ways as well. SFF is surprisingly competitive in cost and completion time with traditional production techniques for runs of 10 to several hundred pieces because it requires no tooling, molds, and related setup. Taking the flexibility of the 3-D software tools even further, some of the application packages can generate a file for your final tooling, taking into account the normal clearances, material shrinkage, minimum radii, and support-spar thickness that the tooling needs to produce the part. For a final step, in some cases you can even use SFF to generate the tooling itself, which then lets you use conventional molding or casting techniques for low- to moderate-volume production runs. □

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Reference

1. Hartwing, Glenn, "Trends in Rapid Prototyping," *Desktop Engineering*, March 1999, pg 56.