Rapid Prototyping of Solid Three-Dimensional Parts

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Abstract

Several new technologies collectively referred to as solid freeform fabrication have been developed in the last decade for use in the rapid prototyping of solid three dimensional parts. These include stereolithography, photosolidification, solid ground curing, 3D printing, fused deposition modeling, ballistic particle manufacturing, selective laser sintering, laminated object manufacturing, and shape deposition manufacturing. The prototypes they produce serve as physical models during design review, allow engineers to perform functional testing of parts, and are often used as mold patterns or positives for secondary tooling to manufacture small batch sizes. This paper describes the technologies used by each of these processes, and compares their strengths and limitations.

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1 Introduction

Until the mid 1980s, prototyping general solid parts was a time and labor intensive process. With traditional NC machining, each feature of the part has to be machined sequentially, and each machining operation may require unique jigs and fixtures. The introduction of layered solid freeform fabrication (SFF) processes revolutionized prototyping, promising to reduce process planning to the automated slicing of a CAD model, thereby making possible quick and economic prototyping of complex three-dimensional parts directly from CAD descriptions.

In all SFF processes, the CAD model of a three-dimensional part is “sliced” into horizontal, 2.5-D layers of uniform (but not necessarily constant) thickness. Each cross sectional layer is successively deposited, hardened, fused, or cut, depending on the particular process, and attached to the layer beneath it. The stacked layers form the final part.

Prototype parts produced with SFF serve as physical models during design review, allow engineers to perform functional testing of parts, and are often used as mold patterns or positives for secondary tooling to manufacture small batch sizes. Many SFF technologies allow the user to design parts with geometries that would be difficult or impossible to produce using traditional machining, such as ships in bottles or parts with inaccessible or even fully enclosed internal hollows.

Using SFF technology typically reduces the time and cost of producing prototypes by 30 - 95% [32]. These reductions make earlier testing and multiple design iterations possible, two factors that have been shown to accelerate product development, particularly for innovative products [42]. With the current emphasis on concurrent engineering and multifunctional teams, it will become even more important to "get physical fast" through prototypes that become the means of communication across disciplinary boundaries [27].

This paper describes the technology used in current commercial SFF systems, as well as a smaller number of research systems under development at universities for a preview of what might be available in the future, and presents a comparison of these different approaches to SFF based on cost, speed, accuracy, geometry, and material and surface properties.

2 Photopolymer Solidification Approaches

Roughly half of the rapid prototyping technologies currently implemented in production systems use a laser or other strong light source to cure a liquid photopolymer. Stereolithography, the first commercially available rapid prototyping technology, uses an ultraviolet laser to cure an acrylate liquid photopolymer [2, 3, 4, 20, 22]. Subsequently, other companies developed laser modeling, photosolidification, and solid ground curing technologies for use with photocurable resins.

2.1 Stereolithography

3D Systems obtained the first U.S. patent for a rapid prototyping technology for their StereoLithography Apparatus (SLA) in 1985 [27]. Their first production system shipped in 1989, and there are now over 400 SLA-series machines installed. These and other stereolithography systems accounted for 75% of the SFF market worldwide as of June 1994 [23].

The first step in stereolithography, as in all SFF processes, is to generate a 3D CAD solid model of the part. In addition, support structures must be designed to connect the part to the support platform during all phases of building and to prevent cantilevered features from sagging downwards or curling upwards. Next the CAD file must be translated into a triangulated boundary representation format (known as .STL [1]) that the SLA machine understands and transferred to the SLA's computer. The SLA software then slices the .STL files for the part and its supports, generating cross sections describing the horizontal layers.

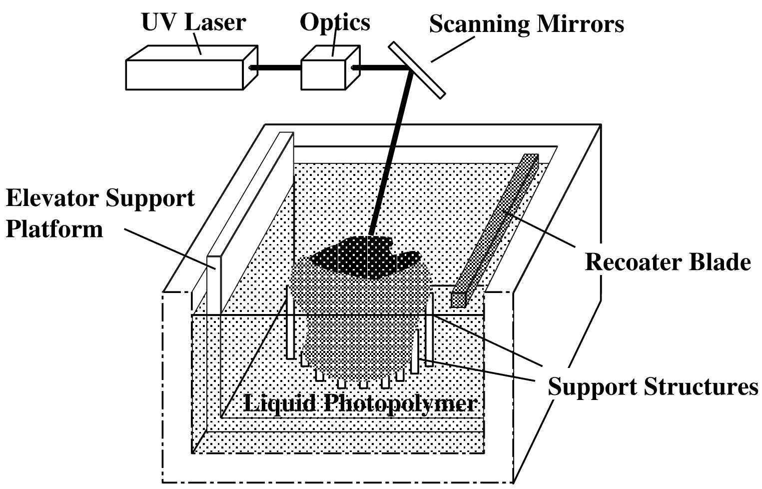


Figure 1: Stereolithography Apparatus

The main components of the stereolithography machine are a vat of liquid photopolymer, an elevator support platform, a recoater blade, and a mirror deflected ultraviolet (UV) laser (Figure 1). The part is built from the bottom layer up, so the elevator starts out raised just below the surface of the liquid resin. The first step for each layer is to adjust the level of the resin to make up for volumetric shrinkage from the curing of the previous layer. The next step is the “deep dip,” during which the platform is lowered below the surface of the liquid resin. As the stage drops, liquid from the edges flows into the depression around the part. This step is important for highly viscous resins and parts with large horizontal surface areas. Next the part is raised to bring its top layer above the resin surface, exactly one layer thickness below the recoater blade. This minimizes the amount of excess resin that the recoater blade must remove as it sweeps across the vat. Finally the platform drops again, bringing the top layer of recoated liquid resin to the free surface level of the resin in the vat. The machine then pauses for a short interval, reducing the effects of surface tension that can cause creases above the profile of the previous layer where the recoated cross section meets the rest of the liquid. Next, the laser beam, controlled by the deflecting mirrors, vector-scans the outline of the new layer’s cross section. The laser initiates a chemical reaction in the photopolymer, causing it to gel in the area exposed. The laser power, spot size, and scanning speed are calibrated with the layer height so that the resin will be cured just deep enough to adhere to the previous layer. If the layer is a horizontal top or bottom surface of the part, it is “skinned” by raster scanning the cross section’s entire interior; otherwise, the interior is merely crosshatched, creating a honeycomb-like cell structure in which liquid resin remains trapped. (The trapped liquid is hardened later during postcuring.) This process is repeated to build up the entire part.

Finally, the partially polymerized “green” part is lifted up out of the vat, allowing the uncured resin to flow off. Additional uncured resin is removed in a solvent bath. The part is postcured in a UV curing oven to harden the trapped liquid resin and bring the part to its final strength. Additional postprocessing is required to remove the supports, and if a smooth surface finish is desired, the part must be sanded and polished by hand.

As the photopolymer goes from liquid to solid, it becomes denser, and the resin shrinks. This can cause the phenomenon of curl distortion if the new layer shrinks after it has been attached to the previous layers, since the edges of previous layers will tend to bend up as the top layer shrinks. The development of new epoxy resins that experience less shrinkage than the original acrylate resins has considerably reduced this distortion. SLA parts can also experience warpage from inhomogeneous stresses caused by the scanned and layered building process. In order to minimize this effect, the direction of rasterization is rotated ninety degrees between subsequent layers.

Build time is minimized by crosshatching the layer interiors instead of skin-filling their entire cross sections. However, as more of the resin is left to be cured by the oven instead of by the laser, the shrinkage and warpage increase. On the other hand, leaving some of the polymer uncured leaves enough give to decrease curl distortion, so complete laser curing would not be desirable even without the time consideration.

Research at 3D systems has attempted to balance warpage concerns with curl concerns. Their third generation crosshatch pattern, STAR-WEAVE, introduced in 1991, improved accuracy by 50% over the original tri-hatch build style. The theory is to have more of the shrinkage occur before the new layer is attached to the old layer, and to only tack the layers together at a few points so that there is more give, while at the same time hardening a large percentage of the polymer to minimize later shrinkage and warpage in the oven [22]. The development of the fourth generation build style, ACES, in 1993 further improved accuracy for many geometries [21].

The automotive industry is a major customer of SLA, using it for making prototype engine parts [32]. Chrysler successfully conducted performance testing on an SLA intake manifold prototype that was able to withstand six hours attached to an operational engine. More commonly, however, the SLA part is used as a pattern for secondary tooling. This is the approach used at Ford, where the SLA part is used as the positive for investment casting in the QuickCast process. QuickCast parts are built with a much looser internal hatching, and all of the uncured resin is allowed to drain out of the skinned honeycombed part, which has drains and vents in its skin for this purpose. These holes are sealed with wax before casting. The mostly hollow internal structure helps to insure that the part will collapse and vaporize easily during burnout. Aluminum, titanium, stainless and tool steel, and copper alloys have all been cast successfully using QuickCast patterns. Unfortunately, Ford has found that the surface finish is not smooth enough for production tooling.

Several other processes also use SLA parts as the first step in tooling. In all of these processes, the SLA part needs to be hand sanded and polished first to obtain a smooth surface [47]. For building flexible reinforced rubber parts, the SLA parts function as the sacrificial mandrel upon which rubber sheets are molded [43]. In spray metal tooling, molten metal is sprayed on the SLA positive to build up a shell that is mounted on aluminum filled epoxy to create an injection mold tool [31]. Unfortunately, the geometries that can be reproduced in this manner are somewhat limited because it is impossible to spray the sides of deep holes. For small runs of two to fifty pieces, RTV silicon rubber tooling, a type of soft tooling, can be used rather than more expensive spray metal tooling. At Chrysler, SLA patterns have replaced patterns made of wood for vacuum form tooling and gray iron foundry casting. One such casting tool was accurate enough to be used for production parts. Chrysler has also incorporated SLA patterns into squeeze molding, silicone molding, and resin transfer molding [22]. Different secondary tooling processes are appropriate when different materials, batch sizes, and accuracies are required, and SLA parts have proved adaptable to many such processes.

Technology similar to that developed by 3D Systems is used in a number of stereolithography systems available abroad [22, 26]. The SOMOS machine was developed by Du Pont and licensed to Teijin Seiki. The Sony Solid Creation System (SCS) line includes a model with one of the largest build areas available for any SFF technology, 40x32x20". Mitsubishi makes the Solid Object Ultra-violet laser Plotter (SOUP) whose advantages include thin layers and no postcuring. Mitsui Engineering and Shipbuilding's Computer Operated Laser Active Modeling Machine (COLAMM) builds parts from the top down: a laser scanner shines up through a glass plate that forms the bottom of the resin vat, and the elevator platform pulls the part up between layers. Electro-Optical Systems (EOS) is a German maker of stereolithography machines. Because of patent considerations, none of these systems are marketed in the United States.

2.2 Laser Modeling

Quadrax Corporation developed a technology called "laser modeling" that was almost identical to stereolithography. The main differences were that they used a visible light laser instead of a UV laser, and instead of the support elevator moving down between each layer, the optics moved up and a new layer of uncured resin was added to the vat. They claimed that the resins used with visible light lasers settled rapidly so that layers could be built up more quickly, and that distortion was reduced when the green walls of the part did not have to move through the uncured resin.

Quadrax shipped a product that used this technology, the Mark 1000 Laser Modeling System, but subsequently sold their patents to 3D Systems and have done no further work in rapid prototyping. So far, 3D Systems has not incorporated the above mentioned Quadrax design differences into their SLA systems.

2.3 Photosolidification

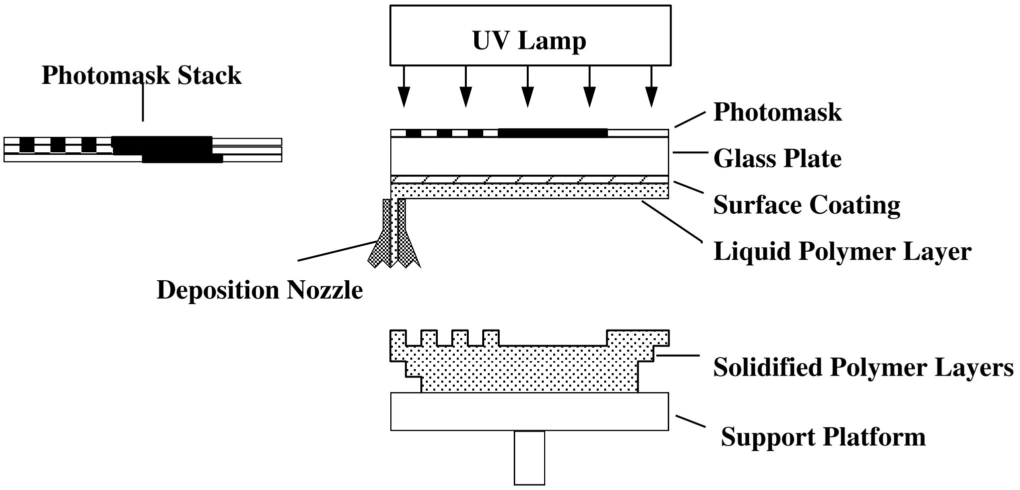


Figure 2: Photosolidification: Light Sculpting, Inc.

With Light Sculpting Inc.'s photosolidification technology, a UV lamp cures an entire layer of photopolymer simultaneously by contact irradiation through a photomask (Figure 2)[3, 4, 17, 20, 28]. Before part building commences, a photoplotter prints masks defining the negatives of all the layers on transparent film and these are loaded into the machine. Then for each layer, its mask is positioned over a glass plate while a deposition nozzle deposits a layer of liquid photopolymer onto the bottom surface of the glass. The layer is exposed to 250 watt UV light through the photomask, selectively hardening it in areas not protected by the mask. Contact with oxygen inhibits polymerization; because the photopolymer is not in contact with the air, energy requirements are reduced by an order of magnitude. A platform supporting the previous layers is raised to join the new top layer to the part. Then the platform drops back down so that the nozzle can deposit the next layer of photopolymer. The underside of the glass plate has a proprietary surface coating that allows the polymer to be separated easily and that inhibits complete polymerization where it contacts the surface of the layer so that the next layer will adhere to it. The glass plate helps prevent warpage and shrinkage, as well as supporting cantilevered beams from above. Light Sculpting claims that this minimizes the number of supports required. A twelve to fifteen minute postcure is required after building is completed.

There are several advantages to this layer-at-a-time approach. UV lamps are far cheaper and more reliable than the UV lasers used in stereolithography [29]. Using a deposition nozzle instead of a vat of liquid makes it easier to change polymers, even between layers [28]. Build time is thirty to forty seconds per layer regardless of complexity, but this does not include the time to plot the photomasks. To simplify the process, Light Sculpting researched replacing the photoplotter and masks with a liquid crystal array that could be reconfigured in place. Unfortunately, the LCD materials currently available are quickly damaged by ultraviolet light.

2.4 Solid Ground Curing

Solid ground curing (SGC) was developed by Cubital Ltd., a company based in Israel that produces a machine called the Solider (Figure 3) [3, 4, 5, 18, 20, 22, 32]. Like Light Sculpting's photosolidification, solid ground curing builds parts by curing a photopolymer a whole layer at a time, but on a much larger scale; the multi-component Solider 5600 system weights four and a half tons and measures over thirteen feet long, four times longer and twice as high as the LSI-1212, the midrange Light Sculpting system [10, 28].

The Solider makes a mask for each layer by using a plotter to electrostatically charge selected areas of a glass plate at 300 dpi, upon which toner is deposited directly

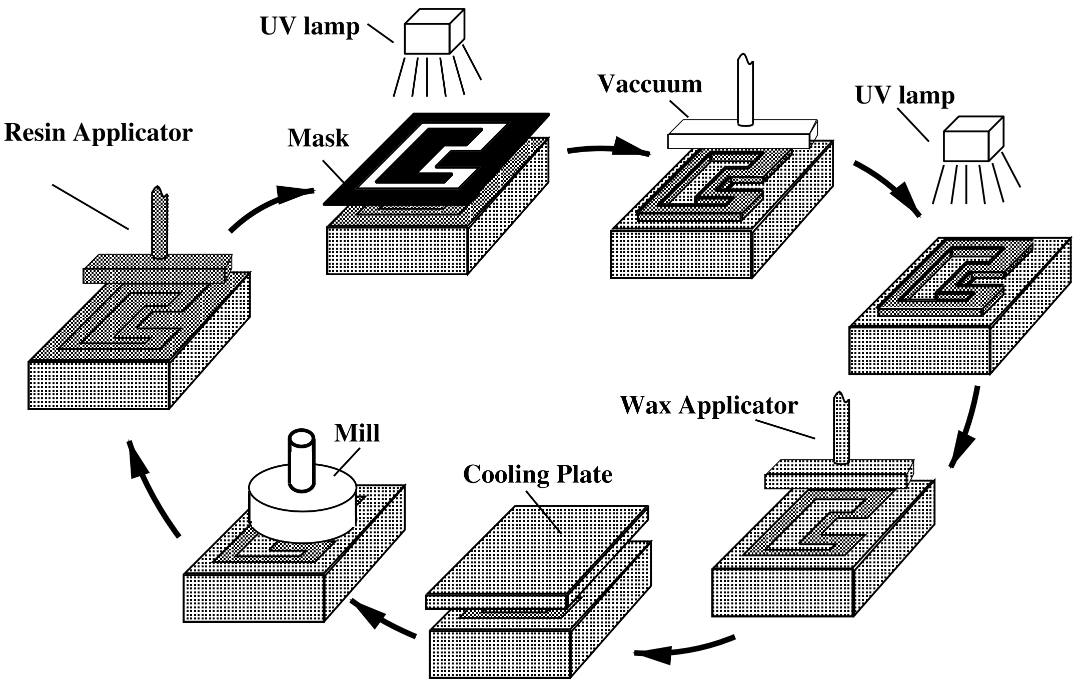


Figure 3: Cubital's Solider

by a drum, much as in photocopying machines. While the mask is being developed, a thin layer of resin is spread on top of the work area. Then the mask is moved into place and the entire layer is exposed through the mask using a strong UV lamp. While the photomask is being erased, uncured resin is removed using a stream of air to blow it away and a vacuum to collect it. The layer is re-exposed to UV light without a mask to cure it completely. Next, molten wax is applied to fill the negative space and cooled with a plate that solidifies the wax. Finally, the surface is milled smooth with a milling disk and then the whole structure is lowered for the application of the next layer of resin. The wax supports the part during fabrication and can be removed easily afterwards since it is water-soluble. This is the only postprocessing required, since no postcuring is needed.

A major disadvantage of this technology is that the dark areas of the mask do not completely block out the UV radiation, so the unhardened resin cannot be reused because it is actually partially cured. At $276/gallon, this can be a considerable expense, as well as creating a toxic waste disposal problem. Software control over the width of the build area mitigates but does not completely solve this problem.

The Solider has several unique build characteristics. Because the entire layer is exposed at once and rigidly supported by wax at all times, SGC parts don't show directional distortions within layers, and exhibit less warpage and curl than SLA parts. The integrated wax support structure makes it possible to build multiple nested parts with the Solider in a single build cycle with only minimal planning. The relatively large build area, and the expense of resin to fill this build area no matter what percentage of it is actually cured, also encourage building multiple, densely packed parts. The wax also makes the construction of fully assembled mechanical systems, such as interlocking gears, possible.

SGC parts have been used successfully as patterns for secondary tooling. The service bureau General Pattern typically builds twenty five to thirty parts at a time with their Solider system out of an epoxy-like composite that is used to create liquid injection molds [32]. Solider parts can also be used as patterns for silicon rubber, epoxy, or spray metal tooling, and sand casting [10].

3 Deposition Approaches

3.1 Fused Deposition Modeling

In fused deposition modeling (FDM), developed by Stratasys Inc., the part is built up in layers formed by extruding melted wax or plastic (Figure 4) [3, 4, 5, 6, 9, 20, 22]. The modeling material is supplied as a thin, .05 inch diameter filament that feeds off of a spool into the FDM head. Both machinable and investment casting wax, and two types of thermoplastics (polyolefin and polyamide), are currently available in filament form for use with the Stratasys system. Inside the FDM head, the filament is heated to just above its melting temperature and then pumped out through a nozzle. Meanwhile, the head, controlled by an NC tool path, moves to trace out the cross section of the layer. The melted material adheres to the platform for the first layer, otherwise to the previous layer, hardening in about a tenth of a second. After each layer has been deposited, an elevator adjusts the distance between the platform and the FDM head so that the next layer can be deposited on top of the previous layers. It is important that the temperature and head velocity are kept constant, even when moving between layers, to prevent visible seams and surface irregularities.

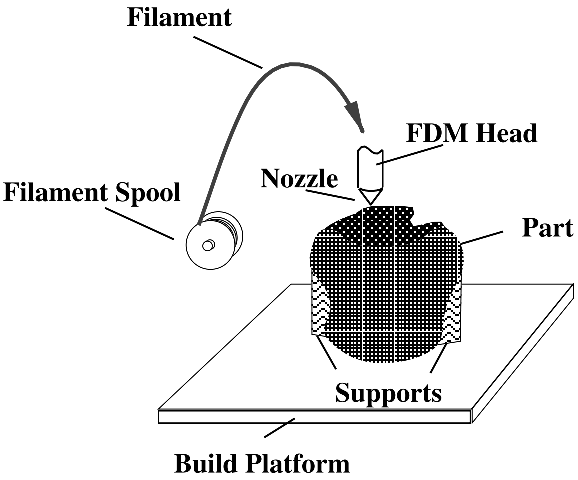


Figure 4: Fused Deposition Modeling

The main advantages of this system are that no postcuring is required, and it is fairly safe because the materials are non-toxic and no lasers are involved. As a result, it is one of the few systems that can be used in an office environment for actual desktop manufacturing, though temperatures must be tightly controlled. Conceptual models can be made from machinable wax and sturdier prototypes for testing can be made from plastics. Machinable wax prototypes can also be used in the spray metal tooling process to produce molds for injection molding. Investment wax has been used successfully for investment casting.

The Stratasys FDM system can take 3D CAD data for input (either solid, surface, or wireframe models), in addition to the faceted .STL files used by virtually every other commercial SFF system. These 3D files are processed by the NURBS based "QuickSlice" slicing software. As a result, parts produced with FDM don't show the faceting artifacts often seen on parts produced by other SFF systems. A disadvantage of the system is that all of the slicing must be completed before the actual building starts; only then are NC tool paths for each slice downloaded to control the movement of the extrusion head. This explicit control of the head movement also makes it possible to download custom tool paths in place of the automatically generated QuickSlice tool paths. Debasish Dutta at the University of Michigan has developed experimental adaptive slicing software for the FDM system that adjusts the height of each layer based on the local geometry to better balance build speed and resolution [13].

Support structures are a bigger problem for FDM than for any other commercialized SFF technology. Since there is no liquid photopolymer or powder bed to support the top layer being deposited, supports will be required anywhere that the top layer extends more than minimally over the profile of the previous layer. The FDM software generates dense, corrugated support structures for these areas, trying to balance strength with ease of removal. To increase the latter, a second extrusion head can be used to deposit a weakly bonded layer of a separate material between the part and the support to create a "break away support structure." Hollow geometries with flat or nearly flat surfaces on the top are poor candidates for FDM because there would be no way to remove the supports from the interior.

3.2 Ballistic Particle Manufacturing

Ballistic particle manufacturing (BPM) is a technology that has been under development for several years at the small South Carolina firm of Perception Systems, Inc.

[3, 4, 22, 29, 36]. BPM uses drop-on-demand ink-jet printing technology modified to "print" with drops of molten wax. The fifty micron drops of wax are sprayed at a speed of 10,000 per second; thirty two such jets are used to increase the build rate. The molten wax bonds to the part by melting the outer layer of the existing structure upon contact. Support structures are simultaneously built up out of polyethylene glycol, a water-soluble wax. After part building is completed, the support structures are dissolved using warm water. The wax parts can be used for investment casting or as design prototypes.

The original system builds up parts in cross sectional layers, lowering the part after each layer is completed to allow the next layer to be deposited. The thickness of each layer is dynamically adjusted by measuring the distance to the layer below and adjusting the amount of wax deposited based on the variation. The position of the print head along the x and y axes is controlled by servo and stepper motors.

BPM has also been used for fabrication of rotationally symmetric metal parts by spraying molten metal at a rotating mandrel. The technology has the potential to be used for truly freeform, non-layered fabrication because the droplets can be ejected at many angles, not just from straight overhead.

4 Powder Bed Approaches

4.1 Three-Dimensional Printing

A group at MIT developed "three-dimensional printing" technology and licensed it to Soligen, which sells parts produced on its Direct Shell Production Casting (DSPC) system (Figure 5). In 3D printing, a powdered material is distributed a layer at a time and selectively hardened and joined together by depositing drops of binder from a mechanism similar to that used for ink-jet printing. The main materials used are ceramics: alumina particles and colloidal silica binder [3, 4, 20, 22, 38, 37, 32].

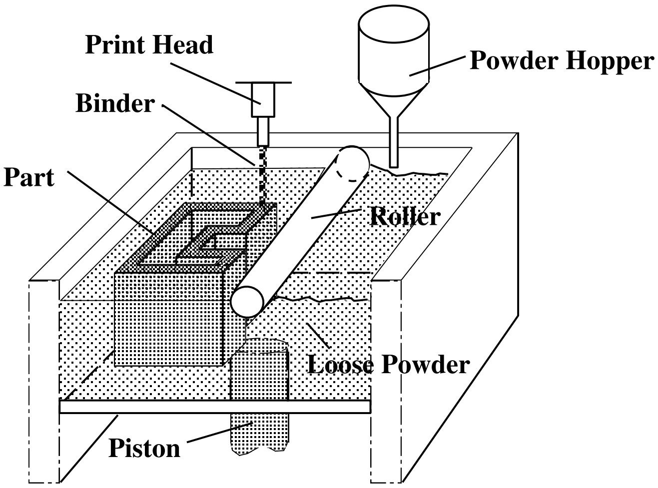


Figure 5: 3D Printing

For each layer, a powder hopper and roller system distribute a thin layer of powder over the top of the work tray. Adapted continuous-jet printing nozzles apply binder during a raster scan of the work area, selectively hardening the part's cross section. Then a piston lowers the part so that the next layer of powder can be applied. The loose powder that wasn't hardened remains and acts as a support for subsequent layers. With ceramics, after the part has been built up, the entire tray is fired in a kiln, and then loose powder is removed.

The 3D printing process is quite flexible in choice of materials. Any combination of a powdered material with a binder that has low enough viscosity to form droplets could potentially be used. In addition to ceramics, plastic, metal, and metal-ceramic composite parts can be made. A potential disadvantage is that the parts will always be porous because of density limitations on the distribution of dry powder. For metal-ceramic composites, the porous ceramic shape is produced using 3D printing and subsequently pressure infiltrated with molten metal to form the composite. The main focus with ceramics, however, has been on ceramic shells and cores that are used for casting metal.

In traditional investment or lost-wax casting, ceramic shells are made by a multi-step process. First a metal die tool is made to define the negative of the part, and if the part has hollows, dies are also made for cores that define the internal geometry. The cores are molded, and then a wax positive is molded around the cores using the primary tool. Wax positives are next attached together with a tree of wax that defines metal inlets and gas vents. The whole wax structure is repeatedly dipped into a ceramic slurry, allowing it to dry between dippings. Then the wax is melted out and the ceramic shell is fired. Finally the metal can be cast in this ceramic mold. As the metal hardens and shrinks, the shell and core crack. The shell is broken off and the cores are chemically dissolved during the final cleaning step.

By using 3D printing to produce the ceramic shells with integral cores directly from the CAD model, a number of disadvantages of the traditional process are avoided. Most significant is that the metal dies are typically expensive and time consuming to produce, with lead times ranging from two to six months. For small batch runs the cost of tooling can be prohibitive. With 3D printing, designs can prototyped quickly and economically. Furthermore, traditional lost wax casting methods require multiple pattern transfers, each with a potential loss of accuracy, that are eliminated by printing the ceramic shell directly. It is not clear whether the resolution of current 3D printing systems is high enough to realize this advantage, however. Finally, printing integral cores means that they will be precisely located and not subject to shifting when embedded in the wax, allowing thinner walls to be cast, and the cores can be made hollow, leaving less material to be leached out.

Soligen's DSPC software takes a CAD model of the positive shape and produces a model of the negative ceramic casting mold to send to the 3D printing system. Diverse metals, including copper, bronze, aluminum, cobalt chrome, stainless steel, and tooling steel, have been successfully cast in the ceramic shells produced by this process. Metal parts can generally be produced in two to three days.

One of the current areas of research in 3D printing at MIT is better curve fitting. With continuous ink-jet printing a steady stream of drops is output, with the drops that are not to be printed electrostatically deflected into a collection tube. It is possible to modify the deflection electronics to more precisely control the placement of the drops that are deposited. This is done at the edges of the part to help control aliasing. Unfortunately, since the input is triangulated .STL files, the droplets are only being placed closer to a faceted approximation of the actual curved boundary.

4.2 Selective Laser Sintering

Selective laser sintering (SLS) was developed at the University of Texas, Austin, and licensed to DTM Corporation [4, 3, 11, 20, 22, 29, 32]. In SLS, layers of powdered particles are selectively "sintered" together by scanning a CO_2 laser over the surface of a powder bed (Figure 6). Powdered materials that can be used include nylon, polycarbonate, investment casting wax, and a metal composite. Research continues on using the process with ceramic powders.

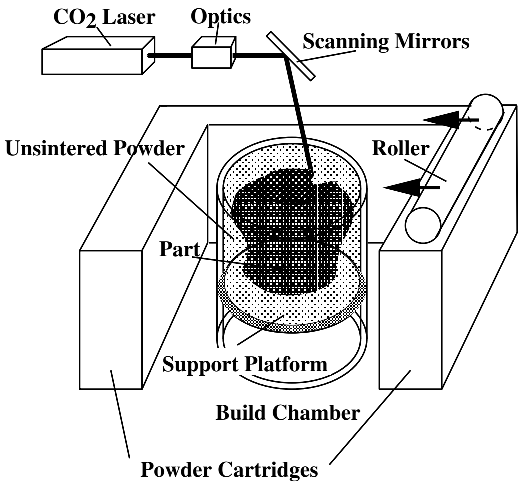


Figure 6: Selective Laser Sintering Apparatus

Each layer of powder is delivered to the cylindrical building area by a cartridge feeding system and a roller that distributes and levels the powder. Then the powder is heated to just below its melting point; inert nitrogen gas fills the rest of the build chamber to prevent explosions and oxidization. During a raster-scan of the work area, the laser beam is modulated so that only the cross section of the desired geometry is heated sufficiently for the viscosity of the particles to drop enough for them to fuse. Then the powder tray is lowered and the next layer of powder deposited. Unhardened powder supports the part being built, eliminating the need for separate support structures. After part building is completed, the part is raised up and much of the unsintered powder falls away. A layer of powder is left in place around the part to insulate it so that it won't cool too rapidly. Once the part has cooled, this powder must be removed by hand with brushes, compressed air, and dental tools.

With DTM's RapidTool process, additional processing steps are required. The parts are made out of a mixture of approximately 95% iron and 5% polymer. After the green part is cleaned, it is put in a furnace to burn out the polymer binder. The remaining metal is sintered, but it is still porous. Copper is infiltrated to make a fully dense metal tool. Tooling produced by this process can be used to manufacture as many as 50,000 parts using standard injection molding equipment.

SLS has been widely used in both the aerospace and automotive industries, primarily for producing polycarbonate parts that are wax-coated for investment casting. Polycarbonate is not as sensitive to temperature changes as wax, which makes it more suitable for shipping, whereas wax may melt or become brittle and break if shipping temperatures are too hot or too cold. Finer details, including thinner walls, are also possible to reproduce with polycarbonate. If the polycarbonate part is going to be used for other purposes, it can be treated with an epoxy resin to make it smoother and stronger, or it can be sanded by hand [50]. Nylon parts are often durable enough to be used directly for testing snap fits and assemblies, and can withstand temperatures up to 150°F. The SLS parts are primarily used as patterns for prototypes; once the design is finalized traditional tooling is generally used for production.

5 Sheet Based Subtractive Approaches

All of the SFF technologies discussed above are additive. The layers are formed by fusing, hardening, or depositing material in the shape of the cross section. In subtractive SFF technologies, the layer is formed by removing the material that is the negative of each cross section.

5.1 Stack First

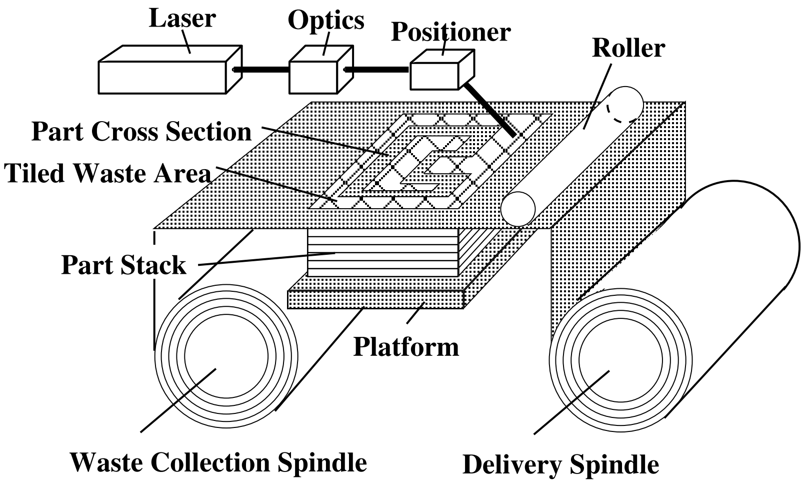


Figure 7: Laminated Object Manufacturing

Laminated object manufacturing (LOM), developed by Helisys, is the only fully automated subtractive SFF technology commercially available [4, 3, 5, 20, 16, 22, 25, 33]. Laminated parts are produced from paper, plastic, foil, or composite sheets, all coated with a thermally activated adhesive. The material is supplied in a roll that is placed on a delivery spindle, unrolled across the top of the work surface, and collected on the other side by a waste collection spindle (Figure 7). At the start of the cycle for each layer, a heated roller bonds the rectangular “work area” on the sheet to the top of the part stack containing the partially built up part. A laser cuts the outline of the new layer and the outline of the work area. The negative space in between, and any holes in the cross section, are crosshatched into “tiles” by the laser to facilitate eventual removal. Then the part stack is lowered, allowing the waste collection spindle to roll up the unbonded waste material surrounding the work area and pull a new section of the roll across to cover the work surface. Then the stack is raised back up to contact the clean sheet, ready to be bonded for the next cycle. The stack is measured after each layer, so that variations in layer thickness can be accounted for when determining the contour to cut. LOM parts can be used as patterns for secondary tooling processes, including RTV molding, spray metal tooling, and investment casting.

Despite the tiling, removal of the waste material from the part block at the end of the process is problematic. Tiling alone does nothing to prevent horizontal part surfaces from bonding to the waste material above or below. The software identifies flat horizontal surfaces, either up or down facing, and uses a finer crosshatching pattern called burnout where they meet the scrap material. For up facing surfaces, the burnout is done on the top part layer; for down facing surfaces, it is done on the layer below them. Burnout does not affect the adhesive bonding, but it weakens the underlying material so that it can be broken off more easily. Initially the software did not identify horizontal surfaces that resulted from stair-stepping in reproducing angled surfaces, so these surfaces were not burned out. This may have been corrected in more recent software releases. The final part always needs to be carefully broken out by hand to avoid delamination.

Another issue in waste removal is hollows within the part. Parts with completely enclosed hollow areas cannot be built using LOM since the waste material will be permanently trapped inside. Helisys's initial prototypes used a suction system to remove waste as the part was being built, but this was not incorporated into the initial commercial systems, which retain the waste material to support the part. Even for hollows that are not completely enclosed, it may not be easy to get inside them to loosen waste bonded to horizontal surfaces, and the waste tiles may be too big to fit through openings for removal.

LOM does offer some advantages over other rapid prototyping technologies. The waste material acts as an automatic support structure, supporting the part and maintaining the exact position of "islands" in the part that won't be connected until higher layers have been attached. Since layers are cut after they have been bonded, shrinkage is not a concern. Any material manufacturable in sheets coated with adhesive can potentially be used, and will often be inexpensive as well. (The early paper used was actually waxed butcher's paper, with the wax coating acting as a thermally activated adhesive.) With a modified system for applying the new sheets, it would be possible to change the color or even material for each layer. Because LOM is subtractive, only the outline of each layer needs to be cut, rather than tracing out the entire interior of each cross section, for a potential speed advantage. This advantage is offset by the need to tile the negative space, however, particularly if the part volume is small compared to the work area, and current LOM systems are slower than other SFF systems for most applications.

Other disadvantages of LOM include delamination, anisotropic material properties, the creation of large amounts of scrap material (though it is at least non-toxic), limitations on part geometry dictated by waste material removal considerations, and warpage caused by internal stresses generated by the heat of laser cutting.

In addition to Helisys, a Swedish company, Sparx, makes a subtractive rapid prototyping system that cuts layers out of polystyrene. The waste material removal and stacking of layers has to be performed manually, however.

5.2 Stack Last

A laminated technology called Computer-Aided Manufacturing of Laminated Engineering Materials (CAM-LEM) is under development at Case Western Reserve University and CAM-LEM, Inc.[8, 30]. A laser cuts each cross section from a thin sheet of material. In future systems, the laser will also approximate the edge tangents at the profile. A selective-area gripper lifts up the positive of the cross section and transfers it to a stacking station, preserving the position of all the elements. This cutting and stacking operation has been performed successfully with ceramics, paper, cardboard, plexiglass, and styrofoam. Then the laser cuts the same profile out of a sacrificial material and the complement of the cross section is transferred to the stacking station, so that the entire layer will be of a uniform height when the next layer is applied. Thus a support structure is generated automatically from the sacrificial material using the same tool paths. The layers are tacked together as they are built up, and after the final layer is attached, the part block is laminated for strength using an isostatic press. With ceramics, a final firing step burns out the sacrificial material and completely fuses the ceramics layers, so that the finished piece will exhibit isotropic material properties.

6 Hybrid: CMU's Shape Deposition Manufacturing

Shape deposition manufacturing (SDM) is a complex SFF technology being developed at Carnegie Mellon's Engineering Design Research Center [15, 46, 45]. SDM's main innovations are software support for embedded components and multiple materials, and the use of 5-axis NC milling to shape the edges of individual layers. A robotic pallet system moves the part between stations that deposit and shape the layers. Each layer is composed of a combination of primary material(s) and a sacrificial support material deposited in the complementary shape.

The 3D description of a part is adaptively sliced into layers of different thicknesses, based on the location of undercut features. These are true 3D layers, unlike the 2.5D layers used by virtually all other SFF process planners. Each layer is further subdivided if it has both undercut and overcut features. If there are any undercut features, the support material is first deposited at their edges in near-net shape (Figure 8 a) by a thermal deposition process (thermal spraying or weld-based for metals). Then the part is robotically transferred to the shaping station, where a 5-axis NC mill machines the exact complement of the undercut feature into the support material (Figure 8 b). Next the part is returned to have the primary material deposited (Figure 8 c); undercut features in the primary material will thus be shaped by the support material. Then the part is transferred back to the shaping station to mill overcut features (Figure 8 d). Finally, the part is returned to the deposition station to have support material deposited around any overcut features, and the layer is milled smooth (Figures 8 e, f). If multiple primary materials are used, similar analysis of undercut and overcut features between the materials will be required to deposit and mill the layer's segments in the proper order. After each milling step, the part is transferred to a cleaning station to have cutting fluids removed. Additional intermediate operations can be performed on the layers, such as embedding electronic components or shot peening (bombarding the area with small pellets) to relieve internal stresses.

A combination of materials that has been used successfully with this process is

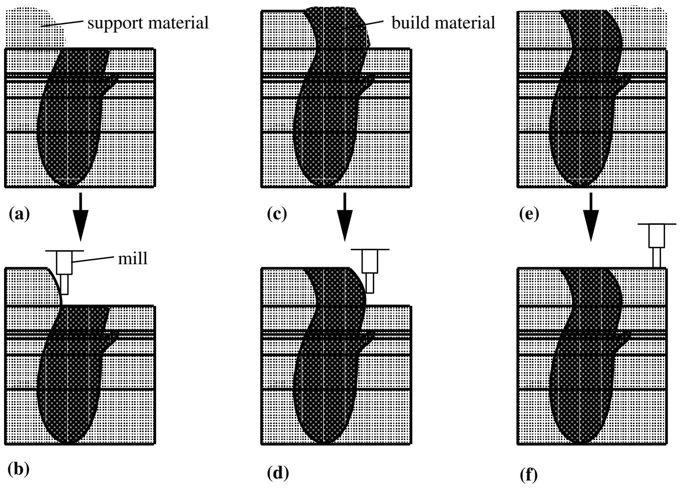


Figure 8: Shape Deposition Manufacturing

stainless steel as the primary material with copper as the sacrificial support material. The molten copper can be deposited on the solid stainless steel without melting it because copper has a lower melting point, and the molten steel can be deposited on the solid copper without melting it because copper has a much higher thermal conductivity. At the end of the process, the copper is dissolved with nitric acid, leaving the stainless steel part intact.

SDM accepts part geometry in the ACIS [40] format, allowing curved surfaces to be expressed as NURBS. Process planning is also performed using ACIS models. Unfortunately, according to Lee Weiss, they have not found ACIS to be as robust as they had hoped [44].

7 Comparison

Rapid prototyping technologies can be compared using a variety of criteria, with cost and speed generally considered the most important. Users are also concerned about what the part looks like: its accuracy and surface finish, what materials can be used, what geometries can be reproduced, and how large a part can be built. Taking a longer view, a process that can be scaled for greater speed or larger build area will have a better chance of survival as the technology matures, and a more environmentally friendly process will win adherents as "green" manufacturing becomes a greater concern. This section compares the SFF technologies that have been commercialized.

7.1 Cost

Operating SFF equipment is an expensive proposition, requiring an minimum expenditure of almost $100,000 on the machine alone, plus maintenance, computers, materials, and in some cases, a postcuring apparatus (Table 1). In terms of capital investment, solid ground curing with Cubital's Solider 5600 is probably the most expensive SFF technology, rivaled only by high-end SLA stereolithography machines. The SLA-500 costs $500,000 and the Solider 5600 costs $445,000, but the size and weight of the Solider necessitates a larger facilities investment. On the low end, systems for about $100,000 are available for laminated object manufacturing, photosolidification, and also stereolithography, for smaller build areas. Systems for LOM and photosolidification are also available with large build areas for about $200,000.

Maintenance costs are another consideration. In general, lasers require frequent and costly replacements, making for more expensive systems than those that use UV lamps. The lasers used by 3D Systems's stereolithography machines, for example, have an expected lifetime of 2,000 hours, compared with the LSI-1212's UV lamps with an expected lifetime of 10,000 hours. An SLA machine operated daily for one eight hour shift would need a new laser about once a year, but since it can run unattended, many large jobs are left to run overnight, and the yearly number of laser replacements could be higher. Chrysler reports replacing lasers roughly every six months after 4,000 hours of use. At a cost of $25,000 per laser for the SLA-500 or $9,200 for the SLA-250 [48], this can be a considerable expense. In contrast, the UV lamps used in the LSI-1212 cost $200. SLA maintenance contracts that include

Technology	Base Cost	Service Contract	Postcurer Cost	Chrysler [22, 49] Part Cost
Stereolithography			$10K[48]	
SLA-190/20	$110K[2]			
SLA-250/30	$250K[2]	$36K[22]		$110-130
SLA-500/30	$500K[2]	$85K[22]		$150-190
Photosolidification				
LSI-0609	$100K[20]			
LSI-1212	$105K[28]	$6K[28]	$8K[28]	
LSI-2224	$160K[20]			
SGC			n/a	
Solider 5600	$445K[10]	$69K[10]		$90-380
Solider 4600	$275K[10]	$49K[10]		
3D Printing				
DSPC (Soligen)	(service bureau)			
FDM			n/a	
FDM-1600	$170K*[41]	$7K[41]		
3D Modeler	$182K[4, 20]	$7K[22]		$150-320
SLS			n/a	
Sinterstation 2000	$330K[12]	$68K[22]		$180-200
LOM			n/a	
LOM-1015	$119K[19]	$4K[19]		$90-110
LOM-2030	$234K[19]	$6K[19]		

*Table 1: Comparison of Rapid Prototyping Technologies : Costs. The Chrysler Part Cost figures are the range of published estimates of the actual cost to produce a small benchmark part on several systems, based on operation data gathered by Chrysler. For more details, refer to Appendix A. (*FDM-1600 quote does not include cost of required Unix workstation.)*

laser replacements can be purchased from 3D Systems for $36,000 and $85,000 for the SLA-250 and SLA-500 respectively [22], as compared with basic service contracts at $25,000 and $45,000. On the other hand, the large number of non-laser components in the Cubital system makes it more likely that one of them will need servicing, reflected in Cubital's high basic service contract price.

Per-part marginal cost can also be extremely high with the SGC Solider system. Material costs are higher, because the support wax and unhardened resin must be discarded after each build. Furthermore, long build times combined with the cost of attended operation can make parts several times more expensive to produce with the Solider than with other systems, according to Terry Wohlers [49]. But, if numerous parts are efficiently packed into the build area and built at the same time (a common practice with the Solider), the cost of the attendant is amortized over all parts, and the total cost per part could actually be lower with SGC than for any of SLS, SLA, LOM, or FDM, as reported by Au and Wright [4].

That estimating the costs of different SFF technologies is inherently subjective is brought into sharp focus by the fact that the authors of both the articles cited obtained their data from the same Chrysler benchmarking study of the manufacture of the same 1.5x1.5x3" speedometer part, yet one found SGC to be the most expensive technology for manufacturing the part, and the other found it to be the least expensive technology. Running the more expensive machines infrequently or without packing their larger build area can raise per-part costs dramatically.

By adjusting parameters such as the shape, size, or number of test parts carefully, most any company could make a case that their system is the most cost effective. Potential customers would need to know the types, sizes, and number of parts they will be producing in order to evaluate the true cost of each system for their particular business. For more details of the Chrysler benchmark and an interpretation of the results, refer to Appendix A.

7.2 Speed

As with cost, SFF speed can be measured in many ways (Table 2). Of the additive approaches to SFF, Cubital's Solider 5600 is one of the fastest when measured by the total cubic inches per hour it is capable of producing. This is the result of layer-at-a-time fabrication over a large build area. Each layer only takes sixty five seconds, regardless of the area of resin hardened, for an estimated build rate (with layers of

.005" and the build volume 33% filled) of 26 inches^3/hr (.33 vertical inches/hour). With LSI's photosolidification machines, the time to form each layer is even shorter, only thirty to forty seconds, for a faster estimated build rate of .6 vertical inches/hour with layers of .005", but this does not include the time to slice the input file and produce the masks, which must be done before part building commences.

Technology	Preprocessing	Build Speed	Postprocessing
Stereolithography	slice, support generation		postcure, remove supports
SLA-190/20		30"/sec scan[2] .25 in^3/hr[20]	
SLA-250/30		30"/sec scan[2] .75-4 in^3/hr[10, 48]	
SLA-500/30		200"/sec scan[2] 3 in^3/hr[10]	
Photosolidification	slice, print masks		postcure, remove supports
LSI-0609		40 sec/layer[26]	
LSI-1212		30 sec/layer[28]	
SGC	(no pre-slice)		wash off wax
Solider 5600		65 sec/layer [10] 26 in^3/hr[10] .33 vert"/hr[20]	
Solider 4600		120 sec/layer [10] 10 in^3/hr[10]	
3D Printing	(no pre-slice)		remove powder, fire in kiln
DSPC (Soligen)		.39 vert"/hr[20]	
FDM	slice, tool path and support generation		remove supports
SLS	(no pre-slice)		remove powder
Sinterstation 2000		.75 in^3/hr[20]	y
LOM	(no pre-slice)	.25–.33 vert"/hr[20]	breakout
LOM-1015		15"/sec scan[20]	
LOM-2030		24"/sec scan[20]	

Table 2: Comparison of Rapid Prototyping Technologies : Speed

Point-to-point laser additive approaches, which include SLA, SLS, and 3D printing, tend to be slower. Cubital estimates the build rate of SLA machines to be only .75–3 in^3/hour [10], and Plynetics, an independent service bureau in San Leandro, CA, gives an even lower estimate of .25 in^3/hour for the entry level SLA-190 system[20]. Plynetics estimates the build rate for SLS to be three times faster, .75 in^3/hr [20]. Soligen claims a .39 vertical inches/hour build rate for DSPC [20]. The vertical build speed of a point-to-point approach, however, is an almost meaningless statistic without knowing the size and shape of the cross sections of the layers being produced. If this measurement was taken for a part that was 33% solid and filled the entire build area, it would be a build rate of better than 10 in^3/hour.

With LOM, a subtractive approach, the ratio of the available build volume that is filled by the part has an enormous impact on speed measurements. A smaller part could actually take longer to build because of the time required to cut the negative of the part into tiles for later removal. Helisys reports a build rate of .25–.33 vertical inches per hour [20].

For small parts, FDM can achieve impressive speeds. Stratasys reports a build speed of two vertical inches/hour for a 3.5" diameter turbine blade [20]. FDM is also a point-to-point approach to SFF, so this build speed cannot be generalized to other geometries. Furthermore, FDM can be run with significantly thicker layers than many of the other processes, achieving better speed at the cost of lower accuracy.

The Chrysler benchmarking study [49] of the time to produce a single speedometer part can be used to verify these figures (see Table 7 in Appendix A for the raw numbers). Chrysler found that FDM had the fastest machine build time, when run with thick layers, of a little over two hours (≈ 1.5 vertical inch/hr, consistent with Helisys's reported speeds), though with thinner layers the build time increased to eight hours, demonstrating how sensitive SFF technologies can be to the choice of build parameters. The second fastest machine build time of three hours was achieved by SLS ($\approx$ .75 in^3/hr if the part is assumed to fill 33% of its bounding box volume, consistent with the Plynetics estimate). With both the SLA-250 and the SLA-500, the part took approximately five hours to build ($\approx$ .45 in^3/hr, faster than the Plynetics estimate for the SLA-190 but slower than the Cubital estimates), and was only twenty two minutes faster with the more powerful SLA-500 than with the SLA-250. This small a difference may seem surprising considering that the scan speed of the SLA-500's laser is over five times faster, but unfortunately the higher scan speed means that the laser doesn't penetrate as deeply, so it can only be run at full speed with much thinner layers. The slowest machine build times of ten hours were from SGC and LOM ($\approx$ .22 in^3/hr). This is somewhat misleading because both these machines have build areas far larger than the part being produced, and neither would be slowed down by packing the build area with multiple parts or a larger part, which would considerably affect the speed of the other machines being benchmarked.

In addition to the actual machine time during the build, the pre- and post-processing operations can add significantly to the total time to produce parts. Preprocessing may include creating support structures, processing the input files, including merging and slicing multiple part files, and machine setup time. For stereolithograpy on SLA machines, FDM on Stratasys machines, and photosolidification on Light Sculpting machines, the part building cannot begin until slicing is completed, so a part that is taller or built with thinner layers will require longer preprocessing. This is not an issue for Helisys's LOM, Cubital's Solider, or DTM's Sinterstation, which slice in parallel with building.

Postprocessing may include cleaning excess material from the finished part, such as unsintered powder or uncured resin, postcuring, and removing support structures. In the Chrysler study, the combined pre- and postprocessing time was the lowest for LOM and SGC, about one and a quarter hours, and about an hour longer for SLS, SLA and FDM with thick layers. With thin layers, FDM had an additional two and a quarter hours of preprocessing time.

7.3 Accuracy

Unfortunately, the Chrysler study did not report on accuracy, so the numbers in Table 3 generally reflect manufacturer's estimates, typically based upon best case scenarios. Although many manufacturers quote absolute tolerances for their process, the accuracy is usually dependent on the size of the part and the axis of measurement.

According to Plynetics [35, 34], SLA parts typically have tolerances of ±.001"/inch, ±.004" minimum; SLS polycarbonate parts have tolerances of ±.002"/inch, and SLS nylon parts, ±.003"/inch. Cubital reports XY tolerances of ±.001"/inch, though an SME video claims that SLA parts are often the most accurate [32].

The best tolerances quoted for stereolithography typically apply only to rectilinear parts [52]. For complicated part geometries, SLA tolerances are closer to ±.015" because warpage and shrinkage are much more difficult to predict and correct for. Although Paul Jacobs, director of R & D at 3D Systems, reports that the accuracy obtained with SLA in 1993 for a standard "user part," a benchmark part with a 9.5x9.5" cross section, was better than ±.004" for 90% of measurements [21], this was a symmetric and mainly rectilinear part.

Any manufacturing process that involves using SFF parts as positives for creating secondary tooling has the multiple pattern transfers and associated loss of resolution found with traditional investment casting. This effect won't be nearly as pronounced with 3D printing's DSPC process — another factor to take into account when comparing tolerance figures.

Technology	Z Resolution	XY Resolution	XY Tolerance
Stereolithography	.0025-.03"[22]		±.004-.015"[20, 35]
SLA-190/20	.004-.01" min[2]	.008-.011"[2]	
SLA-250/30	.004" min[2]	.008-.011"[2]	
SLA-500/30	.004" min[2]	.008-.01"[2]	
Photosolidification			
LSI-0609	.001-.05[3, 20]	.00025-.0015"[3]	
LSI-1212	.0005" min[28]	.0017" as supplied[28]	±.001"[28]
LSI-2224	.001-.05"[3, 20]		
SGC			
Solider 5600	.004-.006"[10]	.004"[10]	.1% $\leq$ ±.02"[10]
Solider 4600	.006"[10]	.004"[10]	.1% $\leq$ ±.02"[10]
3D Printing			
MIT prototype	.068-.175 mm[37] (.003-.007")	.125-.175 mm[37] (.005-.007")	.02 mm std dev[37]
DSPC (Soligen)	.007"[20, 39]	.005"[39]	±.05mm[20]
FDM			
FDM-1600	.002-.03"[41]	.01"[41]	±.005"[41]
3D Modeler	.001-.05"[3, 20]	.009-.025"[4]	±.005"[3, 4, 20]
SLS	.003-.02"[12]		±.005-.03"[20] ±.002-.003"/inch[34]
LOM	.002-.02"[20]		±.01"[4, 20]

Table 3: Comparison of Rapid Prototyping Technologies : Accuracy. Resolution refers to the minimum addressable distance between elements. Along the Z axis, this corresponds to the layer height. In the XY plane, it corresponds to dpi (dots per inch) for a system that raster scans. Tolerance refers to the plus or minus deviation from the ideal measurement.

The best accuracy and the best surface finish are often along different axes, so these two considerations must be traded off when choosing a build orientation. An experienced operator can often produce a far more accurate part than a novice by adjusting build parameters based on a better understanding of the idiosyncrasies of the process.

7.4 Surface Finish

While resolution is one indicator of surface roughness, it is not the only factor. For processes that use powdered materials (3D printing and SLS), surface finish can be worse than the resolution alone would suggest if the powders retain their shape in the process. Ceramic parts produced by 3D printing can be smoothed by post-dipping them in a ceramic slurry with much smaller alumina particles, and polycarbonate SLS parts can be epoxy coated to smooth and strengthen them, or coated with wax for casting. Raster scanning, also used in 3D printing and SLS, leads to poor surface finish at the edges of each cross section. This could be improved by doing an additional vector scan around the profile, as is done with SLA systems.

Any process that requires attached external support structures has the potential for surface flaws where they are broken off. This problem is particularly pronounced with FDM, which requires dense supports that could potentially be attached over the entire bottom surface of the part. To alleviate this problem, the FDM-1600 is offered with multiple material deposition heads and software to support the recently developed break away support system.

7.5 Materials

Different SFF technologies are compatible with a variety of materials. Stereolithography, photosolidification, and solid ground curing are all fundamentally limited to photopolymers, with the original acrylate polymers now largely replaced by tougher epoxies. LOM was initially available for use with paper sheets only, but can now be used with plastics, composites, and ceramics as well. It could theoretically work with any material available in sheets that can be glued together and cut by a laser. 3D printing can be used with ceramics, plastics, metals, and metal-ceramic composites. Any combination of a material that comes in a powdered form and can be consolidated with a liquid binder is a candidate for use. SLS has also been used with a wide variety of materials, including nylon, investment casting wax, polycarbonate, and metal composites. Any material that comes in powdered form and can be sintered together by a laser is a candidate for this process. FDM has been used with machinable and investment casting wax as well as thermoplastics. It is suitable for materials with relatively low melting points, since it does not include a powerful laser.

Material costs for the different SFF systems benchmarked by Chrysler vary by a factor of two. Chrysler reported the lowest per-part material costs (for the speedometer part with a 6.75 in^3 envelope) of \$3.08 and \$3.82 for SLA and LOM respectively, identical costs of \$4.00 for SLA and FDM, and the highest material costs of \$5.96 for SGC. The photopolymers used for SLA cost from \$250-700 per gallon; those used with LightSpeed's system only cost \$150 per gallon. FDM filament spools cost about \$350 and produce a part volume roughly equal to that produced by a gallon of photopolymer.

For most applications, the brittleness of the acrylates used in stereolithography and related processes is a serious drawback. Research aimed at developing less brittle resins has resulted in the introduction of a tougher epoxy resin for building SLA prototypes. However, for one application, building flexible reinforced rubber parts, a process has been developed that relies on the brittleness of the acrylate [43]. Flexible parts are built by applying successive layers of fabric wetted with rubber resin around an expendable tool, resulting in a part with uniform wall thickness. Traditional processes use a master tool and an intermediate tool to form the final sacrificial tool that the part is shaped upon. This final sacrificial tool is washed away once the part is cured. Using SLA, the final tool can be built directly from acrylate resins and removed simply by crushing the cured part with one's hands. The flexible part is undamaged but the brittle tool shatters and falls away.

Many other processes use SFF parts as tools or patterns for creating secondary tooling, greatly increasing the choice of materials for the final part. Direct shell production casting, the first commercial application of 3D printing, is designed specifically for making ceramic molds and cores for casting. DTM uses SLS to produce sintered metal parts that are used as production tools, as well as polycarbonate parts that are coated with wax and used as patterns for investment casting. LOM and SLA parts can be used for RTV molding, spray metal tooling, and investment casting. FDM parts can also be used with spray metal tooling and investment casting. SGC parts can be used with silicon rubber, epoxy, or spray metal tooling, and coated models can be used as patterns for sand casting.

7.6 Part Geometry

Part geometry capabilities are limited by minimum positive and negative feature size, the build area of the system, input formats, support requirements, and by whether material can be removed from internal voids. Table 4 presents a summary comparison of the geometric capabilities of different SFF systems.

One of the advantages of many SFF processes over traditional prototyping is the ease of making complicated shapes with inaccessible interior chambers. The Solider system has the fewest constraints on part geometry, since all unhardened polymer is vacuumed up between layers, and wax fully supports the part during building. This allows fully assembled mechanisms to be built, such as interlocking gears. Completely enclosed voids cannot be manufactured, however; a small outlet is needed to remove the support wax. (See Table 5 for a rating of the applicability of different technologies to a variety of challenging geometries.) Stereolithography and photosolidification can handle small internal voids if drain holes are added to the design to allow uncured polymer to escape, but access to the interior to remove the supports that would be required for any significant overhang remains an issue. The same is true for fused deposition manufacturing. For 3D printing, SLS, and LOM, the

Technology	Max Area(inches)	Min Feature Size	Input
Stereolithography		.008”[20]	.STL, .SLC[2]
SLA-190/20	7.5x7.5x10[2]		
SLA-250/30	10x10x10 [2]		
SLA-500/30	20x20x23[2]		
Photosolidification			.STL[20]
LSI-0609	6x6x9[3]		
LSI-1212	12x8.25x12 [28]		
LSI-2224	22x22x24[20]		
SGC		.006” horizontal, .024” vertical [10]	.STL, .UNV, VDA-FS, IGES, .CFL, Pro/E [26]
Solider 5600	20x14x20[10]		
Solider 4600	14x14x14[10]		
3D Printing		.007”[20]	
DSPC (Soligen)	10x8x8[20]		.STL
FDM			.STL, IGES, NC G-code[26]
FDM-1600	9.5x9.5x10[41]	.01-.1”[41]	
3D Modeler	12x12x12[3, 4]	.01-.125”[20]	
SLS			
Sinterstation 2000	12” cylinder x 14”[12]	.015” PC, nylon; .03” wax[20]	.STL, IGES[22]
LOM		.01”[20]	.STL[20]
LOM-1015	14.5x10x14[4, 20]		
LOM-2030	32x22x20[4, 20]		

Table 4: Comparison of Rapid Prototyping Technologies: Geometric Specifications

requirement of removing unhardened powder or tiled pieces of material from internal voids means geometry with voids with limited access cannot be manufactured. This is a bigger problem with LOM since more force is required to separate the tiled material from the part.

The largest build area for a SFF system available in the U.S. is 32x22x20 inches, i.e. over 14,000 in^3, found in the LOM-2030. Stereolithography, photosolidification, and solid ground curing systems are all available in multiple sizes with a high end machine that has a large build area of over 5,000 in^3, with at least a 20x20 inch cross section in the largest dimension. SLS, FDM, and 3D printing systems are all

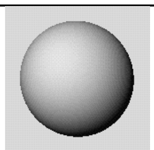
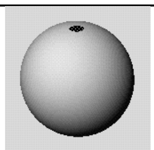
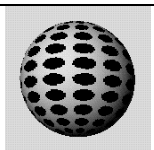
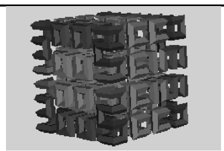
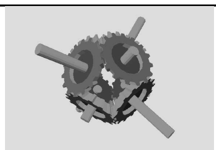
Process	 Hollow sphere	 Hollow sphere with drain and vent	 Two nested, perforated spheres	 Hilbert tube	 Preassembled octagear mechanism
SLA	F	B	C	B	C
SGC	F	A	A	A	A
3DP	F	B	A	A	B
FDM	B	B	C	B	C
SLS	F	B	A	A	B
LOM	F	F	C	B	C

Table 5: Comparison of Rapid Prototyping Technologies: Predicted Part Capabilities. A grade of "A" indicates that the given technology should not have trouble with this geometry. A grade of "B" indicates that supports that could be difficult to remove may be required for this geometry, or that the removal of excess powder could be difficult. A grade of "C" indicates that interior supports that may be difficult or impossible to remove are required for this geometry. A grade of "F" indicates that the given technology would not be able to manufacture this geometry.

limited to models with smaller build areas of under 2,000 in^3.

Parts that are too large to be built in one piece must be segmented into smaller components to be assembled after building. Some SFF systems, including the Solider, provide optional software for breaking up .STL files of larger parts into pieces that can be manufactured individually. Dowels can also be inserted into the part files to aid in assembly.

All of the commercial SFF systems accept data in the .STL format, the simple triangulated boundary representation developed by 3D Systems for the first SLA machine. Cubital accepts a variety of CAD data formats for input, but converts them all to .CFL, its own faceted representation. DTM's SLS machines accepts IGES surface model input in addition to .STL, making it possible to describe curved surfaces exactly. Stratasys's FDM machines include their own NURBS based modeling software, which slices models into layers and converts them to NC G-code programs to control the material deposition. Designs can also be imported from other CAD software packages via solid, surface, or wireframe IGES representations or .STL files, or users can generate their own NC programs and use these to control the machine directly.

7.7 Scalability

The scalability of an SFF technology is a consideration when evaluating its future potential, not just its current implementation. Some technologies are more promising than others for building larger parts than those that current systems can produce. This is a potential advantage of ink-jet based technologies such as 3D printing, which can be parallelized by using a multiple nozzle printhead, allowing larger, faster systems to be built. The size of systems employing lasers may be limited by the focusing capabilities of the laser, which may restrict the maximum size that the build area can reach before more expensive mechanical movements are needed to replace deflection mirrors.

7.8 Environmental Considerations

Other criteria for evaluating SFF technology include energy usage, recycling, and safety.

In theory, photopolymer based approaches can be more energy efficient because the crosslinking reaction that hardens the polymer is merely initiated by the laser. The helium cadmium and argon ion UV lasers used by 3D Systems, however, are less than .01% energy efficient, which tends to cancel out this advantage. CO_2 lasers, used by DTM and Helisys for SLS and LOM respectively, can be approximately 12% energy efficient, but output wattage must be much higher to sinter and cut material than to initiate polymerization, so the input wattage is roughly equivalent. Because of the extreme variations in build times with the different systems, energy usage should be measured and compared for a part's entire build cycle.

Recyclability varies across SFF systems. With SLS, unsintered powder brushed off of the part is strained and reused. Entire FDM parts and supports can be ground up and used to create partially recycled filament [51]. In SLA systems, uncured resin in the vat can be reused. Cubital's Solider has the disadvantage that unused resin is still partially exposed, so it can't be recycled, and neither can the wax used for support. The adjustable build volume helps to reduce the total volume of waste, however. In terms of recyclability, LOM is probably the worst of the commercial technologies because it generates so much solid waste.

SFF systems are industrial tools with industrial safety requirements. Systems with lasers need to have enclosed housings to protect the users' eyes and skin. Many SFF processes generate toxic fumes and require installation in ventilated environments. SLS uses nitrogen gas; DTM recommends using an oxygen monitor in the room with their equipment to ensure that the air remains breathable in the event of a leak. Uncured photopolymers are toxic and cause a potential toxic waste disposal problem. One solution is to cure any waste in sunlight, creating non-toxic solid waste instead. FDM is the best choice for safety, having none of these problems, and it is the only one of these systems that can be installed in an office environment.

8 Conclusion

Each technology has its own advantages and market niche, which is what has allowed each of the machines' producers to survive as a viable commercial enterprise (Table 6, page 40).

Stereolithograpy SLA machines produced by 3D Systems remain the SFF market leaders. SLA was the first to market, leading to a larger installed base and

Technology	Developer
Stereolithography	3D Systems, Inc. 26081 Avenue Hall Valencia, CA 91355 805/295-5600 fax: 805/257-1200
Photosolidification	Light Sculpting, Inc. Distributor: John Webb Results Marketing Corporation 1126 S. 70th St Suite 210A Milwaukee, WI 53214-3151 414/475-2600 fax: 414/475-4384
Solid Ground Curing	Cubital America Inc. 1307F Allen Drive Troy, MI 48083 810/585-7880 fax: 810/585-7884 cubitalam@attmail.com http://www.cubital.com/cubital/index.html
3D Printing	Soligen Technologies, Inc. 19408 Londelius St. Northridge, CA 91324 818/718-1221 fax: 818/718-0760
Fused Deposition Modeling	Stratasys, Inc. 14950 Martin Drive Eden Prairie, MN 55344-2020 612/937-3000 fax: 612/937-0070 fdm@stratasys.com
Laminated Object Manufacturing	Helisys 24015 Garnier St Torrance, CA 90505 310/891-0600
Selective Laser Sintering	DTM Corporation 1611 Headway Circle Building 2 Austin, TX 78754 512/339-2922 fax: 512/832-6753 http://www.dtm-corp.com/

Table 6: Contacts

greater name recognition and end-user expertise. 3D Systems also has the most mature technology, with the support of outside vendors for developing better resins and an automatic support generation program, Bridgeworks. The East Bay prototyping companies Metalcast Engineering and Plynetics perceive that the smoothness and accuracy of SLA parts is the highest in the industry [14].

Cubital's Solider solid ground curing systems produce more accurate parts than SLA, but the huge size and expense of the system have doubtless worked against its widespread acceptance. It is capable of producing the most versatile geometries, including assembled mechanisms, with higher accuracy and without the dimensional stability problems caused by shrinkage and warpage associated with SLA. For the moment, however, the majority of users seem unwilling to make the additional investment to obtain these advantages.

On paper, Light Sculpting's photosolidification systems look comparable to those of 3D Systems and Cubital in every area except cost, being less than half the price. As of 1993, however, they had shipped no units, and no independent verification of the vendor's speed and accuracy claims are available.

Selective laser sintering offers wider material choices than photopolymer approaches, including tougher materials, making it a better choice for producing functional mechanical prototypes directly. Although its accuracy is similar to that of SLA, the rougher surface finish makes it less desirable for casting.

Fused deposition modeling offers the only open architecture and the only machine suitable for use in an office environment. It produces small prototypes rapidly and at a relatively low cost when thick layers are used. It has been less successful in commercial prototyping environments mainly because the seam formed when moving between layers has not been brought to within the tolerances of the rest of the process.

Direct shell production casting with 3D printing is the technology of choice for producing one-shot ceramic molds for molding metal parts. Many companies will want several copies of a prototype of the final part design, however, which can be produced more economically with traditional five step investment casting off of an SLA positive, which can be hand finished to provide a smoother finish than can be obtained with DSPC.

Laminated object manufacturing has much lower quality and accuracy than the other commercial technologies, but it is capable of producing large one-shot parts economically. It is appropriate when material properties and tight tolerances are not an issue.

Unfortunately, shortcomings of many current CAD tools and the .STL interchange format prevent SFF from being used to its full potential. The majority of CAD software systems combine solid and surface based modeling techniques to give users maximum flexibility. Such systems allow the user to create non-solid parts that may nevertheless appear solid, often because round-off errors cause minuscule cracks in boundary surfaces. Such systems may not have a clear semantic distinction between the inside and outside of a model, a distinction that is necessary to produce a valid .STL description. Since .STL stores no connectivity data, it provides no support for verification of the consistency or correctness of a model description.

An inherent deficiency of .STL is the large size of files. Curved surfaces can only be represented approximately, and more accurate approximations require larger files. Repetitive information at the lowest level is required by definition, since each vertex must appear in at least three triangular facets of a valid closed solid, and its coordinates must be specified explicitly for each facet that shares that vertex. The inside and outside of the solid relative to each facet is specified by the ordering of the facet vertices as well as a surface normal. Redundant information is required, yet there are no semantics to define which information to believe if the redundant information is inconsistent. Because .STL is non-hierarchical, patterns and relationships between facets cannot be used to represent the model more compactly.

A simple, hierarchical, high-level language is needed for use as a digital interface for SFF. Such a language should allow models to be represented compactly, accurately, and in a device and resolution independent manner. In addition, the same representation that was used for prototyping could then be used as the basis for production, better integrating SFF into the development and manufacturing process.

Specialized CAD tools to support SFF are also needed, including a robust slicing tool to create the 2.5D layers needed for process planning which will slice realizable non-manifold objects and support adaptive layer thicknesses, a geometry checker to verify that files are closed solids, and rule checkers for realizable features such as minimum separation and feature size. Additional tools could improve accuracy and efficiency, such as a tool to evaluate and optimize the build orientation for its effect on precision and surface finish, and a tool to aid with part placement and packing when building multiple parts.

With the evolution of interchange formats and of design and planning tools, SFF has the potential to come even closer to the ideal of completely automated fabrication of three-dimensional parts.

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Glossary

3D Systems Developer and producer of SLA Stereolithography systems.

ACIS A 3D boundary-representation format and geometric modeler developed by Spatial Technology Inc.

BPM Ballistic Particle Manufacturing; an SFF technology under development at Perception Systems.

CAD Computer Aided Design.

.CFL Cubital Facet List, a faceted but more compact input format to replace .STL that is used as the final interface to Cubital's Solider machines.

Cubital Developer and producer of Solid Ground Curing (SGC) Solider systems.

DSPC Direct Shell Production Casting, the first commercial application of 3D Printing, developed by Soligen Technologies. The systems uses modified ink-jet nozzles to print binder onto a powder bed, producing ceramic molds for casting.

DTM Commercial licenser of Selective Laser Sintering (SLS) technology and producer of the Sinterstation 2000.

FDM Fused Deposition Modeling; an SFF technology, used in systems produced by Stratasys, that extrudes melted wax or plastic filament to build up parts.

G-code The low-level programming language used to control NC machine tools.

Helisys Developer and producer of Laminated Object Manufacturing (LOM) systems.

IGES Initial Graphic Exchange Specification. A non-proprietary graphics exchange format; ANSI standard Y14.28.

Investment Casting A casting process that uses a metal tool to shape a sacrificial positive that is first coated with a ceramic shell and then burned out so that metal can be cast in the ceramic mold, which in turn breaks when the metal hardens.

Lost Wax Casting Investment casting with a wax sacrificial positive.

LOM Laminated Object Manufacturing; a subtractive SFF technology, used in systems produced by Helisys, that builds up parts out of cross sections cut from material supplied in sheets.

LSI Light Sculpting, Inc., developer and producer of photosolidification systems.

NC Numerical Control. NC machine tools are controlled by simple G code programs.

NURBS Non-Uniform Rational B-Spline.

RPM Rubber Plaster Mold process, a form of investment casting using a soft urethane tool to produce plaster molds for the final casting step[7].

RTV Room Temperature Vulcanizing.

SDM Shape Deposition Manufacturing, an SFF technology under development at Carnegie Mellon University.

SGC Solid Ground Curing; a layer-at-a-time, photopolymer based SFF technology used in systems produced by Cubital.

SFF Solid Freeform Fabrication.

SLA Stereolithography Apparatus produced by 3D Systems (and trademark of same).

.SLC New SFF exchange format developed by 3D Systems to supplement .STL.

SLS Selective Laser Sintering; an SFF technology developed at UT Austin and used in systems produced by DTM Corporation that use lasers to fuse powdered particles.

SME Society of Manufacturing Engineers.

Solider The Solid Ground Curing (SGC) system line sold by Cubital.

Soligen Producer of the Direct Shell Production Casting (DSPC) system, the first commercial application of 3D Printing.

.STL The standard interchange format to specify 3D solids for SFF production. Specifies solids via a triangulated boundary representation.

Stratasys Developer and producer of Fused Deposition Modeling (FDM) systems.

.UNV SDRC-IDEAS (Structured Dynamics Research Corporation) "universal file" interchange format for 3D solids.

VDA-FS The standard CAD format used by the auto industry in Europe.

A Estimated Part Costs

A.1 Assumptions

In 1992, Chrysler conducted a widely quoted study of the costs of producing a prototype part (a 1.5x1.5x3" speedometer adaptor part) on the different SFF machines it was considering for purchase. Chrysler already owned two SLA-250 systems that it used to build the part itself, but in order to evaluate the other systems it sent the .STL file for the part to the manufacturers and asked them to build it. Helisys, DTM, and Cubital all produced the part using beta versions of their systems; 3D Systems and Stratasys used a production systems. Today, production versions of all of these technologies are available. Although many of these systems are capable of producing parts within the same range of layer thicknesses, each manufacturer chose a different layer thickness for this study, further complicating the interpretation of the results.

Using the Chrysler data on build times and operating costs, I have re-estimated the cost of producing the part using SLA, SLS, SGC, LOM, and FDM. For these new estimates, depreciation and maintenance costs are calculated based on different usage rates for machines that required attended operation, and the charges for build time and materials are amortized if multiple parts could be built at the same time without affecting build times and/or material costs linearly. These assumptions are most appropriate for a service bureau or other organization that is using its rapid prototyping equipment at near capacity, always having enough jobs to pack the build area and keep the machine running.

Additional factors could be incorporated into the model to obtain even more accurate estimates. No attempts have been made to include the contribution of power requirements, facilities costs for housing the equipment and providing for a safe operating environment (e.g. ventilation systems), or optional software or equipment.

For the machines that don't require attended operation (SLA, LOM, and FDM), hourly depreciation is calculated assuming near continuous utilization, twenty four hours a day, six days a week, consistent with Chrysler's estimate of 4000 hours of laser use on its SLAs in each six month period. For the Cubital Solider, which requires attended operation, and the Sinterstation, which recommends attended operation to improve quality, hourly depreciation is calculated assuming utilization during sixteen hours (two shifts) a day, five days a week.

For SGC, the time to harden each layer and the amount of resin used for each layer is independent of the layer geometry. Thus, both build time and material costs could be amortized over the fifty eight identical speedometer parts that fit into a single layer in the build volume. However, the Chrysler reports of material costs for a single part are inaccurate, so new estimates of the material costs are used. Cubital systems use resin that costs \$276/gallon, and all the resin in the machine must be disposed of even if it is not hardened. Even if the build volume could be reduced to exactly the envelope of the speedometer part, this would still be \$8 worth of resin, more that the \$5.96 reported. But since only the width and height of the build volume can be adjusted, a build volume of 1.5x1.5x14" would have to be filled with resin, at a cost of almost \$38 for the single part. To fill the entire build volume to a height of 1.5" would require \$500 worth of resin. Since the Solider begins building as soon as the first layer is sliced [49], preprocessing time would not increase linearly when multiple copies of the same part are produced. Total preprocessing time for a multiple part build is estimated at three hours, the upper limit Cubital advertises [10], approximately nine times the preprocessing time for a single speedometer part. Preprocessing times for SLA and SLS were adjusted by a similar factor of 15% of the number of parts.

Since SLA systems use point-by-point solidification, the rasterization portion of the build time would increase roughly linearly with the number of parts, but the resin spreading and recoating portions of the build time can be amortized over the number of parts that fit in a layer. For the SLA-250, this is eighteen speedometer parts, and for the SLA-500, seventy two parts. The build parameters were not specified in the Chrysler study, but if default parameters for the recoating values are assumed (30 seconds leveling time, 5 second sweep, 4 second post-dip delay, .2 turns/second elevator velocity), there would be a total of approximately forty seconds before rasterizing each layer [22]. For .01" layers, the 1.5" high part would require 150 layers not including support structures, or one hour forty minutes of recoating time, a significant fraction of the total build time. If the rest of the process was completely linear in area, this would be a total build time of about sixty hours for the eighteen parts for the SLA-250. Based on estimates in [24], however, the total build time for 150 layers would be no more than fifteen hours. Costs are given for both of these estimates.

Similarly, selective laser sintering builds parts point-by-point, but multiple parts can be built at once without affecting the time to deposit and level each new layer of powder. Approximately nineteen speedometer parts fit into the Sinterstation's build area. For SLS, the costs of attended operation and nitrogen gas usage, as well as machine depreciation, can be amortized over the multiple parts produced. The Sinterstation was run with .005" layers for the Chrysler benchmark, requiring 300 layers to be deposited and leveled, for the fastest per-layer speed of thirty six seconds. If fifteen seconds of this time was spent preparing the powder bed and the rasterization time was linear with area, then the time for nineteen parts would be about thirty five hours. Again, Johnson's estimates [24] predict a shorter build time, six hours, so this whole range is considered. Preprocessing time is amortized using the same factor as for the Solider, since slicing occurs during the build. Alternate calculations based on running the Sinterstation unattended were also run.

No amortization was applied to the Helisys LOM figures because this system could only build one part at a time [49]. With modified software, however, LOM could theoretically build as many parts as fit in its build volume without increasing build time significantly. The time to slice the additional parts and cut their profiles would be offset by the time savings of the reduced area to be tiled.

For FDM, the material is applied and shaped in a single point-by-point operation, so there is no advantage in building multiple parts in the same layer. There is, however, a large speed and cost advantage to building parts with thicker layers with FDM that is not always realizable with systems that use lasers to solidify a part. With SLA, the laser scan speed must be decreased to compensate for the increased thickness, allowing the laser time to penetrate more deeply. In fact, for SLA systems, increasing the layer thickness above .005-.01" actually increases the total build time. The two sets of figures for FDM reflect the differing preprocessing and build times Chrysler obtained with FDM, presumably for different slice thicknesses. The lower figures are for a slice thickness of .2 inches. Of course, these parts will not be as smooth or accurate as parts built with thinner layers.

A.2 Estimates and Sensitivity Analysis

The estimated costs for building speedometer parts based on these assumptions are presented in Table 7. Hourly equipment depreciation was calculated based on estimated usage and assuming five year straight line depreciation with no scrap value. All of these cost estimates are based on the system costs and capabilities available in 1992. Today, the cost of SLS and SGC equipment has dropped, and the cost of SLA and LOM has risen.

For the SGC system, the cost of attended operation and depreciation dominate for the single part estimates; the cost of postprocessing dominates for the multiple part estimates. For making a single small part, SGC is the most expensive solution. For making multiple closely packed small parts, however, SGC is the cheapest solution. In the case of multiple parts, SLA is probably the closest rival to Cubital. Unattended SLS has comparable cost to SLA, but the parts would presumably suffer in quality. SGC parts will be cheapest mainly because their postprocessing is faster. There are no supports to remove and no powder that has to be laboriously brushed off; the wax can be removed completely automatically.

For FDM, the preprocessing costs dominate, leading to an extremely expensive part if the layers are thin. Over 85% of the cost of the FDM part is preprocessing cost, suggesting that with improved software this could be the cheapest technology of all.

For LOM, preprocessing costs again dominate, though the total preprocessing time is much closer to that of systems with faster preprocessing and hence probably has less room for improvement than FDM. For a single small part, LOM is the cheapest technology, and it would probably remain the cheapest for a single part with a large cross section.

	SLA250	SLA500	SGC	SLSa	SLSb	FDMa	FDMb	LOM
'92 Equipment cost	$195K	$395K	$490K	$397K	$397K	$182K	$182K	$95K
Maintenance cost	$36K	$85K	$49K	$68K	$68K	$7K	$7K	$17K
Attendant $/hr	0	0	$22	$22	0	0	0	0
Slice thickness	.01"	.01"	.004"	.005"	.005"	.02"	<.02"	.009"
Operating hours	7488	7488	4160	4160	7488	7488	7488	7488
Depreciation $/hr	$5.21	$10.55	$23.56	$19.09	$10.60	$4.86	$4.86	$2.54
Maintenance $/hr	$4.81	$11.35	$11.78	$16.35	$9.08	$.93	$.93	$2.27
single part:								
Machine build time	5:06	4:44	10:00	3:00	3:00	2:10	8:00	9:51
Preprocessing time	:34	:34	:21	:55	:55	2:05	4:20	:46
Postprocessing time	1:45	1:45	1:00	1:20	1:20	:15	:15	:25
Preprocessing cost	$37.80	$37.80	$23.50	$61.14	$61.14	$138.96	$289.00	$51.14
Postprocessing cost	$38.50	$38.50	$22.00	$29.33	$29.33	$5.50	$5.50	$9.17
Materials cost	$4.00	$4.00	$38.00	$5.89	$5.89	$4.00	$4.00	$3.82
Attendant cost	$0	$0	$220.00	$66.00	$0	$0	$0	$0
Depreciation	$26.54	$49.94	$235.58	$57.26	$31.81	$10.53	$38.89	$24.99
Maintenance	$24.52	$53.73	$117.79	$49.04	$27.24	$2.03	$7.48	$22.36
Single part cost	$131.38	$183.96	$656.71	$268.67	$155.42	$161.02	$344.90	$111.48
multiple parts:								
Total parts	18	72	58	19	19	1	1	1
Machine build time	15–60:00	20–80:00	10:00	6-35:00	6-35:00			
Preprocessing time	1:30	6:07	3:00	2:36	2:36			
per part:								
Preprocessing cost	$5.67	$5.67	$3.45	$9.17	$9.17			
Postprocessing cost	$38.50	$38.50	$22.00	$29.33	$29.33			
Materials cost	$4.00	$4.00	$8.65	$3.38–5.05	$3.38–5.05			
Attendant cost	$0	$0	$3.79	$6.95–46.32	$0			
Depreciation	$4.34–17.36	$2.93–11.72	$4.06	$6.03–40.18	$3.35–22.32			
Maintenance	$4.01–16.03	$3.15–12.61	$2.03	$5.16–30.11	$2.87–16.73			
Per part cost	$56.52–81.56	$54.25–72.50	$43.99	$60.02–149.11	$48.10–79.57	$161.02	$344.90	$111.48

Table 7: Estimated Costs of Producing Chrysler Speedometer Test Part. The SGC part was run on a Solider 5600, the SLS part on a Sinterstation 2000, the FDM part on a 3D Modeler, and the LOM part on an LOM-1015. The two columns for SLS represent estimates for attended and unattended operation. The two columns for FDM are builds run with different layer heights. Labor costs are taken from the Chrysler estimates: $22/hr for attended operation and postprocessing, $51.12/hr combined rate for preprocessing labor, and $15.58/hr computer and networking costs during preprocessing.