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An Assessment of the State-of-the-Art in Rapid Prototyping Systems for Mechanical Parts

Final Report

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Executive Summary

This report documents an assessment of the state-of-the-art in rapid prototyping (RP) systems for mechanical parts. This technology area has been identified as one of the key focus areas of the National Center for Manufacturing Sciences (NCMS) Rapid Response Manufacturing (RRM) industry consortium. Several commercial systems for rapid prototyping are discussed, along with current research and developmental work in new prototyping methodologies. The vast majority of RP systems used in industry today are based upon the stereolithography process, initially developed by 3D Systems, Inc. Other systems and prototyping technologies have more recently been commercialized. Applications for RP technology within a manufacturing facility can be quite diverse. Industrial uses of this technology have progressed from product visualization and verification, through design iteration and optimization, to rapid fabrication techniques for cast parts. This report also discusses several technology issues associated with the development and implementation of RP systems. In addition, a view into the future is provided with a comparison of the current state-of-the-practice to the state-of-the-art and a discussion on expected advances in RP technology. Finally this assessment addresses standardization activities and provides recommendations for continued research to support the needs of the RRM program.

Key Words: free form fabrication, rapid prototyping, rapid response manufacturing, RRM, stereolithography

Introduction

In recent years, rapid prototyping (RP) for the design and manufacture of mechanical parts has become one of the fastest growing manufacturing technology areas in terms of industry interest, prototyping system availability, and potential applications within a production environment. Since the first RP systems became commercially available in 1988, approximately 500 rapid prototyping systems have been installed at customer sites around the world. [Miller] [Wohlers4] As many as eleven (11) RP system manufacturers (five from the United States, three from Japan, one each from Germany, Sweden, and Israel) have sold and shipped systems to customers. [Wohlers4]

The primary objective of this research is to assess the state-of-the-art in rapid prototyping systems for mechanical parts. The implementation and application of RP technologies has been identified as one of the key focus areas of the National Center for Manufacturing Sciences (NCMS) Rapid Response Manufacturing (RRM) industry consortium.[1] [Sferro] This assessment will obtain the appropriate background information and provide the first step for integrating rapid prototyping systems into the RRM engineering environment.

Rapid prototyping is typically defined as a process to create three-dimensional (3-D) physical objects (i.e., the prototype part) directly from the computer-aided design (CAD) representation of the part. This capability has also been called desktop manufacturing, free form fabrication, rapid

1. This assessment was performed for the National Institute of Standards and Technology (NIST) Rapid Response Manufacturing Intramural Project, sponsored by the U.S. Department of Commerce Advanced Technology Program. This work was performed by staff of the NIST Factory Automation Systems Division in collaboration with the National Center for Manufacturing Sciences Rapid Response Manufacturing industry consortium. The primary mission of the Factory Automation Systems Division includes research in various manufacturing technologies and manufacturing system integration, and development and application of computer information standards for manufacturing systems.

fabrication, and various other terms by system developers and users. Several different prototyping systems and methodologies have been developed to achieve this capability. Although the various prototyping methodologies may use different technologies for part creation (with corresponding advantages and disadvantages), most RP techniques use a layer-additive fabrication process where the prototype part is built one layer at a time. A comparison between the prototyping methodologies is difficult, however, without the context of a specific application. The suitability of a specific prototyping methodology is dependent upon the intended use of the prototype part.

This assessment will describe several systems and methodologies for rapid prototyping of mechanical parts, including both commercially available and developmental systems. Potential uses and applications of RP technology within a manufacturing facility and technology issues associated with the development and implementation of RP systems are also discussed. In addition, a view into the future is provided with a comparison of the current state-of-the-practice to the state-of-the-art and a discussion on expected advances in RP technology. Finally this assessment addresses standardization activities and provides recommendations for continued research to support the needs of the RRM program.

Applications of Rapid Prototyping

The primary motivation for development of rapid prototyping systems was the need to improve the ability of manufacturers to quickly transition from design concept to final product (i.e., to shorten product development lead times). Manufacturing companies must continually design and build better products with a shorter time-to-market to remain competitive. Other objectives for development and implementation of rapid prototyping systems include reduced product cost, higher quality product, and enhanced responsiveness to customer desires. [Marks] Rapid prototyping systems can achieve these objectives through, for example, improved communication among design, production, and marketing personnel to improve the product design and/or manufacturing process, to obtain customer feedback, or to identify and resolve potential manufacturing problems earlier in the product lifecycle.

One of the technical issues for creating prototypes directly from the CAD product data was the elimination of the numerical control (NC) programming steps and/or tooling development necessary with traditional machined prototype methods. Prototyping has typically been conducted using process steps analogous to actual part production, including the part design, NC toolpath generation, tool design and build, fixture design and build, and machine set-up (depending on whether the part was to be machined or cast). In many cases the conventional prototyping methods required weeks or possibly months for creation of the prototype part. This process often led to expensive prototypes and delayed product delivery schedules. Rapid prototyping techniques and systems are intended to address these problems.

The range of applications for RP technology within a manufacturing facility can be quite diverse. Many RP implementations focus primarily on physically representing a product to accelerate the design verification and optimization process. These sites use rapid prototyping to verify and evaluate the “form, fit, and function” of the part. Common uses of prototype parts created by RP systems include: visual aids during design reviews, design verification and evaluation, communication between various external organizations (e.g., marketing, customers, subcontractors), validation of product functionality, manufacturability analysis, interference checks within assemblies, flow testing, planning and validation of production processes, tooling development, requests for tooling or production quotes from external vendors, master patterns for cast part mold development, working prototypes for field testing and customer evaluation, marketing aids, and packaging development.

The most significant industrial applications of RP systems over the past couple of years have transitioned from the initial 1) design visualization and verification, to 2) design iteration and optimization, to finally 3) product fabrication. [Jacobs2] Product fabrication is included in this progression to emphasize the latest process developments in the casting industry for using RP parts as patterns for investment castings and sand castings, as well as spray metal, epoxy tooling, vacuum forms, and room temperature vulcanizing (RTV) flexible rubber molds. [Thomas] Rapid prototype parts have had a tremendous impact on reducing the time required to develop molds and associated tooling for cast parts. The RP parts can be used in place of the traditional part master or wax/wood pattern for creating the mold. Prior to development of these methods, the mold design and build steps were quite complex and time-consuming operations, with the production mold typically created by use of an NC-machined or hand-formed master part, or by machining of the mold directly.

The medical industry also appears poised for remarkable advances from RP technology. The medical diagnostic imaging techniques of computerized axial tomography (CAT) and magnetic resonance imaging (MRI) both obtain computer images using data slicing techniques. The data contain a three-dimensional grid of points, where each point has a varying shade of grey indicating the density of the body tissue at that point. Thus, a bone or tumor would have a different shade of grey in the scan data than the surrounding muscle or tissue. The CAT scans are typically used for non-invasive viewing of bone structures, where the MRI technique is more effective for scanning soft tissue. These data formats have been imported into RP systems for building models of skulls, jaw bones, vertebrae, and tumors. Medical device manufacturers could use RP systems during the design and build of customized human implants or prostheses, such as for knee or hip joint replacements. Other opportunities exist for combining RP with CAT/MRI scanning in the areas of reconstructive surgery and cancer therapy. Technical issues in the accuracy and standardization of CAT/MRI data must be addressed, however, before medical applications of RP can become more widely used. [Hinzmann] [Jacobs1]

Several studies have been performed to determine the amounts of time an engineer or professional typically spends performing certain activities. The results of these studies indicate that professional staff spend roughly 25% of their time creating and innovating, 50% communicating, and 25% evaluating. [Marks] It is worth noting that the list of common uses of RP systems mentioned above includes activities in each of these three categories. [Marks] also recommends that companies should view rapid prototyping as part of an improved process for designing and building products, rather than as a prototype-making peripheral. According to [Schrage], a company’s policies and business practices regarding prototyping and prototype parts are quite revealing about the company’s culture and operation. The prototypes are as much a medium for managing risks as for exploring opportunities. [Schrage] Companies (and engineering staff) want to ensure a quality part before investing significant amounts of time and money into production tooling and processes, but at the same time want to have the capability to evaluate “what-if” scenarios for optimizing the product.

Methods of Rapid Prototyping

Of the approximately 500 commercial RP systems currently in industrial operation, the vast majority of the systems use a technology called stereolithography, initially developed by 3D Systems, Inc. Approximately 70% of these systems were sold directly by 3D Systems, Inc., with another 15% of these systems based upon the stereolithography process and sold under different product names by other vendors. [Wohlers4] Several variations on the stereolithography process exist through the different vendors, with specific parameters such as resin properties, laser operation and specifications, and machine configuration being the variables. At least 36 different corporations, universities, and research organizations are developing various forms of RP technology and an estimated 22 of these organizations have produced sample parts from their systems. [Wohlers4]

Most RP systems use a layer-additive fabrication process, which builds the part prototypes one layer at a time. The 3-D CAD representation of the part is "sliced" into horizontal cross-sections which are successively built by the RP system. Each new layer is built upon the existing previous layer(s) until the complete part is formed. The thickness of the layers is typically one of the system parameters that can be adjusted by the user and is a significant factor in the accuracy and overall build time of the resulting prototype. Depending on the prototyping process used, the prototype can be built from paper, plastics, wax, metal, or ceramics. Other typical process steps required for the operation of many RP systems include: creation of the part CAD model, translation of the CAD data to an appropriate format for import to the RP system, generation of necessary support structures for use during the part build (not required by some systems), slicing of the data file into layers, building the part, curing of the part material (not required by some systems), removal of support material, and surface finishing to obtain desired surface finish properties.

The five primary rapid prototyping methodologies in commercial use today (based on worldwide marketshare) include:

- Stereolithography
- Laminated Object Manufacturing
- Solid Ground Curing
- Selective Laser Sintering
- Fused Deposition Modeling

Each of these methodologies is described below, along with several other RP systems and techniques. Due to their current predominance in the marketplace, these five methods are presented first and are discussed in somewhat more detail than other less commercialized RP techniques. For each RP system and/or technology, the name of the process and/or commercial product is identified along with the primary developer and/or commercial supplier (primary focus is on the United States market). When applicable, alternative systems that employ the particular prototyping methodology are identified, with a description of their unique characteristics. Further discussion on these systems can be found in several references, including [Jacobs1] [Miller] [MIRC2] [Sprow] [Stevens] [Wohlers1] and [Wohlers3].

1. Stereolithography - 3D Systems, Inc.

   Stereolithography (SL) was commercially introduced by 3D Systems, Inc. (Valencia, CA) in late 1987 based upon a patented process originally developed by Mr. Charles Hull. [Miller] [Jacobs1] Since this was the first rapid prototyping technique and system commercially available to industry, development of the SL process has been considered largely responsible for the current interest in and widespread application of RP systems and technology.

   The SL process uses an ultraviolet laser to cure the slice profiles of a part design into the top layer of a liquid photopolymer resin bath. Photopolymer resins are photosensitive liquids that change from the liquid state to a solid when exposed to certain types of light. The system laser is guided by a computer that stores the data of the sliced part design. Once the layer is hardened (i.e., cured), the work is lowered below the liquid polymer surface using a descending platform. The next part profile is then hardened and the process is continued until the complete part is created. For parts which include overhanging geometry, support structures must be created to attach to the elevator platform to support the part while it is built. Post-processing operations for SL prototypes include removal of excess resin, final curing in ultraviolet light, removal of support material, and surface finishing as required. A schematic of the stereolithography process is provided in Figure 1.

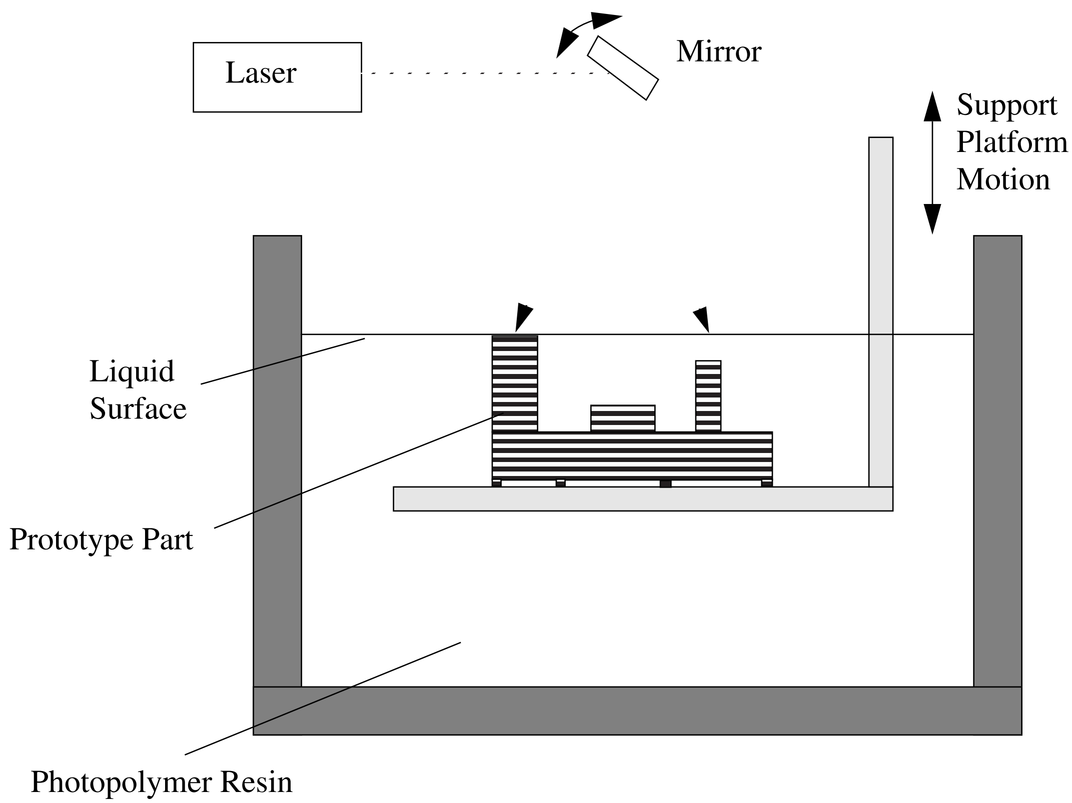

Figure 1: Stereolithography

The RP products marketed by 3D Systems, Inc. include the Stereolithography Apparatus (SLA) product line: the SLA-190, SLA-250, SLA-500, and the recently announced SLA-

400. These systems are characterized by differences in size of working volume (i.e., part size), laser power, speed of operation, and cost. The SLA-250 is currently the most popular model with the highest number of customer installations of any type of rapid prototyping system on the market. The SLA-500, first available in 1990, has the largest working volume, most powerful laser, and fastest operation of the SLA product line. [Miller]

Prototype part materials for the SLA machines consist strictly of photopolymer resins. The resin includes an initiator which is matched to a particular light source, in this case an ultraviolet laser. [Medler] Several photopolymer resins from various vendors (most notably Ciba-Geigy, DuPont, and Allied Signal) have been developed for use with SL systems. Each resin exhibits somewhat different part building characteristics and mechanical properties in the final prototype part. [Jacobs2] Though initial SL parts had the reputation of being brittle, development of new resins has addressed these concerns. Appropriate resins now exist to use SL parts in machining and investment casting applications.

The SLA product line has undergone several recent developments and system improvements, primarily in the areas of increased accuracy, new resins, and a new part building methodology called QuickCast. [Jacobs2] The QuickCast methodology by 3D Systems, Inc. uses a new epoxy resin and a new internal part structure for prototypes targeted for the casting industry. This technique produces prototypes with an internal open lattice structure that is approximately two-thirds hollow. This structure allows effective drainage of resin material and facilitates removal of the SL casting pattern during mold development.

<u>Other Stereolithography-based Systems</u>

- Mark 1000 Laser Modeling System - Quadrax Laser Technologies

  Quadrax Laser Technologies (Portsmouth, RI) developed and marketed the Mark 1000 system based upon the stereolithography process. This system was different from the SLA equipment in that it used a visible-wavelength light source, instead of ultraviolet light, and claimed that its photopolymer resin resulted in less shrinkage and was less brittle. Also, the Mark 1000 cured the polymer more completely, which increased part strength and reduced warping and shrinking during postcuring operations. [Wohlers1] [MIRC2]

  The Quadrax system is no longer marketed, due to a February 1992 court settlement with 3D Systems, Inc. over system similarities and patent rights. [Wohlers3] Under terms of the settlement, the Mark 1000 was discontinued. 3D Systems also received the rights to Quadrax patents and related technology, including a special resin applicator system that quickly deposits material from the top. [Wohlers3]

- Stereos 400 - Electro Optical Systems (Germany)

  The Electro Optical Systems (EOS) company of Germany markets two versions of its stereolithography Stereos 400 system. The two versions have different working volumes (i.e., part sizes) and use different strength lasers. A primary characteristic of the Stereos system is that it uses interchangeable vats to allow a quick change of resin. The EOS product line is not available in the United States. [Wohlers3] [Jacobs1]

- Soliform - Teijin Seiki Co., Ltd. (Japan)

  DuPont Imaging Systems (Wilmington, DE) originally developed a stereolithography-based prototyping system called the SOMOS Solid Imager. The SOMOS system was subsequently licensed to Teijin Seiki company of Japan with exclusive rights to the technology in Asia. Teijin Seiki has improved upon the original system and now markets its product under the Soliform name. Although DuPont has retained the SOMOS materials technology and supplies SOMOS brand resins to users of stereolithography systems (including Soliform), DuPont does not market SOMOS rapid prototyping systems external to the company. [Wohlers3] [Jacobs1] The primary difference in the Soliform system arises from its design as a high-speed RP system, using a Sun Microsystems SparcStation UNIX workstation as its controller and a high-efficiency optical system. The Soliform hardware, software, and resins permit high-speed prototype part creation with a laser scanning speed of a maximum of 24 m/sec (945 in/sec). [FBIS] [Wohlers1]

- Solid Object Ultraviolet Laser Plotter (SOUP) - Mitsubishi CMET (Japan)

  Another system based on the stereolithography process is the Solid Object Ultraviolet Laser Plotter, or SOUP system, from Mitsubishi's CMET division in Japan. Four versions of the SOUP product line are marketed (SOUP 400, 530, 600, and 850). [FBIS] The SOUP 400 is the only version which uses a galvanometer scanning mirror system to direct the laser light (similar to SLA); other SOUP models use an X-Y plotter mechanism to direct the laser light. [FBIS] The plotter mechanism configuration ensures that the laser light remains perpendicular to the resin surface and minimizes undesirable spread in the light. [Wohlers3] Vendors of the SOUP system also claim that prototypes built using SOUP resin do not require postcuring operations. [Jacobs1] The SOUP product line is not available in the United States.

- COLAMM - Mitsui (Mitsubishi) Engineering and Shipbuilding (Japan)

  The COLAMM prototyping system from Mitsui Engineering and Shipbuilding of Japan is also based on stereolithography. The primary difference is that this system builds the prototype parts from top to bottom, rather than from bottom to top as in other SL systems. The initial layers of the prototype part (i.e., the "top") are attached to the bottom of a platform and material layers are formed from beneath the part. The platform is raised after completion of each layer. The bottom of the resin vat in this configuration is a glass window through which the laser light can shine. This system eliminates turbulence in the resin surface due to platform motion (i.e., the platform is not submerged in the resin) and minimizes the amount of resin required for system operation (i.e., only a thin layer is needed on the bottom glass surface). [FBIS] [Jacobs1]

- Solid Creation System (SCS) - Sony and D-MEC, Ltd. (Japan)

  The Solid Creation System (SCS) is a stereolithography-based system jointly developed by Sony Corporation and Japan Synthetic Rubber Company (now D-MEC, Ltd.). Two product lines based on this technology are marketed by D-MEC, the standard JSC series (1000, 2000, and 3000) and the high-precision SCS series (1000HD). New SCS 2000HD and 3000HD versions are scheduled to be released in the future. [FBIS] The primary differences in the SCS system in comparison to the SLA are the larger SCS build chamber (1016 mm (40 in) x 813 mm (32 in) x 508 mm (20 in)) and a faster laser scanning speed in the SCS version. [Wohlers3] [Jacobs1] The SCS and JSC product lines are not available in the United States.

2. Laminated Object Manufacturing - Helisys, Inc.

   The laminated object manufacturing (LOM) process from Helisys, Inc. (Torrance, CA) uses solid sheet materials, most typically bleached "butcher" paper, to create prototype parts. The reverse side of the paper is pre-coated with a heat-sensitive adhesive (i.e., polyethylene). The sheets are laminated to each other using a heated roller to build successive layers of the part. For each part layer, a laser is used to cut the outline of a cross-section of the desired part. Another layer of paper is then indexed from the spool, bonded to the previous layer, and the next part cross-section is cut by the laser. This automatic process continues until all part layers are cut to form the final part shape. Part removal from the surrounding block of material is facilitated by cutting the excess material (i.e., outside the part volume) with the laser into small sections during fabrication of each layer. Additional support structures and postcuring are not necessary with this process. [Jacobs1] [Wohlers1] [Wohlers3] The general operation of the LOM process is illustrated in Figure 2.

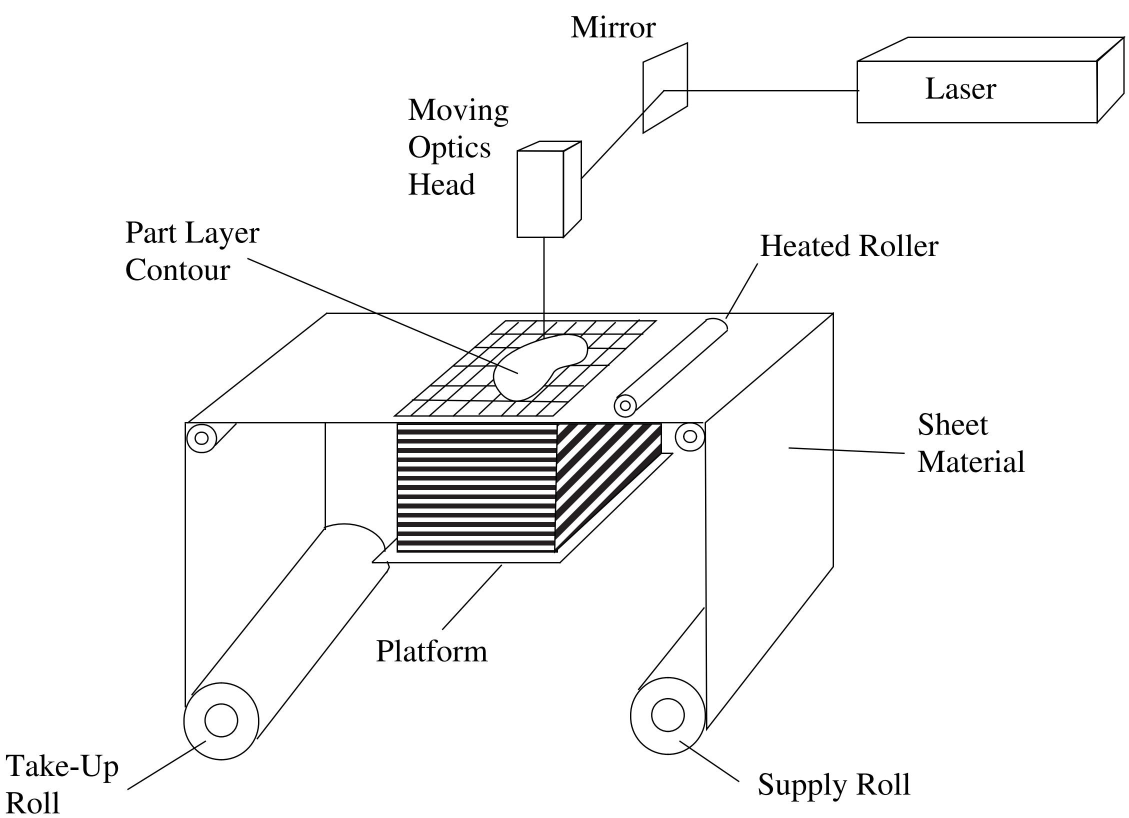

Figure 2: Laminated Object Manufacturing

The Helisys product line consists of the LOM 1015 and LOM 2030 machines. These machines differ only in their working volume and laser strength. [Miller] The prototype parts resulting from the LOM process look and feel like wood. Many users coat the parts with a polyurethane sealant to keep out moisture. The parts are dimensionally stable since the starting laminated structure is already solid, which eliminates potential thermal stresses, shrinkage, and warpage caused by a liquid to solid conversion. [Sprow] Another advantage is that since only the edges of the prototype part are cut by the laser, no processing time is spent filling in the body of the part as in other RP methods. The parts are typically strong in the X and Y directions, but have exhibited a tendency to delaminate in the Z direction on intricate parts. Other part materials available to use with the LOM process include a polyester film to create plastic parts. Many other potential materials are also possible, including composites, metal foils, and ceramic sheets. Helisys is currently developing the capability to form ceramic parts using the LOM process. [Sprow]

<u>Other LOM-based Systems</u>

- HotPlot - Sparx AB (Sweden)

  The HotPlot system from Sparx AB of Sweden is a low-cost prototyping technique based upon laminated object manufacturing principles. The HotPlot system operates by cutting sheets of expanded polystyrene material with a heated electrode. The polystyrene sheets are bonded together using an adhesive. The cutting electrode is controlled by an X-Y table plotter mechanism. The primary disadvantage of this system is the considerable operator assistance required to build the prototype. Removal of excess material and positioning of new polystyrene sheets are manual operations performed by the machine operator. [Jacobs1] [Wohlers3]

3. Solid Ground Curing - Cubital, Limited (Israel)

   Cubital, Limited has developed an RP system based upon a technology called solid ground curing (SGC). This system, called Solider, has been commercially available from the Cubital America, Inc. subsidiary (Troy, MI) since 1991. In this process, successive layers of a liquid photopolymer resin are cured using an ultraviolet light to form the desired shape of the prototype part. The polymer prototypes are built in a wax-supported solid environment which eliminates the need to create additional support structures. The system uses a mask plotter to generate an optical mask of the part layer on a glass plate. An ultraviolet light is then exposed to the photopolymer resin through the glass plate to cure the entire cross-section of the part in a few seconds. The photopolymer resin is selectively solidified where no mask exists on the glass plate. The unexposed resin is then removed for later reuse in subsequent layers. Melted wax is spread onto the cured resin layer to fill remaining cavities. The resin/wax layer is then cooled and machined to the proper thickness to start the next layer. When all layers are complete, the prototype part is encased in a water-soluble wax that can be washed away to reveal the finished prototype. Since the Cubital photopolymer resin is completely cured during fabrication of each layer, no postcuring is required. [Jacobs1] [Lewald] [Miller] [Sprow] [Wohlers1] [Wohlers3]

The process used by the Solider system can be summarized as follows. This sequence is repeated until all part layers have been built.

1. Developing: Generate the layer mask on a glass plate
2. Exposing: Expose the resin to ultraviolet light to cure selected areas
3. Wiping: Remove excess resin from the current layer for reuse in subsequent layers
4. Wax Filling: Fill areas where resin is not cured with wax to build support structure
5. Cooling: Cool the wax/resin surface
6. Milling: Machine the wax/resin surface to obtain proper thickness
7. Spreading: Add resin layer for next cross-section
8. Exposing (repeat back to Step 2): Mask for next layer (i.e., Step 1) was created in parallel to Steps 2-7 for previous layer

The Cubital product line includes the Solider 5600 system and the new entry-level Solider 4600 system. The Solider 4600 machine is similar in operation to the original Solider 5600, but has a smaller working volume, operates at a slower speed, and costs less. For the Solider 5600 version, the approximate total processing time is one minute per layer, with a typical build rate of one vertical centimeter (0.39 in) over the entire working volume per hour. The Solider system consists of two primary components: the data front end (DFE) and the model production machine. The DFE serves as the software user interface for the 3-D layout of the prototype parts and for CAD model slicing operations. The Solider system can build as many prototypes in a given run as can be positioned within its work volume. Proper nesting of parts within the volume allows for high capacity and efficient operation. An option also exists for flexible definition of the work envelope so that a reduced volume can be used for few or small parts. The Solider system also has the capability to build working assemblies, such as Geneva mechanisms or interlocking gears, directly from the assembly CAD data.

4. Selective Laser Sintering - DTM Corporation

The Sinterstation 2000 selective laser sintering (SLS) system from DTM Corporation (Austin, TX) builds prototype parts layer by layer using a laser to bond powdered material into the desired part shape. As the laser traces the geometry of the part layer on the powder surface, a thin layer of powder softens and chemically bonds (i.e., sinters). When the part layer is complete, the platform holding the prototype lowers, another layer of powder is deposited, and the process repeats with the next layer building upon the existing part structure. In the SLS process, parts are built inside of a cylinder 381 mm (15 in) long and 305 mm (12 in) diameter, rather than in a cubic volume as with other RP methods. The unsintered powder within the cylinder acts as a support structure for the part. The part building chamber is filled with inert gas, typically nitrogen, and heated so that the powder material is just below its melting point. This configuration reduces the laser temperature needed for material bonding and reduces thermal shrinkage of the layers during fabrication. Figure 3 illustrates the basic components of the SLS process.

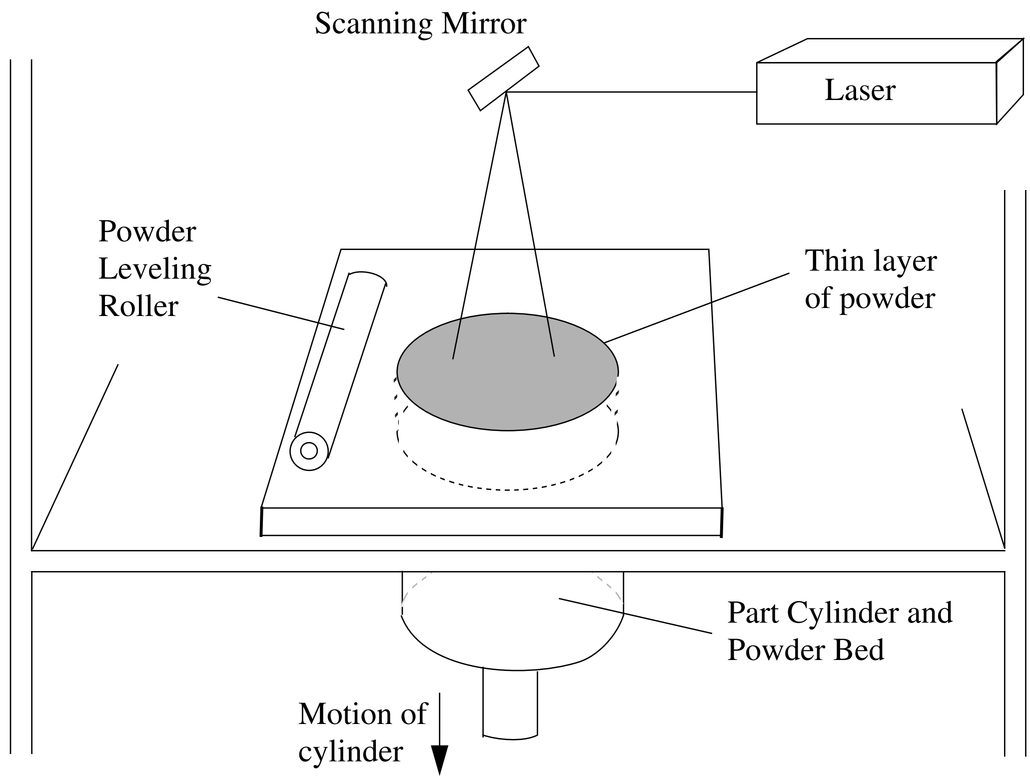

Figure 3: Selective Laser Sintering

Current prototype part materials for the SLS process include thermoplastic materials (i.e., polycarbonate and nylon) and investment casting wax. A top priority for DTM Corporation is the creation of metal and ceramic parts using the SLS process. DTM research efforts have teamed with BFGoodrich Corporation and the University of Texas at Austin to develop and commercialize techniques for building SLS parts using a wide variety of materials. Research issues in this area have included the need for higher temperatures to initiate bonding, use of more powerful lasers, and differences in powder material conductivities and reflectivities. Sample parts have already been created from powdered metals on demonstration SLS systems, with commercial versions scheduled to be available by the summer of 1994. [Jacobs1] [Miller] [Sprow] [Wohlers3]

5. Fused Deposition Modeling - Stratasys, Inc.

   Fused deposition modeling (FDM) is the name of the technology used by commercial RP systems from Stratasys, Inc. (Minneapolis, MN). The Stratasys systems are primarily targeted for the engineering office environment for use during the conceptual design stage of product development. The systems' simple operation, inert materials, and lack of fumes and excessive heat make the FDM process quite compatible with an office environment. [Hartfel] System operation consists of feeding a spool of solid 1.3 mm (0.050 in) diameter filament material, resembling plastic wire, into a heated reservoir in the FDM extruding head. The filament material is melted and extruded through a nozzle at a controlled rate. The material is positioned by the motion of the FDM head and is deposited in thin layers onto a fixtureless base to form the prototype part cross-sections. Since the air temperature surrounding the nozzle is below the material melting point, the part material quickly solidifies in place to form a solid lamination. Part layers are bonded together through heating and solidification to form the complete prototype part. Between each layer, the extruding head pauses briefly while the part platform indexes downward. No laser is involved in this operation and no postcuring of the parts is required. Prototype parts achieve their final mechanical properties upon cooling. Support structures are sometimes required when building FDM parts, primarily with flat or near-flat surfaces (in the Z direction). [Hartfel] [Jacobs1] [Miller] [Sprow] [Wohlers1] [Wohlers3] A general overview of the FDM process is provided in Figure 4.

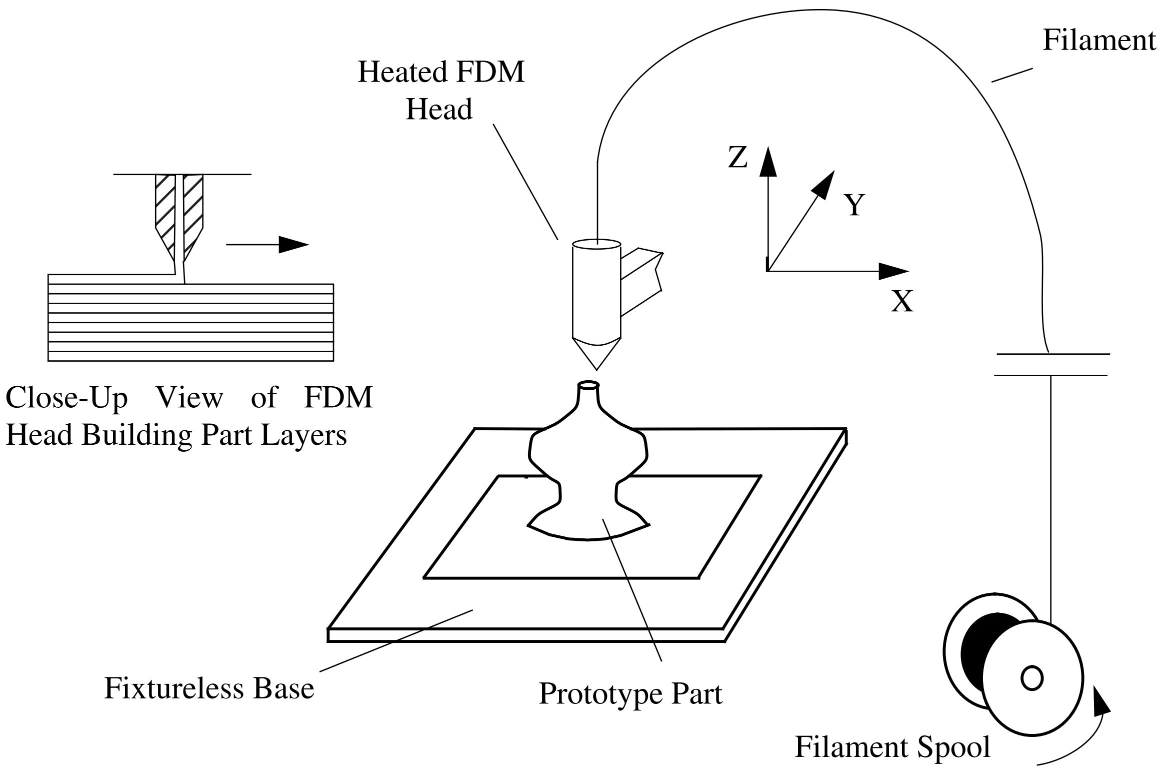

Figure 4: Fused Deposition Modeling

The Stratasys product line includes the original “3D Modeler” and the recently released desktop FDM 1000 and FDM 1500 machines. Prototype part materials for the FDM process are currently limited to low-temperature materials, including investment casting wax, machinable wax, and plastic polymers Plastic 200 (polyolefin) and Plastic 300 (polyamide). [Miller] The plastic materials exhibit nylon-like properties. Material changeover for the Stratasys systems is relatively quick and simple, with little material waste. The material changeover procedure has been compared to changing the lead in a mechanical pencil. [Sprow]

6. Three-Dimensional Printing - Massachusetts Institute of Technology (MIT)

   The Massachusetts Institute of Technology (MIT) (Cambridge, MA) is currently developing a prototyping system for creation of ceramic parts that uses a jetting mechanism similar to that used in ink jet printers. The system first spreads a layer of ceramic powder on a build platform. Cross-sectional layers of a part are then solidified using the jetting mechanism to deposit a stream of ceramic binder on the powder. Selective application of the binder joins the ceramic particles where the object is to be formed. Similar to other RP methods, the platform is then lowered and the process is repeated. When the final part layer has been deposited, the part is placed in a furnace to cure the binder and strengthen the part. Following the heat treatment, the unbound ceramic powder falls from the part. [Wohlers1] [Wohlers3] [Jablon]

7. Direct Shell Production Casting - Soligen, Inc.

   The direct shell production casting (DSPC) technique of Soligen, Inc. (Northridge, CA) is based on the process developed at MIT. Soligen has licensed the MIT three-dimensional printing technology to form expendable ceramic molds directly from the prototyping machine. This capability would eliminate the need for wax patterns and tooling for cast metal parts. [Wohlers3] The application of DSPC is focused specifically on the casting industry. The system is not currently a commercial product, but Soligen Alpha machines have been released on a developmental and testing basis. The commercialization by Soligen has modified the original MIT prototype system somewhat, most noticeably by increasing the work volume to form larger ceramic parts. [Sprow] The ceramic material used in the Soligen Alpha is typically alumina, held together with a liquid colloidal silica binder. [Miller] Metals that have been successfully cast in molds developed by the DSPC process include aluminum, cobalt-chrome, and Inconel, a high-performance nickel alloy. [Stevens]

8. Ballistic Particle Manufacturing - BPM Technology, Inc. / Incre, Inc.

   The ballistic particle manufacturing (BPM) prototyping technology is being developed by Perception Systems, BPM Technology, Inc. (Greenville, SC). Rapid prototyping systems based on the BPM technique are currently in a developmental stage, with commercial systems not yet to market. The BPM technique uses an ink-jet mechanism to eject molten wax droplets through a nozzle. The molten wax momentarily melts the previously deposited layers and a bond is formed when the resulting structure solidifies. The motion of the ink jet head is controlled by a small three-axis manipulator. Multiple ink jet heads can be operated simultaneously to increase the part build rate. A second material is also ejected on each layer to form the part support material (for overhanging geometry, etc.). The support material is typically polyethylene glycol, a water-soluble synthetic wax. When the prototype part is complete, the support material is dissolved by soaking the structure in a warm water bath. [Jacobs1] [Wohlers1] [Wohlers3]

   The BPM technology has been licensed by Incre, Inc. (Corvallis, OR) to develop a variation on this prototyping technique, called incremental fabrication. The Incre, Inc. process intends to build metal prototypes by ejecting small droplets of molten metal through a nozzle one drop at a time to form thin layers of the desired part shape. Current developmental efforts have primarily used tin as the prototype part material, with some investigation into building aluminum parts. [Jacobs1] [Stevens] [Wohlers3]

9. Printed Computer Tomography - Texas Instruments

   Texas Instruments (McKinney, TX) is developing a prototyping system based on a form of jetting technology called printed computer tomography (PCT). The current developmental system is called the ProtoJet 3D Print System. The ProtoJet system is similar in operation to the BPM process in that an ink jet printing mechanism deposits wax material layer by layer to form the part. The ProtoJet system can deposit two materials to, for instance, differentiate between part features using material colors. The part support structures are also deposited on each layer in a water-soluble material that is removed with warm water at the completion of the process. [Stevens] [Wohlers3]

10. Jetting - Visual Impact Corporation

    The Sculptor system from Visual Impact Corporation (Windham, NH) is again based upon a similar jetting technology. Two materials are deposited by the jetting mechanism: the part material and the support material. Prototype parts are built up layer by layer using a plastic as the primary part material. When processing is complete, the prototype object is encased in a cube. The cube is then heated to an appropriate temperature to melt away the support material, while leaving behind the solid part material. The Sculptor prototyping unit is expected to be about the size of a standard office laser printer and to operate as a desktop computer peripheral. Targeted part size for this system includes prototypes that fit within a 152 mm (6 in) cube. [Stevens] [Wohlers3]

11. Photosolidification - Light Sculpting, Inc.

    The photosolidification process used by Light Sculpting, Inc. (Milwaukee, WI) is called design-controlled automated fabrication (DesCAF). Three versions of a system using this process have been developed under the LSI (for Light Sculpting, Inc.) product name. The three versions differ only in the sizes of their working volumes (i.e., part sizes). The systems operate much like the Cubital Solider system in that conventional light (i.e., non-laser) is used to irradiate a photosensitive liquid polymer through a series of masks. An entire layer of the part cross-section is solidified at once. The primary difference in this system as compared to Cubital is that a human operator must create each of the part cross-section masks using a photoplotter. The masks are also manually positioned by the operator for each part layer. Research has been ongoing to replace the manual mask operations. Potential solutions are under evaluation and development, including use of a liquid crystal display (LCD) as an electronically writable mask. [Jacobs1] [MIRC2] [Wohlers1] [Wohlers3]

12. Photochemical Machining - Battelle Memorial Institute / Formigraphic Engine Company / Osaka Prefecture (Japan)

    Photochemical machining (PCM) is an RP technology being researched by Battelle Memorial Institute (Columbus, OH), Formigraphic Engine Company (Bolinas, CA), and Osaka Prefecture (Japan). This prototyping technology is unique in that prototype parts are not produced layer by layer, as in most RP systems. The PCM process solidifies prototype part material within the interior of the material, rather than forming layers on the surface. This technique cures a photochemically-sensitive polymer resin at the point of intersection of two laser beams. Two lasers of different wave lengths are used to initiate cross-linking (i.e., polymerization) in the part material. The lasers are aligned perpendicular to each other to create an overlap volume that is controlled by focusing the laser lenses. The prototype part material is chemically altered and solidified at the point of intersection of the two lasers. Figure 5 illustrates the general concept of the photochemical machining process.

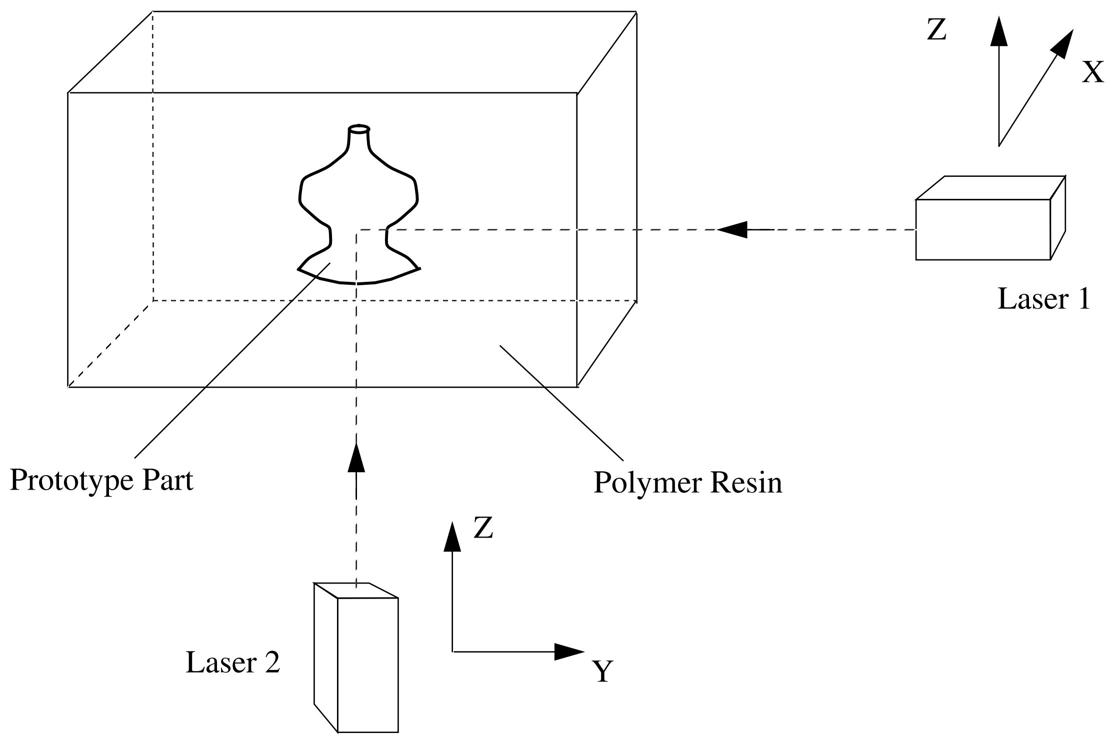

Figure 5: Photochemical Machining

The strategy used in this fabrication technique is to cure the resin at the farthest intersection point first. This process also uses higher-molecular-weight polymer resins to ensure minimal shrinkage of the prototype part. Several PCM techniques are being evaluated, including the following possibilities.

- Solid block: scanned areas would become insoluble; prototype part would appear after soaking in solvent
- Block of soft gel: gel would solidify where the lasers meet
- Frozen solution: unscanned material would liquefy when heated; scanned material of the prototype part would remain solid
- Degrade unwanted material from a solid block: process comparable to machining the part with the two lasers

Several technical issues are yet to be resolved in the PCM methodology. Further system development and commercialization, however, are currently delayed due to lack of continued funding for this effort. [Jacobs1] [Lavoie] [Stevens] [Wohlers3]

13. Recursive Material Deposition - Carnegie Mellon University

    Recursive material deposition (MD*) (pronounced MD star) from Carnegie Mellon University (Pittsburgh, PA) is currently a developmental shape deposition system which combines recursive masking and spray-metal deposition. Researchers first develop a geometric model of a desired part, which is then sliced into cross-sectional layers. For each layer, a laser cuts a mask of the desired part shape from paper. Thermal spraying (i.e., forced air blown through molten material) is then used to deposit metal material through the mask to form the desired part layer. The part mask is then replaced with a complementary mask to expose the previously covered regions. A layer of low-melting-point alloy is then sprayed to build a support structure around the part. This process is repeated until all layers have been created. The support material is then removed through melting to reveal the desired part.

    The MD* system also incorporates other processing cells during the formation of the part layers, including NC machining to improve layer accuracy and shot-peening to control internal stress build-up. Part materials that can be used with this system include metals and plastics, with ceramics a subject of investigation. Benefits of this methodology include realistic metal part materials with high material densities, the capability of multi-material structures and assemblies that are not feasible with other approaches, and automatic component assembly operations. One of the current areas of development is to accelerate the rate of system operation through the several-step process of deposition, machining, and stress relief. [Jacobs1] [Stevens] [Weiss]

14. Laser-induced Chemical Vapor Deposition - Rensselaer Polytechnic Institute

    Research at Rensselaer Polytechnic Institute (RPI) (Troy, NY) includes a prototyping system for micromechanical fabrication of micro- and millimeter-scale parts and mechanical systems. The process under study is called laser-induced chemical vapor deposition (LCVD), also known as selective area laser deposition. With this process, parts are built through deposition of a vapor, literally atom-by-atom. The vapor is pumped into the path of a laser which “grows” the part material. Each layer of the part is defined through a masking technique. Candidate materials for this process include metals (e.g., copper, aluminum) and ceramics. Several potential applications exist for this technology, primarily in the microelectronics industry for custom integrated circuits. One benefit of this fabrication technique for micromechanical parts and systems is that it can eliminate the need for assembly operations. The largest practical part size for use of this technique is thought to be roughly a cubic centimeter (0.061 cu. in.). [Maxwell]

Other RP techniques and processes are also currently under development, including shape melting technology which uses arc welding to produce components directly from weld metal (Babcock & Wilcox, Alliance, OH), electrosetting techniques which use an electric field to shape liquid resins into solid 3-D objects (Electroset Synergistic Technology / United States Navy David Taylor Research Center, Annapolis, MD), and multi-color prototype part creation based on coloration of each layer (Landfoam Topographics, Needham, MA). Additional information on these prototyping methodologies can be found in [Wohlers3] and other references. Table 1 provides a view of the RP industry as of April 1993. [Wohlers4] The information provided in this table should not be considered current since several sales have undoubtedly occurred since April in this fast-moving field. This table is provided to give a rough indication of the number of organizations involved, the types of technology, and an approximate view of relative market share. This table should also not be considered a complete list of all organizations affiliated with RP system development, as the author may not be aware of the work of some organizations.

Table 1: Rapid Prototyping Systems *

Organization	Technology	Product(s)	Approx Unit Sales
1. 3D Systems	Stereolithography	SLA 190,250,400,500	350
2. CMET (Mitsubishi)	Stereolithography	SOUP 400,530,600,850	56
3. Sparx AB	Laminated Object Mfg.	Hot Plot	15
4. Cubital	Solid Ground Curing	Solider 5600 and 4600	16
5. D-MEC (JSR/Sony)	Stereolithography	SCS 1000HD	10
6. Stratasys	Fused Deposition Modeling	3D Modeler, FDM1000	14
7. Helisys	Laminated Object Mfg.	LOM 1015, 2030	14
8. DTM Corporation	Selective Laser Sintering	Sinterstation 2000	12
9. Electro Optical Systems	Stereolithography	Stereos 400	12
10. Soligen	Direct Shell Production Casting	Alpha units available	3
11. Teijin Seiki Co.	Stereolithography	Soliform 300, 500	1
		TOTAL	503
12. Fockele & Schwarze	Stereolithography	Laser Modeling System	0
13. MIT	3-Dimensional Printing	Not Available	0
14. Light Sculpting	Photosolidification	LSI product family	0
15. BPM Technology, Inc.	Ballistic Particle Mfg.	Not Available	0
16. Mitsui	Stereolithography	COLAMM	0
17. Texas Instruments	Printed Computer Tomography	ProtoJet	0
18. Laser 3D	Stereophotolithography	SPL 1000/LSA	0
19. Babcock & Wilcox	Shape Melting	Not Available	0
20. Univ. of Nottingham	3D Welding	Not Available	0
21. Electroset Synergistic Technologies	Electrosetting	Not Available	0
22. Carnegie Mellon Univ.	Spray Metal Deposition	Not Available	0

Table 1: Rapid Prototyping Systems *

Organization	Technology	Product(s)	Approx Unit Sales
23. Incre, Inc.	Ballistic Particle Mfg.	Not Available	0
24. Visual Impact Corp.	Jetting	Not Available	0
25. Formigraphic Engine Co.	Photochemical Machining	Not Available	0
26. Battelle	Photochemical Machining	Not Available	0
27. Osaka Prefecture	Photochemical Machining	Not Available	0
28. Univ. of Texas - Austin	Chemical Vapor Deposition & Selective Laser Sintering	Not Available	0
29. Chem-Form	Masked Photosolidification	Not Available	0
30. Bowling Green St. Univ.	Stereographics	Not Available	0
31. Univ. of S. California	Precision Droplet Stream Mfg.	Not Available	0
32. Laser Fare	Proprietary	Not Available	0
33. Cybervid	Sheet Material Folding	Not Available	0
34. Landfoam Topographics	Laminated Object Mfg.	Not Available	0
35. Rensselaer Polytechnic	Chemical Vapor Deposition	Not Available	0
36. E-Systems Corp.	3-Dimensional Printing	Not Available	0

* SOURCE: Wohlers Associates, April 1993 [Wohlers4]
Note: Entries 35 and 36 were added to the original table by the author of this report.

<u>Comparison With Conventional Prototyping Methods</u>

Rapid prototyping systems and techniques may not always be the best prototyping method available to a product development team. Others methods of prototyping, primarily use of traditional numerical control (NC) machine tools, may be more practical, depending on the part shape and material requirements. In many organizations, machined prototypes can be generated with acceptable turn-around times using the concept of a “model shop” within the production facility or by using outside contracted services. Conventional machining processes are typically more attractive for geometrically simple products, due to the fact that the specific material of the final product can be used in the prototype, the prototype can be rapidly constructed, and moderate costs are involved. More complex prototypes can also be constructed by assembling or bonding machined parts together. Complex and detailed parts are generally better suited to use of RP techniques. Machine tool cutters may not be able to reach small interior cavities of the part or be able to create complex internal geometry.

A study by [Prioleau] compared various prototyping methods based upon the following criteria: set-up time, special tooling required, fixturing required, geometric limitations, size, accuracy, and materials. The prototyping methods assessed by this study included stereolithography, selective laser sintering, and NC machining. A conclusion of the study is that each of these prototyping methods has their own strengths and all are valuable prototyping methods. This study also concluded that NC machining is the best method to use on prototyping projects when part geometries can be machined in two or three machine setups, the parts are larger than the building envelopes of available RP systems, the tightest tolerances are required, or exact production materials are required. The stereolithography and selective laser sintering RP methods were found to be better suited for prototyping projects when complex part geometry makes machining difficult or when prototype parts will be used as tooling masters for investment casting.

Other case studies have shown that recent advances in desktop milling machines and NC programming software have created a viable prototyping option with several potential advantages over stereolithography and other RP methods, including less cost, use of a wider variety of materials, and good part surface finish. [Cassista1] [Dvorak] Desktop milling machines have been installed in some product design departments to function as inexpensive design visualization and verification tools. Many times these systems have illustrated product design improvements that would simplify the manufacturing process. These machines enable validation of the manufacturing process, as well as the product, due to their use of the standard NC codes used by production machinery. The desktop mills have also served to facilitate improved communication between design and manufacturing staff, many times simply providing a "common language" or frame of reference. Recent improvements in desktop milling machines have included use of direct current (DC) servo motors with rotary encoders to control axis movement with better resolution and repeatability and software improvements to provide capabilities to parametrically define a surface to enable three-axis machining, to perform scaling of part features to produce prototypes at a reduced size, and to execute "roughing" routines to quickly remove much of the unwanted material to the rough outline of the part. Typical prototype part materials cut by the desktop mills include metals, such as aluminum and steel, as well as machinable wax and plastics.

New technologies, commercial systems, and industrial applications can also impact the practicality of using machining processes for prototyping. Several advances are being made in the field of high-speed machining, primarily for non-ferrous materials (e.g., aluminum, magnesium, plastics), but also for ferrous materials (e.g., steels, cast iron) and hard metal milling. [Coleman] [Granger] High-speed machining is a relative term because of the different speeds at which different materials can be machined with acceptable tool life. For example, it is easier to machine aluminum at approximately 1830 m/min (6000 surface feet per minute (sfm)) than it is to machine titanium at 183 m/min (600 sfm). Regardless of this fact, a practical definition of high-speed machining can be roughly viewed as machining with cutting speeds of at least 610 m/min (2000 sfm).[2] [ASM] Specific advances in the field of high-speed machining have included improved axis motion control systems, cutting tool materials, spindle and bearing designs, and tool retention devices. [ASM] Suitability and availability of these advanced machining techniques should be considered when determining solutions to prototyping needs.

One disadvantage of machined prototype methods is the requirement for NC programming and the associated time and skilled personnel. Even for parts designed using CAD systems, effort is still required to generate the NC program from the CAD file. The NC programmer must specify the

2. Cutting speeds of between 1830 m/min (6000 sfm) and 18300 m/min (60,000 sfm) have been termed very high-speed machining, with speeds over 18300 m/min (60,000 sfm) called ultrahigh-speed machining. [ASM]

tool, the direction of the tool path, cutting parameters, and the area to be machined for each part surface (including intermediate part shapes). This process can become quite tedious for complex geometries with a large number of surfaces. Research and development efforts in the area of automated or generative NC code generation should reduce this concern in the future.

System Implementation and RP Technology Issues

Several system implementation and technology issues need to be considered when specifying, developing, and/or implementing rapid prototyping. These issues must be compared and evaluated when determining a solution for specific prototyping needs within a given application. Some of these implementation and technology issues are discussed below, with a primary focus on current commercially available RP systems. These issues have been categorized into the following areas: CAD interface, materials, accuracy, part preparation and finishing, size, cost, and environmental concerns.

<u>CAD Interface</u>

The need for an accurate and complete 3-D surface model or solid model CAD definition of the prototype part is of primary importance to all RP systems. The electronic part definition must be "water-tight". In other words, if the electronic part volume could be filled with water, it would be impossible for the water to leak out. This requirement mandates that all surfaces be trimmed appropriately, no gaps are present in the surface definition, and all surface normals are correctly defined. Many organizations are not routinely creating part models of this type, instead using 2-D drawing or 3-D wireframe techniques. This lack of 3-D product models has slowed the transition to rapid prototyping methods. Company business practices for creation of product geometry must change to accommodate effective use of RP equipment. This change, however, can represent a substantial initial cost to the company, primarily considering that cultural changes are quite significant when converting from 2-D to 3-D product representation. For any given new technology, productivity improvements are typically realized only after full implementation of the technology and evaluation of the overall product delivery cycle.

Current CAD system interaction with RP systems is primarily through the STL (stereolithography) format.[3] This format has become an industry *de facto* standard for interfacing with RP systems. The STL part file format consists of a mesh of connected three-dimensional triangles which represent the part shape. The vertices of the triangles are ordered to indicate which side of the triangle contains the part mass. [Jacobs1] The STL format is actually an approximation of the part shape. The more triangles that are used in the representation, the more accurate the approximation. An objective of RP system implementors is to represent the part shape in the minimum number of triangles necessary to process the part, but still keep the resulting prototype within desired tolerances. More triangles than required results in longer processing times for support generation, data slicing, part creation, and other process steps.

The CAD interface is primarily a unidirectional transfer of electronic information from the CAD system to the RP system. Automated feedback mechanisms to incorporate suggested product design changes from the RP system or prototype part back into the initial CAD definition have not

3. This report uses the following convention to avoid confusion: The acronym STL is used strictly when referring to the stereolithography part file format. SL is used when referring to the stereolithography process or methodology. SLA is used when referring to the specific product line from 3D Systems, Inc.

yet been developed.[4] An “STL Verify” function is provided with many RP system controllers and executed prior to actual machine operation to identify potential problem areas in the 3-D CAD file (e.g., disconnects in the triangle mesh, improper surface normals). Results of this evaluation are human-interpreted with operator action required to correct the 3-D CAD (and corresponding STL) input file.

Future and continued use of the STL file format as the CAD interface is a current subject of debate within the rapid prototyping community. A desire for a more advanced interface between CAD and RP systems has been identified and discussed. The primary advantages of the STL file format appear to be that it is easily generated by CAD systems, easily manipulated by RP systems, and currently widely used. The disadvantages, however, include a large file size for complex parts, little product intelligence contained within the file (e.g., no knowledge of geometrical features or part surfaces), and the fact that it is an approximated part representation. [Fuller] Development of a better interface, such as direct use of the CAD data to the slice level, would require better cooperation between CAD vendors and RP system manufacturers than currently exists. Modifications and further development would most likely be required for both CAD and RP vendor products. [Jacobs1]

<u>Materials</u>

Current commercial RP systems primarily build prototype parts from plastics, wax, and/or paper. Metal and ceramic prototypes are also currently available through secondary tooling operations using the initial RP part as the master pattern. Other RP systems will soon be more widely available to directly produce metal and ceramic prototypes. The specific prototyping material required by an organization is dependent upon the intended application(s). For example, different material needs are indicated by a prototype used for marketing purposes than one used for functional evaluation of fluid flow through a product assembly. One case study has also indicated that the prototype material used can affect the resultant product design. According to [Schrage], “Hewlett-Packard used to do its calculator modeling in cardboard, which explained why all their calculators featured angles and edges. When the company switched to foam, you saw calculators that had a softer and more rounded look.”

Some of the technical issues and concerns with prototype part materials include use of realistic production materials (e.g., metals, ceramics, investment casting materials), limited material selection within a given RP system, and improved material properties (e.g., durability, strength, density). These issues are being addressed through research and development efforts within several organizations. For instance, DTM Corporation expects to market a metal prototype capability using the SLS process within the coming year. Also, the MD* system from Carnegie Mellon University is focused on building prototypes with multiple metals (including the ability to switch materials during system operation) and the Soligen system builds investment casting molds from ceramic powder. Other materials research and new material developments have reduced former problems with shrinkage, warping, and curling when liquid resins undergo the transition to a solid state.

4. Research efforts have been initiated in this area, primarily through intelligent interpretation of digitized or scanned data obtained from physical shapes in reverse engineering applications. An objective is to generate high level geometrical entities compatible with CAD system representation from digitized data points.

Material properties of the prototype part, such as durability, strength, and density, have also been the subject of study. Prototypes created from initial stereolithography systems were thought to have durability problems (i.e., too brittle) when compared to other types of prototypes. These concerns have since been addressed through new resins, system improvements, and a variety of resin types now available to meet specific prototyping objectives. Material properties within a prototype may not be homogenous, specifically with regard to strength, due to the layered fabrication techniques used to build the part. Some prototypes, such as those created using the Helisys LOM technique, have exhibited tendencies to delaminate under excessive stress. Part finishing operations are typically needed to prevent this problem. Another desirable property of the prototype part for many applications is high part density (i.e., proportion of part material to air within the internal part structure). Parts of low density usually consist of a weaker structure than parts that are more solid. Using the SLS process from DTM Corporation as an example again, SLS parts of polycarbonate material typically have a part density of 75-95% (i.e., 5-25% air), while the density of SLS parts made from nylon material approaches 96%. [Wohlers3]

<u>Accuracy</u>

Prototype part accuracy has been a concern of system users since the inception of rapid prototyping. System users understandably compare the accuracy results obtained from RP equipment with the accuracy of previous prototypes developed using traditional machining processes. The previously mentioned study by [Prioleau] determined that typical accuracies obtained using stereolithography, selective laser sintering, and NC machining are as follows:

SLA	+/-0.13 mm (0.005 in) to +/-0.38 mm (0.015 in)
SLS	+/-0.13 mm (0.005 in) to +/-0.38 mm (0.015 in)
NC machining	+/-0.05 mm (0.002 in) to +/-0.10 mm (0.004 in) (with tolerances of +/-0.02 mm (0.001 in) readily obtained from NC machining for features machined in the same setup)

[Sprow] has also indicated that the typical accuracy of the Helisys laminated object manufacturing system is a function of the X-Y positioning table of the laser, typically +/-0.25 mm (0.010 in) anywhere in the work envelope. Similarly, the Stratasys fused deposition modeling system accuracy is governed by the positioning mechanism for the extrusion head, generally +/-0.13 mm (0.005 in) over the 305 mm (12 in) cube working volume. [Sprow]

Part accuracy is impacted by the amount of shrinkage, warping, curling, and other negative effects that may occur during prototype creation. Internal stresses developed during the transition from liquid resin to solid part can cause changes in the part shape. [Jacobs1] [Jacobs2] Other RP methodologies must address similar technical issues to maintain part accuracy. The amount of post-finishing required to obtain the desired prototype surface finish is another primary consideration. [Prioleau]

System accuracy is typically reported by creation and measurement of the accuracy benchmark part developed by the Stereolithography Apparatus Users Group. [Jacobs1] This part was designed to study accuracy only in the X-Y plane, however, where distortions from curl, warpage, and other effects are less frequent. Rapid prototype parts are typically more accurate in the X- and Y-axes than in the Z-axis. Accuracy reports using this benchmark part should be analyzed to determine if stated results are valid over the entire system working volume. “Real world” parts created by the

SLA and SLS techniques typically have accuracies of +/-0.25 mm (0.010 in) over the entire building envelope. [Prioleau]

Part Preparation and Finishing

Several preparation steps are required to prepare the part design information for input to the prototype part build process. These steps typically include CAD model creation and STL format translation (as discussed previously), generation of part support structures, selection of operational parameters for the part creation, and electronic slicing of the part shape to accommodate layered fabrication techniques. [Jacobs1] One of the most frequently referenced part preparation steps is the generation of part support structures to hold, or "fixture", the part as it is being built. As previously noted, this process step is not required as a separate operation for all RP systems or methodologies, as it may be an inherent part of the prototyping process (e.g., Cubital solid ground curing or Helisys laminated object manufacturing processes). For other systems, such as stereolithography, supports must be generated for the base part, overhangs or cantilevered sections, horizontal portions of arches, and generally unsupported regions of the part design that would result in free-floating "islands" of solidified part material not joined with other portions of the part or base due to the layered fabrication technique. These supports prevent curl of the part overhangs and sag of the part arches and ceilings. [Jacobs1] It should be noted that these supports are added strictly to enable RP system operation and do not represent a value-added step for other applications in the product life-cycle. Many times during the part build cycle, support structures may take longer to build than the part itself. The supports also increase the labor and clean-up steps necessary for the finished part. Various types of part support structures are illustrated in Figure 6.

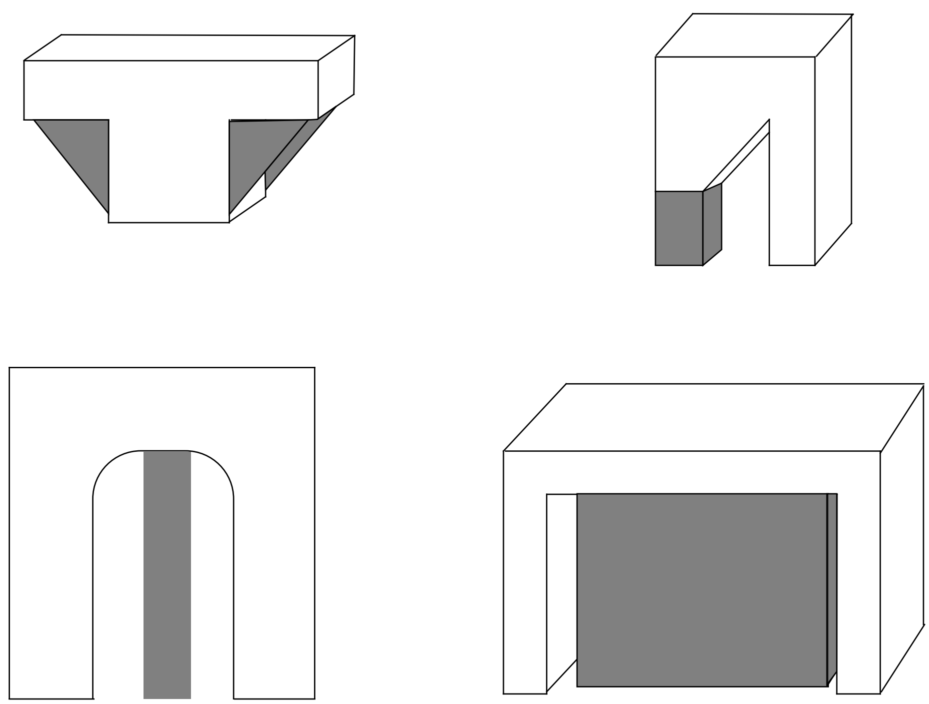

Figure 6: Support Structure Examples

Part support structures can be generated either manually or using an automated support generation software tool. System users without an automated support generation tool typically develop a library of standard support structures. A user would analyze a part design for support structure needs, select appropriate supports from the library, and then position the selected supports in relation to part geometry features. Although this manual operation could be a substantial effort for many part geometries, the task can be minimized by proper selection of part orientation within the build platform. Commercial software packages to assist support generation for stereolithography systems include "BridgeWorks" by Solid Concepts, Inc. (Valencia, CA) and a more recently announced package called "Magic" from Materialise (Leuven, Belgium). [Brake] These systems automate the process by generating necessary supports based upon an analysis of the input part file. The BridgeWorks package applies a set of standard support structures, with categories for gussets, webs, columns, and projected feature edges. [Jacobs1]

Primary part finishing steps for many RP systems include curing and surface finish processing. Curing steps are often required to solidify liquid resins. The parts are typically heated in an oven or cured under an ultraviolet light to complete the solidification process. Implementation issues regarding curing operations include allocation of sufficient space for the curing equipment and allowances for sufficient time to fully cure the part.

All RP systems (with the possible exception of the PCM process currently under development) produce a vertical "stairstep" surface finish because of the fact that discrete layers are used to build the part. [Jacobs1] The layer thickness is usually a variable in the RP process established by the user. System capabilities of current commercial systems range from a possible layer thickness of 0.02 mm (0.001 in) to approximately 1.02 mm (0.040 in), with typical layer thickness values used in actual production situations between 0.13 mm (0.005 in) and 0.25 mm (0.010 in). [Miller] These discrete layers necessitate extra surface finishing steps (e.g., sanding, polishing, sealing) to obtain desired surface finish properties. These steps are typically required only for the vertical part surfaces, with the horizontal surfaces not normally a problem. Although prototype parts from all commercial systems require manual surface finishing to some extent, part surfaces from prototypes made using the SLS process from DTM Corporation are particularly rough in comparison due to the use of powdered material, rather than continuous material. The part surfaces have a granular texture due to the limitations in powder size. [Jacobs1]

Size

Two size considerations must be evaluated when determining RP system suitability to a given situation: the physical size of the machine (and associated accessories) and the prototype part size limitations resulting from the system working envelope. The physical size of various RP systems ranges from desktop units for some of the developmental systems, to a size suitable for an office environment, to a full-sized machine tool. The relatively large machine size for some RP systems, the Cubital Solider and SLA-500 systems in particular, may be a physical and/or psychological barrier to implementation. In addition, the machine tool aspects and general operation of the Cubital system typically require the attention of a dedicated operator. The physical machine sizes of some of the commercial RP machines are provided in Table 2 below. [Miller]

The working envelope of the RP system limits the largest part size that can be built. Many system vendors suggest, however, that large parts can be created by segmenting the part design into pieces, building prototypes of each piece, and reconstructing the overall part using glue, dowels, or other methods. The sizes of the working envelopes of some of the commercial RP machines are provided in Table 2 below. [Miller]

Table 2: RP System Size Considerations

System Name	Physical Machine Size	Working Envelope
SLA-250	0.69 m x 1.24 m x 1.64 m (27 in x 49 in x 64.5 in)	254 mm x 254 mm x 254 mm (10 in x 10 in x 10 in)
SLA-500	1.83 m x 3.45 m x 2.03 m (72 in x 136 in x 80 in)	508 mm x 508 mm x 603 mm (20 in x 20 in x 24 in)
Stratasys FDM	0.76 m x 0.91 m x 1.73 m (30 in x 36 in x 68 in)	305 mm x 305 mm x 305 mm (12 in x 12 in x 12 in)
Cubital 5600	4.14 m x 1.73 m x 2.49 m (163 in x 68 in x 98 in)	508 mm x 356 mm x 508 mm (20 in x 14 in x 20 in)
DTM SLS	1.50 m x 2.92 m x 1.93 m (59 in x 115 in x 76 in)	305 mm diameter x 381 mm deep (12 in diameter x 15 in deep)
LOM 2030	2.06 m x 1.52 m x 1.45 m (81 in x 60 in x 57 in)	559 mm x 813 mm x 508 mm (22 in x 32 in x 20 in)
Soligen Alpha	2.18 m x 1.30 m x 2.87 m (86 in x 51 in x 113 in)	305 mm x 203 mm x 203 mm (12 in x 8 in x 8 in)

The speed of prototype part creation is also somewhat related to the working envelope size. Some systems (e.g., Cubital) provide a flexible working volume so that the entire build chamber does not need to be used when creating small prototype parts. Other systems (e.g., SLA, Stratasys) only require use of the portion of the working envelope that directly encloses the prototype part shape. One convenient system feature found in some RP systems is a build-time estimator to indicate the time required to build a part given specific conditions. [MIRC1]

Cost

System cost is not normally the top consideration when choosing to buy an RP system. Users generally are more interested in the system functionality and suitability to specific applications. Nevertheless, the reality of system cost and funding availability must be considered in any purchase decisions. Approximate machine costs for several commercial RP systems are provided in [Miller]. Initial purchase costs of current commercially available systems typically range from approximately $180,000 to $210,000 for lower-priced systems, with an upper range of approximately $420,000 to $550,000 for more expensive systems. Several other cost considerations besides initial system cost must be taken into account, however. Operating costs and other associated costs will include CAD system use, computer workstations, consumable materials (e.g., resins, wax, toner, paper), system maintenance, staffing, training, system installation, and site preparation. [Wohlers2] As an example, one RP system vendor may require a higher initial equipment investment, but have lower continuing costs, such as for maintenance service contracts.

Laser life and laser maintenance costs are a primary concern for users of laser-based RP systems. Expected laser life is approximately 2000 hours for stereolithography systems. At a 60% operating rate (i.e., percentage of time the laser is actually in use) over the course of 24-hour days, the laser will have to be replaced every four to five months. Full maintenance service contracts, including unlimited laser replacement, are available from some RP system vendors. [Brake] [FBIS] [Miller] [MIRC1]

A recommended procedure for potential users new to the field of rapid prototyping is simply to contract with an engineering service bureau with RP capabilities for a period of time to meet your application's prototyping needs. Annual usage costs can then be determined and tracked based on real data to evaluate if there is proper justification for RP system procurement. [Sprow]

Environmental Concerns

Environmental concerns may be an issue for some prototyping applications, especially those which require use in an office environment. Current environmental considerations of commercial RP systems include generation and control of harmful fumes, handling and storage of resins and chemicals, and disposal of used part and support materials. Desired characteristics of RP systems for office use include clean and self-contained operations, low noise volumes, and convenient disposal of by-products. Of the primary commercial RP systems, the Helisys LOM and Stratasys FDM systems appear to be the most suited for an office environment. A primary consideration for RP system implementations within shop environments or production work areas is the facility air ventilation and air handling capacity.

Expected Advances in RP Technology

The fast pace of current RP technology development and implementation indicates that many technological advances will occur in the not-too-distant future. The use of RP systems within industry will also increase due to several factors, including enhanced functionality and ease of operation of RP systems, increased use of 3-D CAD systems and solid models as standard business practice, commercialization of current research systems, and transfer of RP technology to additional applications. Future prototyping systems will be considered more of a standard and accepted tool for product design and manufacturing personnel to improve productivity and create better products. Rapid prototyping technologies are expected to advance past the stage of simply prototyping and into flexible manufacturing of short production runs (i.e., small part quantities). Other advances will occur in better system accuracies, more cost-effective systems, and physical modifications to accommodate an office environment.

Current development work in the area of new prototype part materials will lead to a new generation of systems. Future prototype parts will exhibit more desirable material properties, including better stability to reduce shrinkage and warpage in plastic parts, higher part densities, and higher temperature materials. The primary focus is on creating prototype parts from more commonly used production materials, such as metals and ceramics. Several systems capable of making metal or ceramic parts are in their final stages of development. Other innovations will allow use of multiple materials within a given prototype. Material advancements will enable the capability to develop casting molds that allow higher quantities of parts to be produced (e.g., several thousand cast parts from a mold). As would be expected, use of new materials will also result in process modifications to accommodate new material properties, including higher-power lasers to reach appropriate melting and/or bonding temperatures and possibly different mechanisms of material transport within the system.

Many RP system improvements result strictly from software enhancements. Expected advances in software functionality, user interfaces, and networking will enable eventual push-button operation to create the part prototype from a CAD system design. RP equipment will be considered a computer peripheral, just as a laser printer or graphics plotter is today. [Jacobs1] The concept of "faxing" prototype part information for production at a remote site will not be uncommon. [Stevens] Plans have also been discussed at the University of Nottingham (England) for development of an automated system to perform part finishing operations using sensors and part definition information, while still maintaining part accuracy. [Dickens] This system would replace the current manual finishing operations needed for many prototype parts developed with today's systems.

The envisioned future of rapid prototyping was discussed from three different perspectives at the Rapid Prototyping & Manufacturing '93 Conference (Dearborn, MI, May 11-13): Chrysler Corporation (Detroit, MI) [Schmidt], Wohlers Associates (Fort Collins, CO) rapid prototyping consulting firm [Wohlers5], and Digital Equipment Corporation (Maynard, MA) [Cassista2]. The emphasis from [Schmidt] is the urgent industry need for development of a "fast concept modeler" for use in the product design environment. This type of tool is required due to the estimate that approximately 20% of all prototype parts currently built have a shelf-life of approximately 15 minutes. In many cases, design changes and improvements are instantly recognized when the product designer analyzes the physical prototype. Chrysler has developed a high-level set of parameters and "user requirements" for development of such a concept modeler. This set of requirements was recently distributed to known RP system vendors to stimulate product development and discussion. A primary characteristic of the fast concept modeler is that users would have the option to sacrifice system accuracy to obtain a faster model creation speed (i.e., a part with +/- 6.4 mm (0.25 in) tolerance may be acceptable for the application if it could be created within one hour). Potential uses of the fast concept modeler include product design "printers" for iterative product development.

Rapid prototyping industry consultant Terry Wohlers has also made several predictions on expected advances and developments in the RP field. [Wohlers5] Some of his thoughts on the future of RP are outlined below.

- The biggest advances in RP technology will be made in system software capabilities and ease of operation (e.g., interfaces, push-button operation).
- RP industry growth will be tied to the expected growth in the 3-D CAD and solids modeling market.
- Future RP systems will be more commonly used to build mechanical systems and assemblies, rather than a single component.
- RP industry vendors will gain profitability through an enhanced customer base and expanded applications of the technology.
- RP technologies will continue to improve and system costs will continue to decline.
- Low-volume production runs will become practical with RP technology.

- RP vendors will target specific markets and applications for their products (e.g., metal casting, medical, architecture, large vs. small parts, high vs. low part volumes).
- Users will be able to build prototype parts in the desired color, including parts with multiple colors.
- Markets for complimentary products will grow along with the RP industry (e.g., support generation systems such as BridgeWorks, part digitizing and reverse engineering systems, virtual reality systems and components).

One of the most significant visions of the future of rapid prototyping is that of a prototyping system that is truly a “desktop system.” The goal is to have a unit approximately the size of a standard office laser printer that can maintain acceptable accuracies and surface finish, use more realistic part materials (i.e., metals and ceramics), and sell for under $20,000. Systems with these expected characteristics are already under development and it is estimated that this capability will exist by the end of 1994. It is also expected that these systems will use a technology fundamentally different than those used by current commercial systems, most likely based upon a form of “jetting” technology. [Wohlers5]

A more long-term view of expected advances in rapid prototyping is provided by [Cassista2]. Due to the rapid and significant advances in both hardware and software technologies, this view predicts that most, if not all, information needed about a product will be captured and represented by computer. Prototyping as currently discussed and product development in general will again undergo a transformation. New technologies, including holographic projection, virtual reality, real-time analysis of product or process design using on-line expert advisors, faster computer processing speed, and enhanced data storage/access, will shift the user’s focus to rapid process development, rather than rapid prototyping. The users would be able to “experience”, as well as visualize, the development stages of a new product and a physical prototype of a part would be looked upon as redundant in this scenario. This view is shared by [Penoza] and other researchers and system developers in the fields of virtual reality, “virtual manufacturing”, and “virtual prototyping.” Further discussion on this subject, however, is beyond the scope of this assessment.

State-of-the-Practice vs. State-of-the-Art

The state-of-the-practice of a given manufacturing technology is typically viewed as current commercially-available or internally-developed systems or methodologies in use within production facilities. The focus of this designation is on current use of the technology through normal business practices. The state-of-the-art, on the other hand, implies that use of a specific system or process would advance the state of the technology through improved and innovative techniques or applications that are not yet considered common throughout industry. The state-of-the-art designation emphasizes initial implementation of research and development systems and applications, rather than focus on the existing commercial marketplace.

The technology field of the RP industry is relatively young, with the first systems introduced in late 1987. Since RP systems of any type in actual production use number only in the hundreds and use of RP systems is just recently becoming a common practice within many organizations, a fine line separates the state-of-the-practice and state-of-the-art in rapid prototyping. Many people may consider that for all practical purposes, the state-of-the-practice and state-of-the-art may be the same thing. Some distinctions can be made, however, between current commercial systems and applications and research and development efforts that have recently created new applications of RP technology or have produced sample parts using new techniques.

The state-of-the-practice in rapid prototyping can be characterized primarily by industrial use of the five primary commercial prototyping methodologies discussed previously in this report (i.e., SL, LOM, SLS, etc.). These systems are most commonly used for design visualization, iteration, and optimization and for communication of product information between organizations. Another aspect of the state-of-the-practice is the common use of engineering service bureaus to meet prototyping needs. The number of engineering service bureaus with RP capability has grown substantially, primarily due to the initial start-up expense of purchasing RP equipment. These service bureaus contract to perform discrete manufacturing jobs for other organizations, including prototype part creation, secondary tooling operations, and production of cast parts.

The state-of-the-art in rapid prototyping would include such research and development efforts as production of metal and ceramic parts, production of prototype parts comprised of multiple materials, and creation of functional product assemblies. In addition, the recent introduction of new part build structures, materials, and rapid fabrication techniques to enable development of molds and associated tooling for cast parts would be considered on the leading edge of RP applications. Other developments in cost-effective functional desktop systems and electronic exchange (e.g., "faxing") of product information to an off-site RP system will soon be commercially available.

Standardization Activities

An additional objective of this state-of-the-art assessment is to review applicable standardization activities to assess their relevance and impact on development and implementation of RP systems. Two primary areas are identified where standardization would benefit the rapid prototyping industry: the interface between RP systems and other computer-aided design / computer-aided manufacturing (CAD/CAM) systems and specifications of the mechanical properties of prototype part materials.

The current interface to most rapid prototyping systems is through the STL *de facto* industry standard data format. As previously discussed, this data format, though widely used and easily processed, is not an ideal representation. Many RP system vendors have expressed interest in participating in development of a new standard interface to replace STL. A standard data interface for prototyping systems has been compared to the analogy of the PostScript data format used by current laser printers. [Jacobs1] A continued concern by both system vendors and users, however, is to retain backwards compatibility with STL so that current customers can remain functional without major system upgrades. Other avenues being pursued by RP vendors include development of specific interfaces for selected CAD/CAM systems. This movement away from standardization is further indication that the current STL format is not fully acceptable and that development of a new standard interface for the RP industry should be initiated without delay.

Existing standardization work which may provide the basis for a new data interface between RP and CAD/CAM systems includes development of the Standard for the Exchange of Product Model Data (STEP) by the International Organization for Standardization (ISO), or more formally called ISO 10303. [ISO] The STEP standard will supply a formalized and nonproprietary mechanism for representing information about a product, including geometry, tolerances, product structure, and material specifications, and for exchanging this information between various CAD/CAM systems.

Data input formats for future prototyping systems may include information conforming to the STEP standard.

Procedures and regulations for the specification and testing of prototype part materials is another needed area of standardization for the RP industry. [Kimble] Currently there are no uniformly accepted material testing standards in use by RP system vendors. Since material properties are generally process specific, mechanical properties of a material published by one manufacturer cannot be compared directly to those published by another manufacturer. Often the results were obtained using different testing methods. The user is left with the difficult situation of selecting a material for a specific application through published properties alone. Additionally, there is no accurate method to compare properties of materials used in the RP industry with those commonly used in other industry applications. Many RP customers desire to transition their prototype building operations to use of common production materials.

The American Society of Testing and Materials (ASTM) has developed a series of standard tests for determining mechanical property data of a material. ASTM specifications include standard test procedures for tensile testing, flexural testing, impact testing, heat deflection temperature testing, and several others. The ASTM methods have been adopted by the Society of Plastics Engineers (SPE) for specification of the mechanical properties of plastic materials. [Kimble] The primary recommendation from [Kimble] is that the RP industry should develop or adopt procedures and regulations for specifying and testing materials uniformly through ASTM or ISO-type standards. A standard test methodology would allow users to compare materials directly and select materials and processes based on the requirements of an application. If the ASTM testing standards used by the plastics industry were adopted, a comparison of RP materials to commonly used plastic materials would also be possible.

Conclusion

This state-of-the-art assessment has discussed several rapid prototyping methodologies, typical applications, and some of the technical issues associated with developing and implementing RP systems. Multiple prototyping systems and technologies will continue to coexist due to their relative strengths in different application areas and corporate situations. Several advancements are expected in the near term commercial marketplace from this rapidly changing technical field. Other advancements from basic and applied research will generate new ideas and new methods of prototyping in the future.

Implementation of RP technology can provide a company with an improved ability to transition from design concept to final product. Shorter time-to-market, higher quality product, and reduced product cost can be achieved through application of RP techniques. Companies must take full advantage of emerging technologies, such as rapid prototyping, and modify business practices accordingly to increase productivity and remain competitive in the marketplace.

Much like current trends in computer hardware, RP systems and technology are advancing so quickly that a user waiting for release of the ideal prototyping system will be forever evaluating and never implementing. New products and innovative applications will always be just a few months away and last year’s technology will always be outdated. The sage advice from many RP system users is to anticipate the next generation of prototyping systems, but not to wait for them to implement a solution to current needs.

Recommendations for Further Research

Much research and development in the field of rapid prototyping is currently ongoing in corporate and academic research laboratories. This work, primarily in the areas of new techniques for rapid prototyping, new prototype part materials, and new software capabilities, should continue. Standardization efforts, such as that proposed for uniformly specifying and testing materials, should be initiated through a focus group of RP industry representatives.

This state-of-the-art assessment was performed and sponsored through the NIST Factory Automation Systems Division (FASD) technical collaboration with the NCMS Rapid Response Manufacturing (RRM) industry consortium. Future work within FASD in this area should focus on the continued support of the RRM program and anticipated future efforts within the division. Information contained in this assessment should be used as background material to advise RRM consortium members and other NIST customers regarding the technology, fabrication processes, implementation, and integration aspects of rapid prototyping. The Factory Automation Systems Division should not become involved in the development of new RP systems or methodologies. Other developmental efforts are quite well-established with the capability to produce sample parts. One possibility is to apply NIST resources to advance the technology through pursuit of partnerships with current development efforts.

One of the primary components of the NIST mission is to help industry through activities that enable technology transfer. FASD staff should remain knowledgeable in technological advances in rapid prototyping and related fields to make recommendations to industry and to transfer information and techniques from this emerging technology into production applications. FASD efforts should also be applied in the replacement and standardization of the STL data format for CAD/CAM system interface. Previous experience in computer data formats, manufacturing system integration, product data representation, and the standardization process would prove beneficial in assisting RP industry representatives to create a more functional and acceptable alternative. Future FASD work in rapid prototyping should emphasize the application and demonstration of RP technology in various production settings and stages of the product lifecycle. Initial prototype part fabrication should be performed remotely, however, through use of an engineering service bureau rather than procurement of an on-site machine. This strategy will enable most effective use of project funding until either desktop units are available or prototype quantities justify procurement of a dedicated machine. FASD should also pursue possible collaboration and/or consultation with other NIST divisions performing research in similar or related topics. Possible opportunities for collaboration exist with the NIST Fabrication Technology Division for use of RP systems in fixture design and NIST materials science divisions for application of new materials to RP fabrication methodologies.

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