rapid Product Realization

Snapshot: Rapid product realization is a new method of manufacturing prototypes based on optical and laser systems. These techniques shorten product cycle times and reduce costs. They present a host of opportunities for the optics and photonics communities. **By Allan J. Lightman**

There is a revolution underway in mechanical manufacturing processes. It is being driven by the need to compete in an international marketplace that is characterized by smaller production runs, shorter windows of opportunity, and higher customer expectations. As a result of these driving forces, manufacturers are radically changing the product realization process. They are switching from iterative, serial design and production techniques to concurrent processes that integrate all aspects of business needs, from establishing customer specifications to marketing strategy (see Fig. 1). The manufacturing component of this new approach focuses on the production process. The expectation is that if the process is under control there will be no need for high cost, post-production functions such as quality control. In the present vernacular, this design paradigm is referred to as Integrated Product and Process Development (IPPD). It embodies many concepts, such as concurrent engineering, and, in its fullest realization, incorporates the latest paradigms, such as agile manufacturing.

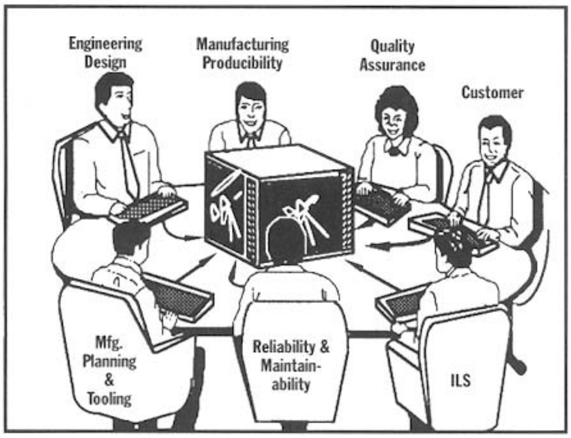

Figure 1. The integrated product realization environment (courtesy of USAF ManTech).

A cornerstone of IPPD is rapid prototyping (RP), which permits designers to quickly create three-dimensional (3-D) physical models directly from a 3D computer-aided design (CAD) model. These prototypes provide design teams with rapid feedback for evaluating their concepts. They also provide design phase models for customer evaluation, manufacturing engineering study, and every other step needed in the product realization process. RP systems are particularly important because of their speed (simpler models can be produced overnight) and reduced personnel requirements. By and large, these systems fabricate models by adding material on a layer-by-layer basis. By contrast, traditional processes start with a "block" of material and cut away whatever is not needed. Many RP systems are optical or laser-based and they will drive optical system development to meet their system needs.

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Manufacturer	Technology[a]	1994 Sales	Total Systems[b]
United States			
3D Systems	SLA[c]	70+	460+
Helisys	LOM	70	100+
Stratasys	FDM	45+	80+
DTM	SLS	26	60+
Soligen	DSPC	3	7
Sanders Prototype	3D Plotting	16	16
BPM	BPM	0	0
Japan			
CMET	SOUP	5	50+
D-MEC	SCS	3	30+
Teijin Seiki	Soliform	3	5
Mitsui Zosen	COLAMM	1	2
Denken Engineering	SLP	8	10
Kira	Solid Center	3	3
Europe			
Cubital	SGC	3	20+
EOS	STEREOS, EOSINT	15	30
Sparx	Hot Plot	0	15
Fockele & Schwarze	LMS	1	1

Table 1. RP systems and market share. (Courtesy of Wohlers Associates)

[a] The underlying technologies are: laser photopolymerization (SLA, SOUP, SCS, Soliform, COLAMM, SLP, STEREOS, LMS); lamination (LOM, Solid Center, Hot Plot; fused deposition FDM); laser sintering (SLS, EOSINT); jetting into powder (DSPC); jetting of plastic or wax (3D Plotting); mask photopolymerization (SGC).

[b] Most of the data is through December 1994.

[c] Acronyms are listed in alphabetical order: BPM™ (Ballistic Particle Manufacturing—BPM Technology Inc.); COLAMM™ (Computer Operated Laser Active Modeling Machine—Mitsui Engineering & Shipbuilding Co. Ltd.); DSPC™ (Direct Shell Production Casting—Soligen, Inc.); FDM™ (Fused Deposition Modeling—Stratasys, Inc.); LMS™ (Laser Modeling System™—Fockele & Schwarze Stereolithographictechnik); LOM™ (Laminated Object Manufacturing—Helisys, Inc.); SCS™ (Solid Creation System—D-MEC Ltd.); SLA™ (StereoLithography Apparatus—3D Systems, Inc.); SLS™ (Selective Laser Sintering—DTM Corp.); SOUP™ (Solid Object Ultra-violet Plotting—CMET, Inc.); SLP™ (Solid Laser Plotter—Denken Engineering Co., Ltd.); SGC™ (Selective Ground Curing—Cubital, Ltd.)

The RP industry will impact the business of optics and photonics (O&P) in many areas. The O&P industry is driven by the same forces that impact general manufacturing. The lessons learned through IPPD, such as improved time-to-market, apply to O&P. RP systems may be used to directly fabricate optical elements or their molds. Future micro-RP sytems may be extended to create 3D integrated optical networks. In addition, many RP systems are based on techniques that require specialized optics and laser systems. The rapid growth in the RP market will provide impetus for the development of new and improved laser systems, such as higher power pulsed and continuous UV lasers, that underlay these faster, better RP machines.

As a result of their mode of operation, even the simplest RP systems, which appear to be $2^{1}/_{2}$-axes machines (bi-directional X and Y, unidirectional Z), are capable of producing parts whose intricacy exceeds the capability of traditional 5-axes machining systems.

The first commercial RP machine (1988) was developed and marketed by 3D Systems (Valencia, CA). They associated the name stereolithography (SLA) with their process.[1] Since then, many other processes have entered the global marketplace. Presently, at least 17 companies (Table 1) offer RP machines, and many more are preparing to enter the market. The name rapid prototyping is somewhat misleading when used in its strictest sense. A prototype should be equivalent to the final production part, both in functionality and in the process by which it was produced. Currently, RP processes almost exclusively build models. While these models enable the evaluation of form and fit, their ability to evaluate function is limited. Recently, RP models have been used to create tools which are then used to produce functional prototypes. These tools have also been used for limited production (many of these tools are capable of more than 1000 operations). Efforts are underway to produce tools directly and some vendors have been successful.

Rapid product realization systems

Stereolithography

All current RP systems are based on layer-by-layer fabrication of a prototype. The 3D CAD data is sectioned into a set of parallel slices. This data form is input into the RP system which then forms each layer in sequence, in registration with the preceeding layers. The result is a layered fabrication of the 3D part.[1] The most common RP method (SLA) is based on laser photopolymerization. A liquid photopolymer is selectively solidified by exposure to an ultraviolet laser, either HeCd (325 nm) or argon (350 to 360 nm). The laser is directed to the desired location by a variety of delivery systems, such as scanning galvanometer, gantry, and robot arm (see Fig. 2). The laser exposure is adjusted to restrict energy deposition. The chemical reaction initiated by the exposure has a critical threshold before solidification begins. Since

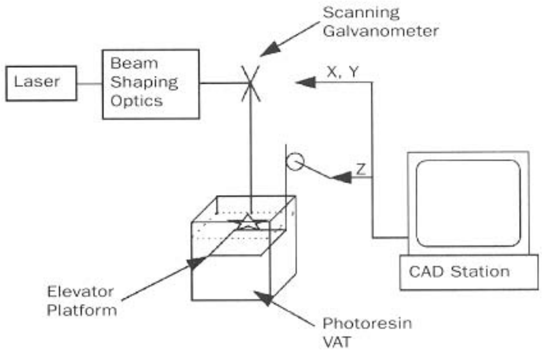

Figure 2. Typical photopolymerization RP configuration.

the exposure beam's absorption is determined by Beer's law, cure depth can be controlled to match the thickness of the slices in the CAD system. Typical RP performance uses slice thicknesses between 75 and 250 mm (0.003" to 0.010"), which is satisfactory for many parts. Some systems have achieved 25 mm (0.001"), and others can operate with much thicker layers. Layers of 25 µm yield part surface definition, which is much improved compared to that of larger thicknesses, but build time increases dramatically (faster than linear extrapolation). For larger thicknesses (75 to 250 µm), surface "staircasing" may require substantial post-fabrication rework.

The initial SLA solidified layer is formed on an elevator platform. After formation of the initial layer is complete, the platform is lowered into the vat of the liquid photoresin. A uniform layer of fresh liquid material is flowed over the top, and the next layer is solidified in this liquid. Sufficient energy is deposited during solidification to cause adhesion of the new layer to the layer beneath. The process is repeated, one layer at a time, until every layer needed to create the part has been formed, each in perfect registration with those preceeding. After the part's topmost layer has been built, the elevator is raised from the vat, allowing the excess liquid photoresin to flow off. Except for some post-processing, the part fabrication is then complete.

Laser sintering

Another popular RP system is based on laser sintering (SLS).[2] The operation resembles laser photopolymerization, with one key difference: the laser is used to fuse powder material. If the material is a thermoplastic, it is heated above the melting point using a CO_2 laser. To reduce the laser energy requirement, the powder bed is maintained at a temperature just below the melting point. If the melting point is too high (*e.g.*, metals, ceramics), either sufficient energy is applied to cause some sintering or a thermally activated particle coating is used to create adhesion. Again, the part is built layer by layer with fresh powder spread over the descending part platform after the current layer is complete. The resulting "green" part is then taken to a sintering oven where the binder, if used, is burned off and the part is sintered more thoroughly. If higher density is required, such as in metal parts that form injection molding dies, liquified metal (copper) is wicked into the interstitial spaces to densify the part.

Laminated object manufacturing

The laminated object manufacturing system (LOM)[2] is quickly gaining popularity as a result of its large part capacity and the notable straightness of final parts. Once again, a layering system is used but, in this case, each layer is created from a preformed sheet of material. Rather than exposing the raw material at every point where solid material is required, this system

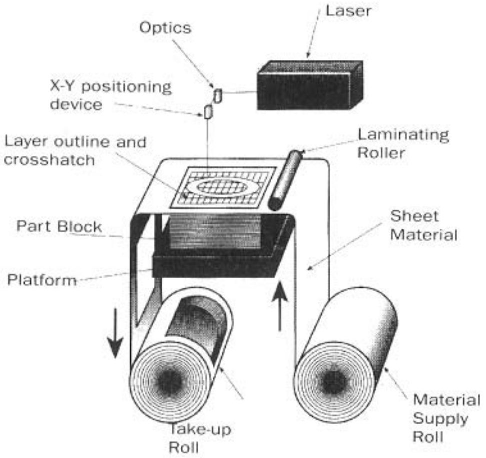

Figure 3. LOM using gantry delivery laser cutting system. (Courtesy of Helisys Inc.)

uses a laser to cut the periphery. The material currently available is a specially formulated paper with a bonding agent. It is adhered to the build area and the CO_2 laser cuts the layer outline (see Fig. 3) Laser deposition energy is controlled to allow a cutting depth sufficient for only the topmost layer. The process is currently being extended to work with ceramics and fiber-reinforced composites. In these cases, the thermal process currently used to define the boundary is deleterious to the material at the edge. A photoablation process is needed to remove the material at the edge without heating the material on either side. This requires the use of a pulsed-laser system operating in the visible or UV. The market growth for this RP system will provide strong motivation for the development of suitable lasers for this application.

Applications

These RP technologies are having significant impact in manufacturing. Their ability to dramatically shrink new product development times has been documented in numerous case studies presented both in the U.S.[3, 4] and abroad.[5] In the future, RP capabilities will permit the use of designs that can not be made by conventional manufacturing processes.

Many other applications will emerge as the capabilities of these new fabrication processes are more widely considered. One application currently being developed results from the direct connection of the build-by-layer technique and the layer-by-layer presentation of tomographic data. Tomographic data is obtained by scanning systems, such as computed tomography (CT) and magnetic resonance (MR). When the data represents human subjects, the RP systems provide the capability to produce anatomically accurate models that can be used for diagnostics, surgical planning and practice, and preparation of prosthetics (see Fig. 4) prior to invasive procedures. Advances in RP systems and materials may soon permit the fabrication of bio-compatible components for direct implantation and the building of models and templates that can be used as guides during surgery. The goal is to reduce the time needed in surgery, reduce the number of surgeries needed in complex procedures (which are often iterative), and improve the results.

Figure 4. Patient injured by gunshot. Model can be used for constructing implant.

Impact on the optics and photonics industry

The economics driving the RP industry provide a strong motivation for the development of laser and optical solutions to the RP system needs. Current delivery systems push the existing technological limits. Typically, the largest surface envelope is approximately 1 m × 1 m. Laser positioning accuracy should be within 10 µm everywhere in this envelope and repeatability should be significantly better. As the laser beam profile control improves, some applications will require improvement of accuracy and repeatability by an order of magnitude

The LOM process will open a large market for efficient, medium energy, pulsed visible or UV lasers (30 to 100W, 10 to 20 kpps, 250 to 500 nm). This market could potentially generate sufficient demand to

Glossary

Computer aided design (CAD): Computer programs assisting design engineers conceptualize and reduce models to engineering practice.

Integrated Product and Process Development (IPPD): Multifunctional teams converting concepts to customer deliverables using concurrent practices.

Laser Phototopolymerization: Laser induced polymerization of liquid monomers resulting in a solid material.

Laser Sintering: Surface binding of powders as a result of chemical bonding induced by laser exposure.

MicroElectronic Mechanical System (MEMS): Mechanical rotation and translation devices created on silicon wafers using integrated circuit lithography techniques.

Photoablation: Material removal using light-induced breakup of the material's structural bonds and subsequent eruption of the plasma. Input energy is carried away as kinetic energy of the effluent.

Rapid Prototyping (RP): A set of technologies that fabricate models by creating material only where material exists. Most technologies build parts on a layer-by-layer basis. (Some exceptions, such as LOM, are still considered RP systems.)

Rapid Tooling: Generation of tools for molding and forming using RP models.

Stereolithography: An RP process based on laser photopolymerization.

spur the development of these lasers. An interesting feature of a gantry delivery system (such as that used in LOM) is that the delivery head can be oriented tangential to the surface, thereby sloping the surface to remove the staircasing associated with normal-to-the-layer formation processes, such as those using galvanometer systems. This will overcome the staircasing issue, providing superior surfaces while allowing the use of thicker layers and resulting in reduced fabrication times. The technology may also be implemented in other lithography applications where side wall sculpting provides performance enhancements.

An application area that is currently under development is the use of these technologies in microfabrication. Some systems have demonstrated the capability to produce full 3D structures with features on the order of 10 mm or less. The key issue is the 3D capability, compared with the extruded $2^1/_2$D forms fabricated by MicroElectroMechanical Systems (MEMS) techniques. Other layering systems have been presented that should improve on the feature dimensions.[3]

Final product

The impact of RP on manufacturing is just beginning. In many cases, the product and process development stage is being redefined in ways that will incorporate RP so that full competitive advantage can be obtained from RP's capability. Most of the current RP systems are based on optics and laser systems. As the RP market develops, its size will provide economic incentive for enhancement of current laser and beam guidance capability and the development of new laser systems.

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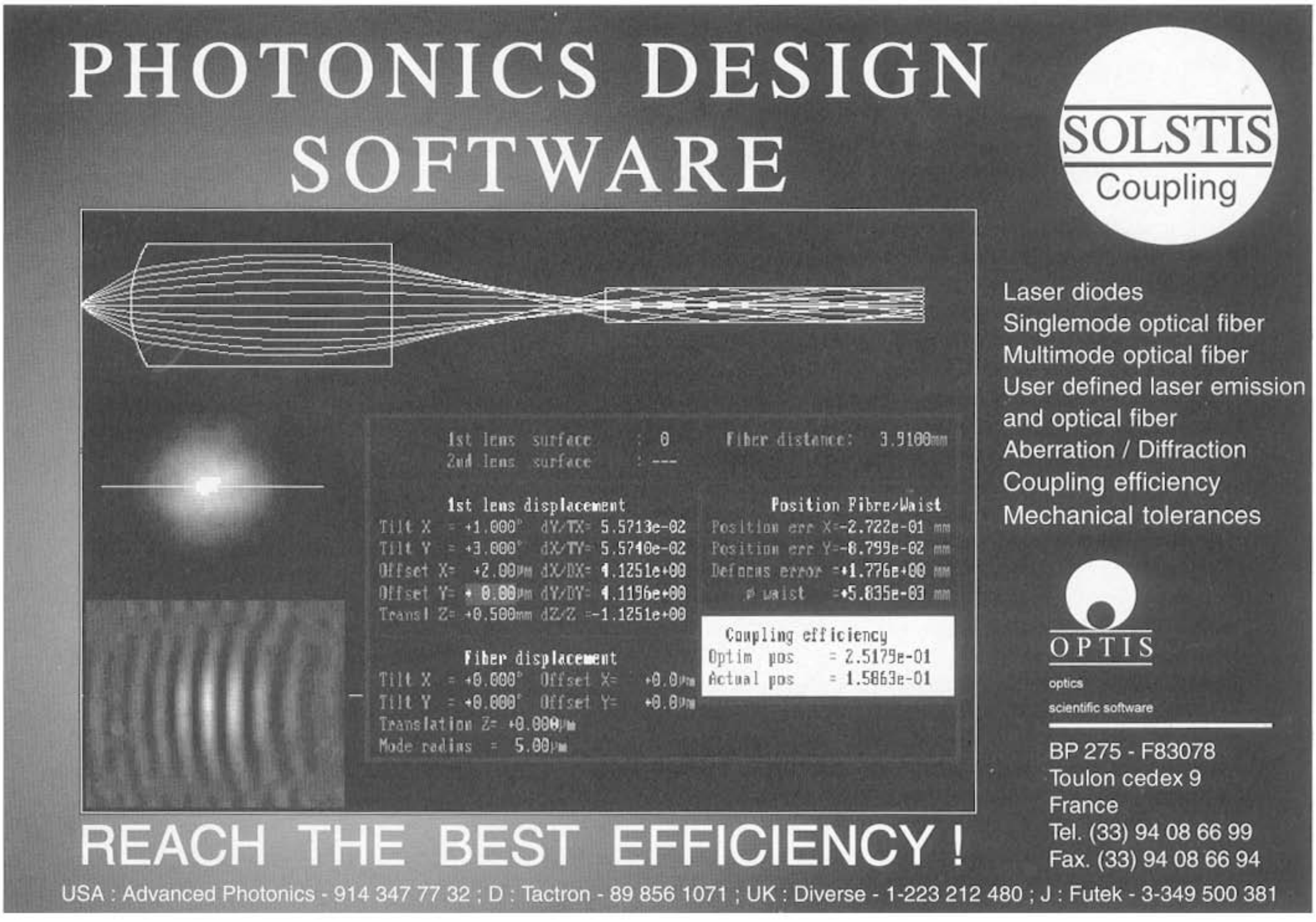

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