Early Research & Development

by Terry Wohlers

The first attempt to create solid objects using photopolymers using a laser took place in the late 1960s at Battelle Memorial Institute. The experiment involved intersecting two laser beams of differing wave length in the middle of a vat of resin, attempting to polymerize (solidify) the material at the point of intersection. The photopolymer resin used in the process was invented in the 1950s by DuPont.

In 1967, Wyn K. Swainson of Denmark applied for a patent titled Method of Producing a 3D Figure by Holography on a similar dual laser beam approach. Subsequently, Swainson launched Formigraphic Engine Co. (Bolinas, CA) in hopes to further develop and eventually commercialize his technology. Work, reportedly, was still underway in 1994, although it never led to a commercially available system.

In the early 1970s, Formigraphic Engine Co. used the dual laser approach in the first commercial laser prototyping project, a process it called photochemical machining. In 1974, Formigraphic demonstrated the generation of a 3D object using a rudimentary system. Later, Formigraphic became Omtec Replication, apparently at a time when an alliance was formed with Battelle (Columbus, OH). Dr. Robert Schwerzel, then with Battelle, led the development of similar techniques with the help of DARPA funding. Co-developer Dr. Vincent McGinniss was one of the team members employed by Battelle.

In the late 1970s, Dynell Electronics Corp. was assigned a series of patents on *solid photography.* The invention involved the cutting of cross sections by computer control, using either a milling machine or laser, and stacking them in register to form a 3D object. Dynell merged with United Technologies Corp. in late 1977. As a result, an independent company called Solid Photography was formed and an affiliated retail outlet named Sculpture by Solid Photography was opened. In mid-1981, Sculpture by Solid Photography changed its name to Robotic Vision. Solid Photography and another company, Solid Copier, operated as subsidiaries of Robotic Vision at least until mid-1989.

Development of stereolithography

Hideo Kodama of the Nagoya Municipal Industrial Research Institute (Nagoya, Japan) was among the first to invent the single-beam laser curing approach, according to several sources. In May 1980, he applied for a patent in Japan, which later expired without proceeding to the examination stage, a requirement of the Japanese patent application process. Kodama claimed to have difficulty in securing funds for additional research and development.

In October 1980, Kodama published a paper titled Three-Dimensional Data Display by Automatic Preparation of a Three-Dimensional Model that outlined his work in detail. His experiments consisted of projecting UV rays using a Toshiba mercury lamp and a photosensitive resin called Tevistar manufactured by Teijin. The method involved black and white film used to mask and control the region of exposure, corresponding to each cross section. The paper also discusses the use of an x-y plotter device and optical fiber to deliver a spot of UV light. CMET used a version of this technique in its SOUP 530, 600, and 850 machines.

Kodama published a second paper in November 1981, titled Automatic Method for Fabricating a Three-Dimensional Plastic Model with PhotoHardening Polymer in *Review of Scientific Instruments.* Kodama describes three basic techniques he used to create plastic parts by solidifying thin, consecutive layers of photopolymer. In the paper, Kodama claims, “If the solidified layer is immersed into the liquid with the top at a depth equal to the thickness of the layer to be solidified, its top surface is covered with unsolidified liquid polymer,” essentially describing a key element of the stereolithography process. Kodama's experiments with the three techniques were perhaps the first evidence of working RP techniques in the world.

Work in the U.S. and France

In August 1982, Alan Herbert of 3M Graphic Technologies Sector Laboratory published a paper titled Solid Object Generation in the *Journal of Applied Photographic Engineering.* In this paper, Herbert described a system that directs an Argon Ion laser beam onto the surface of photopolymer by means of a mirror system attached to an x-y pen plotter device. With the system, Herbert was able to create several small, basic shapes. The primary purpose of the work, however, was to develop an understanding of the requirements of a real system, according to Herbert.

In 1989-1990 timeframe, Wohlers Associates received a hand-written note from Alan Herbert, attached to a copy of his 1982 paper, saying that, unfortunately, his company elected not to commercialize his work. He was apparently very disappointed with 3M's decision. His interest in the development of RP techniques continued, as indicated by his August 1989 paper titled A Review of 3D Solid Object Generation published in the *Journal of Imaging Technology.*

In July 1984, Jean-Claude Andre, now with the French National Center for Scientific Research (CNRS) in Nancy, France, and colleagues working for the French Cilas Alcatel Industrial Laser Company, filed a patent titled Apparatus for Fabricating a Model of an Industrial Part, involving a single-beam laser approach. The French patent was granted in January 1986. Laser 3D, also of Nancy, France, tried to make the technique outlined in the patent available commercially on a service basis with no plans to sell systems.

In the late 1980s, Andre explored the dual-beam approach. He found that many problems existed with it, yet a team at CNRS continued to research the technique. Andre led the development of stereolithography at CNRS for Laser 3D.

Formation of 3D Systems

In August 1984, Charles Hull, co-founder and chief technical officer of 3D Systems (Valencia, CA), applied for a U.S. patent titled Apparatus for Production of Three-Dimensional Objects by Stereolithography, which was granted in March 1986. At the time of the patent application, Hull was working for UVP, Inc. (San Gabriel, CA) as vice president of engineering. In March 1986, Hull and Raymond Freed co-founded 3D Systems Inc. According to Alan Herbert, published illustrations show impressive detailed parts produced by Hull's early system, much more so than those shown by Kodama or himself.

Hull's 1986 patent describes a process of photo hardening a series of cross sections using a computer-controlled beam of light. Also in 1986, Yehoram Uziel, then of Operatech (Israel) had invented a basic machine resembling stereolithography. Uziel had read about Hull's work so he traveled to the U.S. to visit him and Ray Freed. In January 1989, he joined 3D Systems as vice president of engineering. In late 1987, 3D shipped its first beta units to customer sites in the U.S., followed by production systems in April 1988. These were the first commercial RP system installations in the world.

Uziel left 3D Systems in 1991 to form Soligen, Inc. (Northridge, CA). Today, Uziel serves as chief executive officer of the company. Around the time Uziel founded Soligen, he licensed MIT's ink jet printing technique for exclusive use in the metal casting industry. Soligen presently uses MIT’s technology in its Direct Shell Production Casting, a process that creates ceramic investment casting shells (molds) by adhering together thin layers of ceramic powder material using droplets of liquid binder.

In 1986, Hull was not the only one with patent activity on his mind. The same year, Takashi Morihara of Fujitsu Ltd. patented two elements of stereolithography. One of them involved passing a blade over the surface of a new layer of resin to speed the leveling of the layer. This technique is especially important when the resin is viscous. For many years, 3D Systems used this leveling technique in its SLA family of stereolithography products. Another approach developed by Morihara involved the dispensing of the resin from a slot moving above the surface of the resin. From early 1990 to early 1992, Quadrax Laser Technologies (Portsmouth, RI) used this resin deposition technique in its fast resin applicator, a feature contained in its Mark 1000 stereolithography machine.

Quadrax developed and sold the Mark 1000 system until February 1992, when its technology was acquired by 3D Systems after patent litigation that began in September 1990. Under the terms of the settlement, Quadrax transferred its laser modeling patent (granted in December 1991) and related technology to 3D in exchange for 130,000 shares of 3D common stock. At the time, the stock was worth about $325,000. As part of the agreement, Quadrax was required to discontinue marketing its RP system. Former employees of Laser Fare Ltd. (Smithfield, RI) developed some of Quadrax's original technology and later became employees of Quadrax. Laser Fare sold the technology rights to Quadrax in 1990.

Osaka Prefectural Industrial Research Institute

In 1984, Yoji Marutani of the Osaka Prefectural Industrial Research Institute (OPIRI), also referred to as the Osaka Institute of Industrial Technology, developed and demonstrated a stereolithography process. It’s not clear whether his work was connected with Kodama’s early work, although there’s a very good chance that Marutani at least studied Kodama’s May 1980 patent application and his October 1980 and November 1981 technical papers. It’s also possible that Marutani obtained a copy of Herbert’s 1982 paper, but it’s doubtful that Marutani knew about Hull’s and Andre’s work in 1984.

Marutani's patent document, titled Optical Molding Method, dated May 23, 1984, describes his invention in detail. The document describes many key elements of stereolithography, including the use of photocurable liquid material, focusing rays of light onto the surface of the liquid resin and presenting a fresh layer of material on top of the hardened layer.

Marutani continued his research and development of stereolithography, at least until mid-1987. In a paper dated August 7, 1987, Takashi Nakai and Yoji Marutani explained that they had developed a new type of system for constructing 3D models using a UV laser and liquid polymer. Rather than discussing the development of a new type of system, however, the paper discusses refinements to already known processes—refinements that increase speed and dimensional accuracy. At the time of publication, both Nakai and Marutani were working in the Department of Electronics at the OPIRI. Kodama's 1981 paper and Herbert's 1982 paper were included as references. It is believed that Marutani is still involved with RP today.

Commercialization of OPIRI technology

OPIRI, operated by the Ministry of International Trade and Industry (MITI), licensed its stereolithography technology to a group of Japanese companies, including Mitsubishi Heavy Industries, NTT Data Communications, Asahi Denka Kogyo, Toyo Denki Seizo, and YAC. Together they formed Computer Modeling and Engineering Technology (CMET) to develop, manufacture, and sell RP systems. The exact licensing date is not known, although Mitsubishi announced in July 1988 that it would sell a stereolithography machine developed jointly with OPIRI. It has been documented that these five companies supported the development and commercialization of the technology in 1989, leading to the introduction of the SOUP system in 1990. A dated SOUP product brochure, published by CMET, states that the "product had been developed on the invention of Osaka Prefectural Industrial Research Institute."

Mitsubishi with a 54% stake, was responsible for planning and development; NTT Data Communications, with 20%, was responsible for software development; Asahi Denka Kogyo, 20%, photosensitive resins; Toyo Denki Seizo, 3%, development of the x-y plotter mechanism and other hardware; YAC, 3%, precision machine manufacturing technology. Mitsubishi Heavy Industries reportedly spent 3 billion yen on further developing the OPIRI technology. At 40–50 million yen per unit, Mitsubishi reportedly sold nine SOUP systems from early 1989 to early 1990.

Sony and Mitsui enter the picture

In 1989, Design-Model and Engineering Center (D-MEC) was launched as a joint venture between Sony and Japan Synthetic Rubber (JSR). In April/May 1989, D-MEC introduced its Solid Creation System (SCS) for 53 million yen. The system was capable of building urethane acrylate resin parts up to 1000 x 1000 x 750 mm in size from layers at thin as 50 microns (0.002-inch). According to one reliable source, the system was developed behind closed doors and details about its origins have been kept quiet. Clearly, Sony had knowledge of OPIRI and CMET's technology, as well as the technology developed by 3D Systems.

3D Systems began to establish a presence in Japan in early 1988 when the company formed a joint venture with Japan Steel Works, Ltd. (JSW), a Mitsui company. 3D executives signed the agreement with JSW in March 1988. The new company, JSW-3D Co., Ltd. (Tokyo), served as a sales, marketing, and service organization for 3D Systems in Japan. SLA machines were made available to the Japanese by the third or fourth quarter of 1988. Near the end of 1989, 3D terminated the agreement and formed a wholly owned subsidiary, 3D Systems Japan.

Mitsui Engineering and Shipbuilding Company announced its COLAMM system in March 1991 and introduced it in July 1991 when it offered a series of introductory seminars. Mitsui's approach to stereolithography is different than the systems from 3D Systems, CMET, and Sony/D-MEC. Rather than building up layers from the top, a laser beam is presented through a transparent plate at the bottom of the build chamber. Each new layer of resin rests between the previously cured layer (which is above the resin) and the transparent plate (which is below the resin). With each new layer, the part moves upward into air space, rather than being submerged in resin.

Mitsui sold one unit to an automobile modeling company in Kyoto in December 1991, but has not reported sold any since then. The company had hoped for sales of 20-30 units in fiscal year 1992. The original COLAMM system, equipped with an engineering workstation, sold for 41 million yen. The company worked with Sanyo Chemical Industries to develop an improved resin with reduced shrink properties.

In January 1989, Mitsui and Nippon Steel announced their plans to form a joint venture called Plamedia Research Corp. The company would design and develop metal molds for producing parts made from plastics. It's not clear whether this venture was related to the development of Mitsui's RP system.

The June 92 issue of *Jetro* explains Mitsui's RP approach, verbatim, as a recent invention by professors N. Nakajima and T. Takagi of the Faculty of Engineering, University of Tokyo. According to the article, the process can build mechanical parts with 8-micron (0.00032-inch) features at an accuracy of ± 1 micron (0.00004-inch). Yet the article does not mention the Mitsui COLAMM system.

Teijin Seiki enters with DuPont's help

In 1989, DuPont announced the development of its SOMOS 1000 Solid Imaging System, a technology similar to 3D Systems' SLA. Because of their similarities, DuPont petitioned the U.S. Patent Office in September 1988 for a reexamination of Hull's 1986 patent. DuPont made the Patent Office aware of Kodama's publications, as well as those of others. Seven months later, the Patent Office told 3D Systems that it had rejected all claims in Hull's patent. This was about the time DuPont chose to go public with its SOMOS system, which occurred around June 1989. In late 1989, the U.S. Patent Office reversed its decision after 3D Systems produced strong evidence to support the claims in Hull's patent, but required the addition of new language that narrowed its scope. This was a turning point for DuPont.

Teijin Seiki acquired DuPont's SOMOS stereolithography technology through a licensing agreement in late 1991. In March 1992, at the Optomechatronics Show '92, Teijin Seiki announced the availability of its Soliform RP system for

50 million yen. The machine was an enhanced version of DuPont's original SOMOS system, according to Teijin Seiki. With its impressive laser draw speed of up to 2,400 cm (945 inches) per second, the company considered it a second-generation RP system. Teijin Seiki had introduced two versions of its SOMOS technology, the Soliform 300 (300 mm build chamber) and the Soliform 500 (500 mm), and had made them available for sale in Asia.

Teijin Seiki obtained the exclusive rights to manufacture and sell DuPont's SOMOS technology, although it was limited to Asia. The Japanese company paid approximately 700 million yen to obtain the license, including the system's blueprints, operating know-how, and patent and sales rights. After securing the SOMOS technology, Teijin Seiki moved 10 researchers from the electromechanical development department of its Iwakuni plant to it Kanagawa Science Park laboratories to work on the SOMOS project. In 1991, Teijin projected annual sales of 10 billion yen in 3–4 years.

In 1989, DuPont filed several patent applications related to stereolithography. Four of them concentrated on photopolymer developments. In the mid 1990s, DuPont supplied resins to Teijin Seiki, Electro Optical Systems (Germany), and users of 3D Systems' SLA-250 and SLA-500 models.

Others jump in

In early 1989, Hans J. Langer, formally of General Scanning (German branch), and a few associates started Electro Optical Systems (EOS). By mid-1990, BMW ordered its first system from EOS, and later a second for about DM 1 million. European Technology Holding, a venture capital company in Amsterdam, provided the basic financial support for Langer to go into business. Langer also secured DM 1 million from the German Federal Government's program for young technology entrepreneurs. Between mid-1991 and July 1993, EOS had shipped 15 STEREOS stereolithography systems to sites in Europe and Japan. Another customer, Hitachi Zosen Information Systems, had begun to market the EOS system in Japan.

In 1991, Nissei Sangyo Company announced the availability of an RP product, a combination of elements from Matsuo Sangyo and 3D Systems Japan. During the first year, Nissei Sangyo expected to sell 15 units, priced at about 100 million yen. Little is known about this development.

In early 1993, Denken Engineering (Oita City, Oita Pref., Japan) and Austrada Corp. jointly introduced a 7.8 million yen stereolithography system called the Solid LD Plotter System, SLP-3000. The unit uses visible light and a laser diode, rather than expensive lasers used in other stereolithography systems. According to Denken, the overall size of the SLP-3000 is small compared to competitive systems, yet it is capable of producing parts up to 200 x 400 x 300 mm (about 8 x 16 x 12 inches). The company hoped to sell about 50 units per year, many going to Japanese government labs.

Non-stereolithography approaches

While the Japanese concentrated on the stereolithography process, companies and individuals in the U.S. and Israel were developing other approaches to rapid prototyping.

In June 1986, Itzchak Pomerantz, founder and former president of Cubital (Raanana, Israel), filed for an Israeli patent in June 1986. At the time, Pomerantz was working for Scitex Corporation, an Israeli company that owned a small percentage of Cubital. Pomerantz' patent, titled Three-Dimensional Mapping and Modeling System, laid the ground work for the Solider 5600, which Cubital introduced in July 1987. In May 1988, Cubital and 3D Systems cross licensed certain parts of their technologies to minimize the possibility of subsequent legal conflicts.

In 1986, Russian immigrant Dr. Efrem Fudim of Light Sculpting (Milwaukee, WI) offered one of the first commercially available part building services using an RP technology he invented. His system projects a flood of light from a UV lamp through a mask onto the surface of photopolymer. This mask approach was similar to Cubital's photo mask, although Cubital had automated the process. With Fudim's system, individual masks were produced on a Gerber photoplotter and manually positioned over the build chamber for each new layer. This labor intensive, time-consuming approach did not win the hearts of buyers. Consequently, Fudim did not sell a single system.

Missing from Fudim's machine was a fast way to transfer the cross section information to the build chamber. In October 1991, Sanyo Electric applied for a patent involving a flat LCD panel as a mask through which UV light would shine onto the surface of photopolymer. Tests, however, indicated that the UV light would deteriorate the liquid crystal, shortening its effectiveness to hours. Fudim had also considered this approach.