Solid Freeform Fabrication:

An Historical Perspective

Joseph J. Beaman

The University of Texas

Austin, Texas

Today, several new technologies are capable of producing complex freeform solid objects directly from a computer model of an object without part-specific tooling or knowledge. They are, for the most part, additive processes and have been termed *Solid Freeform Fabrication*. In this paper, an historical perspective is given for this relatively new field.

Symposium History

The name Solid Freeform Fabrication (SFF) grew out of the name for a symposium at the University of Texas at Austin (UT). This group was composed largely of representatives from companies forming beta sites for the SLS machines being designed and built by DTM. In 1987 and 1988, meetings of the group were held both on the UT campus and at host industrial sites, including Ford and United Technologies Research Center. Based on the successful discussions and presentations at these meetings, under the leadership of Harris Marcus of UT, a formal SFF Workshop of researchers in the area was held in 1989 at UT. Held in a conference room in the College of Engineering, approximately 20 researchers presented 7 formal presentations of research and development in the area of SLS were given by the academic participants over 1.5 days. The formal presentation format of the Workshop was well received by the small group. Encouraged by this, an organizing committee was formed to offer in 1990 an open research conference on SFF. This meeting was the first SFF Symposium, held in Austin on August 6-8, 1990. Seventeen talks were presented with 54 participants at the meeting. Ten presentations were by the UT group with external representation by notable researchers including Ely Sachs, Mike Cima, Paul Fussell, Lee Weiss, Fritz Prinz and Dick Chartoff. The first proceedings of the meeting were hardbound published and were 187 pages long. At this meeting, and as what turned out to be the operating guideline for all the following SFF Symposium, no explicit commercial talks or presentations were given. The spirit of the meeting was for open exchange to promote the research and development of the many SFF approaches that were being investigated.

The meeting grew each year to a steady state attendance of about 150 people over the next seven years. In that period, the diversity of topics expanded considerably to a wide variety of techniques and processes. Harris Marcus chaired the organizing committee for the 1990 through 1995 meeting. Since 1996, David Bourell has chaired the organizing committee. The focus of the meeting has been on reporting of current research in the field.

The SFF Symposium is the longest continuous annual meeting in the field of freeform fabrication and is one of the oldest such forums. In 2001, the 12th Annual SFF Symposium hosted almost 130 participants from 13 countries. Approximately one third of the meeting attendees are students. The remaining participants represented foreign and domestic universities (50%) and industry (35%), with the balance from national and government laboratories. The 2001 proceedings contains almost 70 papers.

Prehistory of Solid Freeform Fabrication

Of course, Solid Freeform Fabrication did not magically appear in the 1980's. It grew out of at least two early roots: topography and photosculpture.

Topography

As early as 1890, Blanther (Blanther, 1892) suggested a layered method for making a mold for topographical relief maps. The method consisted of impressing topographical contour lines on a series of wax plates and cutting these wax plates on these lines. After stacking and smoothing these wax sections, one obtains both a positive and negative three-dimensional surfaces that correspond to the terrain indicated by the contour lines. After suitable backing of these surfaces, a paper map is then pressed between the positive and negative forms to create a raised relief map. This is shown in Figure 1.

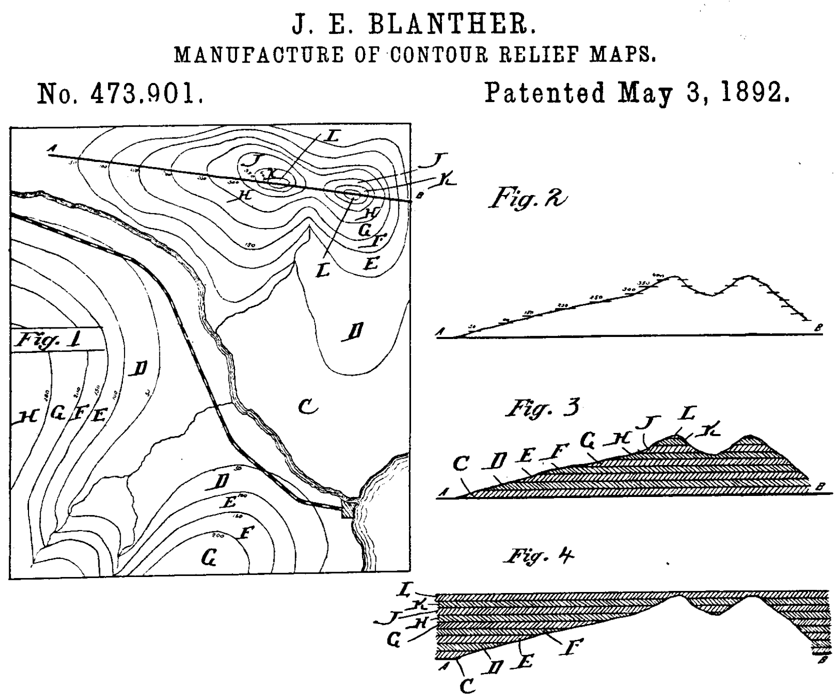


Figure 1: Blanther patent to fabricate 3-D relief map with layered method.

In a similar fashion, Perera (Perera, 1940) proposed a method for making a relief map by cutting contour lines on sheets (cardboard) and then stacking and pasting these sheets to form a three-dimensional map. Further refinements of this approach are found in Zang (Zang, 1964) who suggested using transparent plates with topographical detail inscribed on each plate and Gaskin (Gaskin, 1973) who described a three dimensional geological teaching device. In 1972, Matsubara of Mitsubishi Motors (Matsubara, 1974) proposed a topographical process that uses photo-hardening materials. In this process, a photopolymer resin is coated onto refractory particles (e.g., graphite powder or sand). These coated particles are then spread into a layer and heated to form a coherent sheet. Light (e.g., Mercury vapor lamp) is then selectively projected or scanned onto this sheet to harden a defined portion of it. The unscanned, unhardened portion is dissolved away by a solvent. The thin layers formed in this way are subsequently stacked together to form a casting mold. In 1974, DiMatteo (DiMatteo, 1976) recognized that these same stacking techniques could be used to produce surfaces that are particularly difficult to fabricate by standard machining operations. Examples he mentions include propellers, airfoils, three-dimensional cams, and forming of dies for punch presses. In one embodiment, a milling cutter contours metallic sheets, these sheets are then joined in layered fashion by adhesion, bolts, or tapered rods as depicted in figure 2. This process has obvious similarity to the earlier 19th century work.

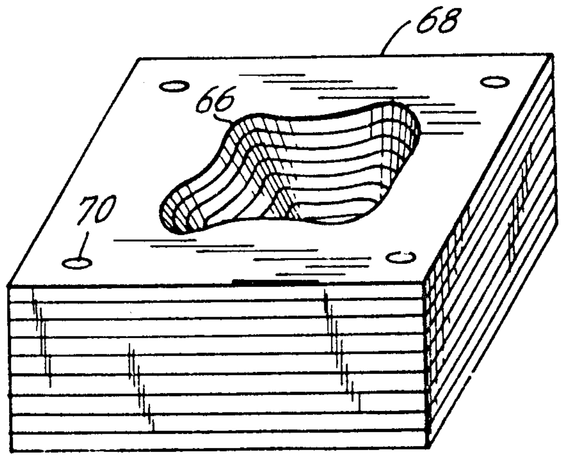


Figure 2: Layered mold by DiMatteo (1974).

In 1979, Professor Nakagawa of Tokyo University began to use lamination techniques to produce actual tools such as blanking tools (Nakagawa, *et al* 1979), press forming tools (Kunieda and Nakagawa 1984), and injection molding tools (Nakagawa, *et al* 1985). A laminated punch tool and the resultant part are shown in Figure 3.

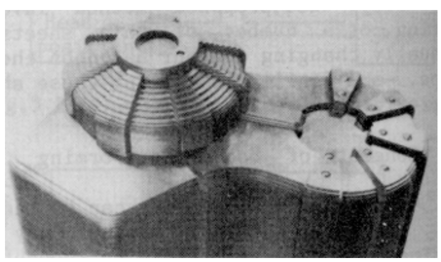


Figure 3: Laminated tool (unfinished) by Nakagawa (1984)

Work continues in this area today, with the recent formation of Solidica (2000), which combines lamination with ultrasonic welding and milling to create a tool.

Photosculpture

Photosculpture arose in the 19th century as an attempt to create exact three-dimensional replicas of any object - including human forms (Bogart, 1979). One, somewhat successful realization of this technology, was designed by Frenchman François Willème in 1860. As shown in Figure 4, a subject or object was placed in a circular room and simultaneously photographed by 24 cameras placed equally about the circumference of the room. An artisan then carved a 1/24th cylindrical portion of the figure using a silhouette of each photograph as seen in Figure 5.

Figure 4: 1860's photosculpture

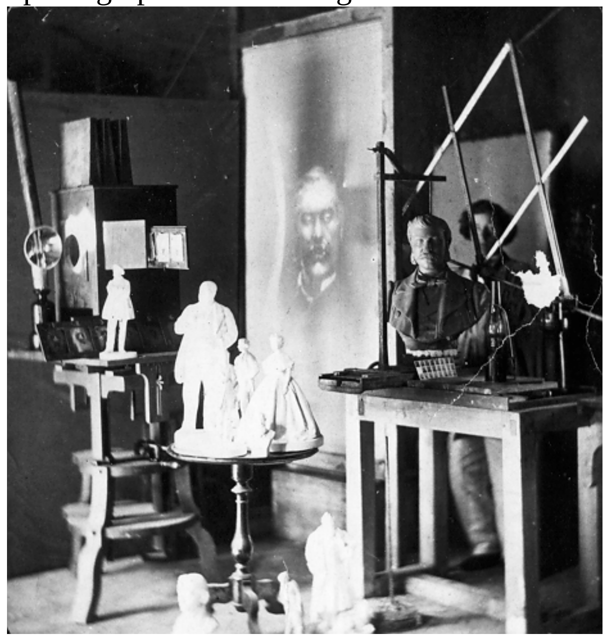


Figure 5: Solid reproduction from Willème's photosulpture

In an attempt to alleviate the labor-intensive carving step of Willème's photosculpture, Baese (Baese, 1904) described a technique using graduated light to expose photosensitive gelatin that expands in proportion to exposure when treated with water. Annular rings of this treated gelatin could then be fixed on a support to make a replica of an object as shown in Figure 6.

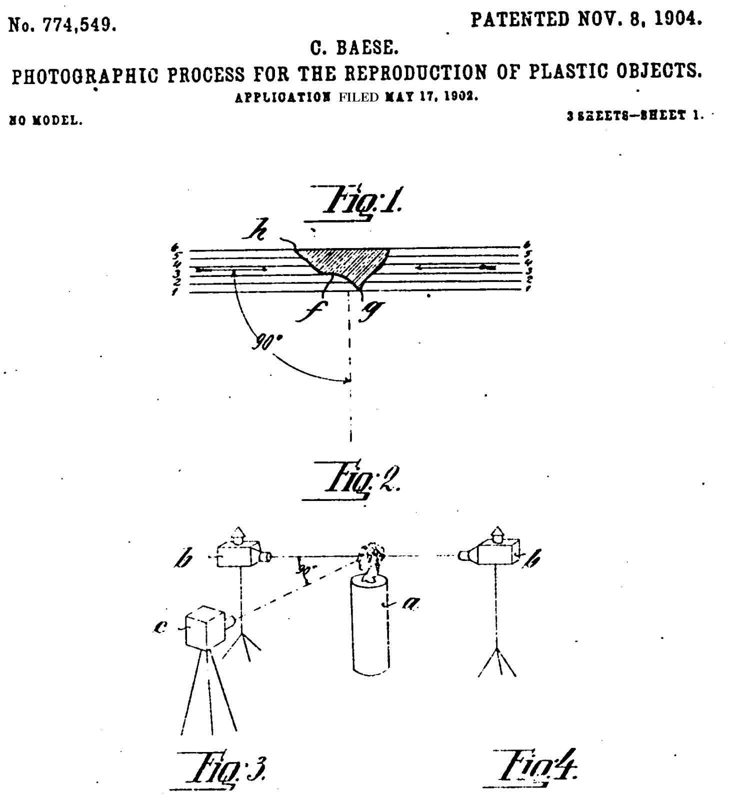


Figure 6: Baese photosculpture technique.

Monteah developed similar techniques (Monteah, 1924). In some of the earliest work in Japan, Morioka (Morioka, 1935,1944) developed a hybrid process between photosculpture and topography. This method uses structured light (black and white bands of light) to photographically create contour lines of an object. These lines could then be developed into sheets and then cut and stacked or projected onto stock material for carving.

In 1951, Munz (Munz, 1956) proposed a system that has features of present day stereolithography techniques. He disclosed a system for selectively exposing a transparent photo emulsion in a layerwise fashion where each layer comes from a cross section of a scanned object. Lowering a piston in a cylinder and adding appropriate amounts of photo emulsion and fixing agent create these layers. After exposing and fixing, the resulting solid transparent cylinder contains an image of the object. Subsequently this object can be manually carved or photochemically etched out to create a three-dimensional object. This system is shown in figure 7.

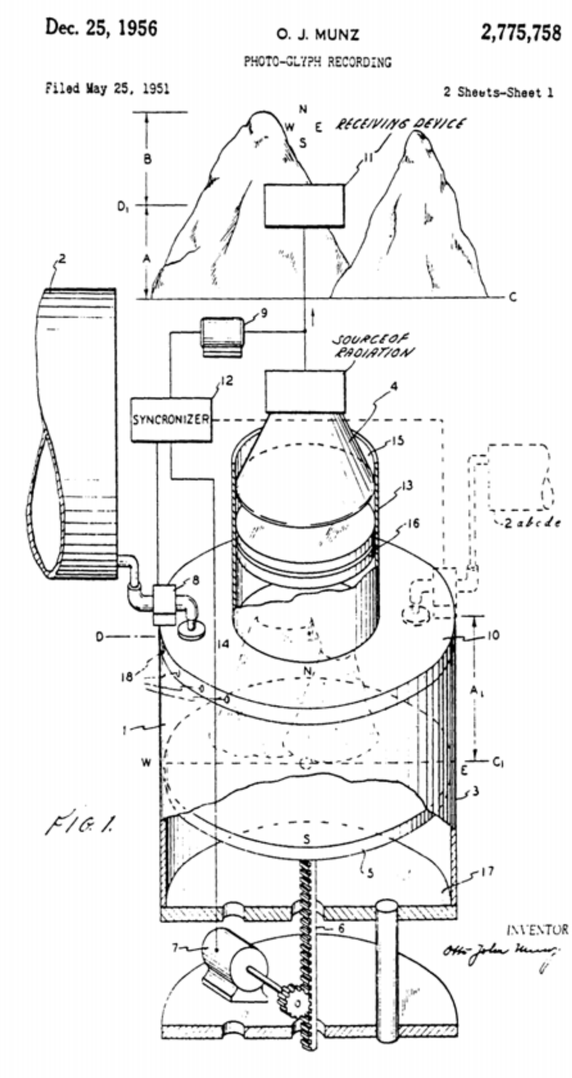


Figure 7: Photopolymer technique of Munz

Early Solid Freeform Fabrication

In 1968, Swainson (Swainson, 1977) proposed a process to directly fabricate a plastic pattern by selective, three dimensional polymerization of a photosensitive polymer at the intersection of two laser beams. Parallel work was conducted at Battelle Laboratories (Schwerzel, 1984). The essential features of this process, termed Photochemical Machining, are depicted in Figure 8.The object is formed by either photochemically crosslinking or degrading a polymer by simultaneous exposure to intersecting laser beams. Although laboratory hardware was constructed, it is not believed that a commercially viable process was achieved.

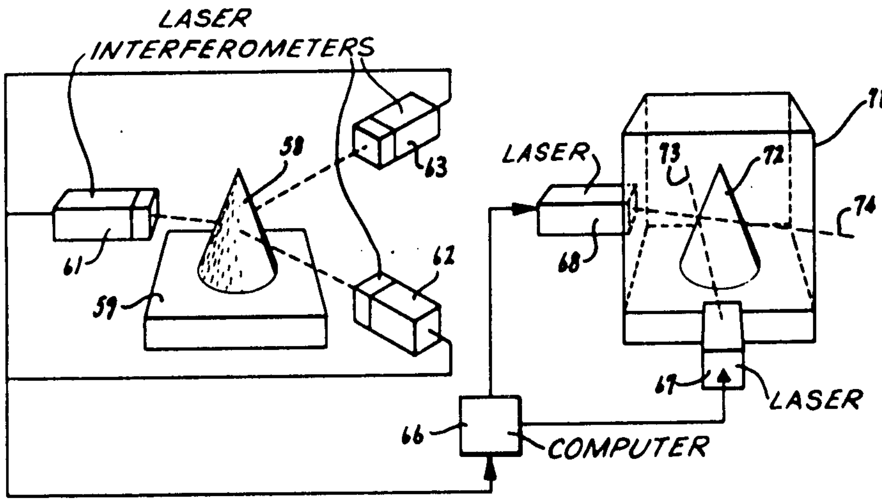


Figure 8: Photochemical SFF system of Swainson

Ciraud proposed a powder process that has all the features of modern direct deposition SFF techniques in 1971 (Ciraud, 1972). This disclosure describes a process for the manufacture of objects from a variety of materials that are at least partially able to melt. In order to produce an object, small particles are applied to a matrix by gravity, magnetostatics, electrostatics, or positioned by a nozzle located near the matrix. A laser, electron beam, or plasma beam then heats the particles locally. As a consequence of this heating, the particles adhere to each other to form a continuous layer. As shown in Figure 9, more than one laser beam can be used to increase the strength of the union between the particles.

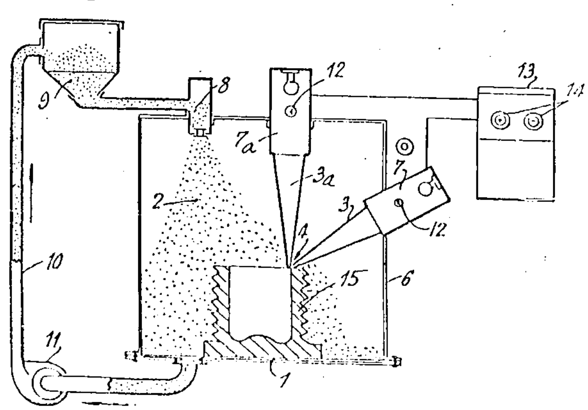


Figure 9: Powder SFF process of Ciraud.

Housholder (1979) presented the earliest description of a powder laser sintering process in a patent. He discussed sequentially depositing planar layers and solidifying a portion of each layer selectively. The solidification can be achieved by using heat and a selected mask or by using a controlled heat scanning process (Figure 10).

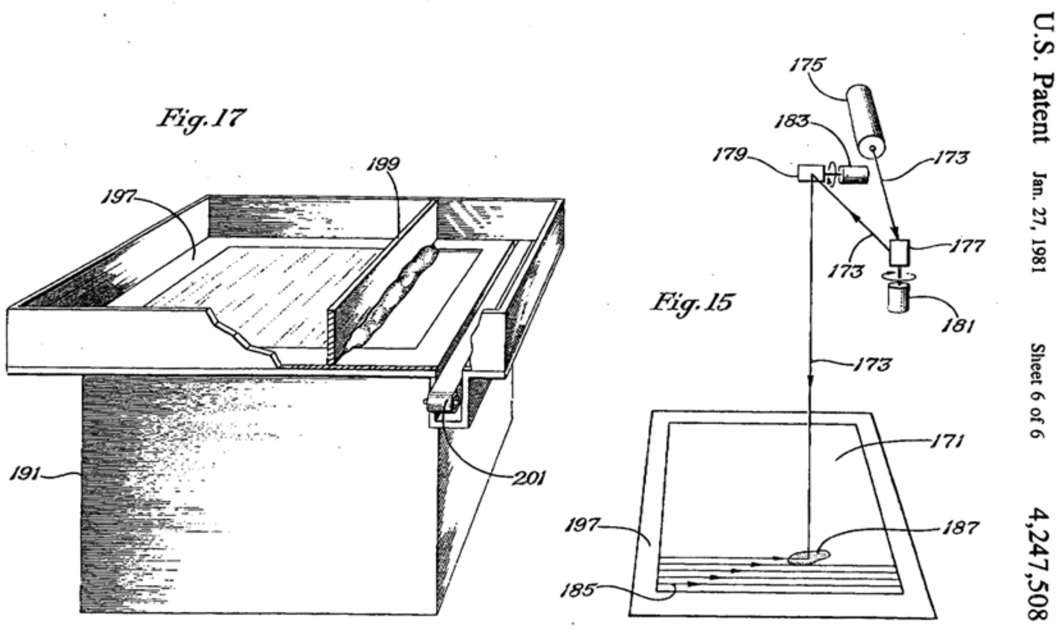


Figure 10: Powder process of Housholder.

Hideo Kodama of Nagoya Municipal Industrial Research Institute was the first to publish an account of a functional photopolymer rapid prototyping system (Kodama, 1981). In his method, a solid model is fabricated by building up a part in layers where exposed areas correspond to a cross-section in the model. He studied three different methods for achieving this:

(a) Using a mask to control exposure of UV source and immersing the model downward into a liquid photopolymer vat to create new layers.
(b) Using a mask, as in (1), but the mask and exposure is positioned on the bottom of the vat and the model is drawn upward to create a new layer.
(c) Immersing the model, as in (1), but using an x-y plotter and an optical fiber to expose the new layer. (See Figure 11).

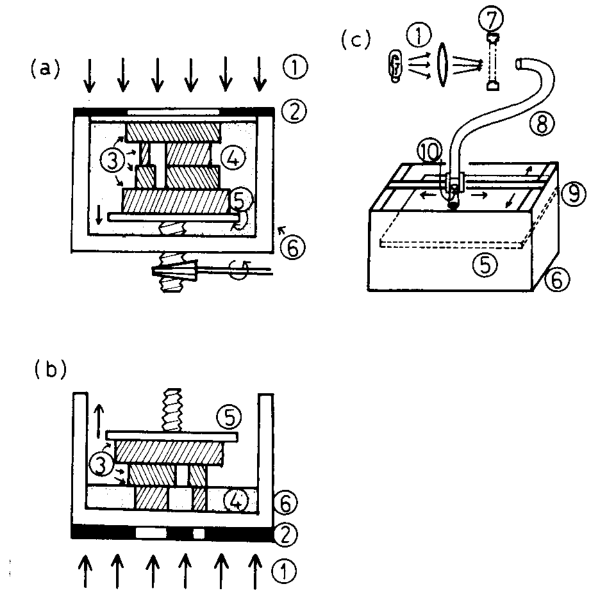
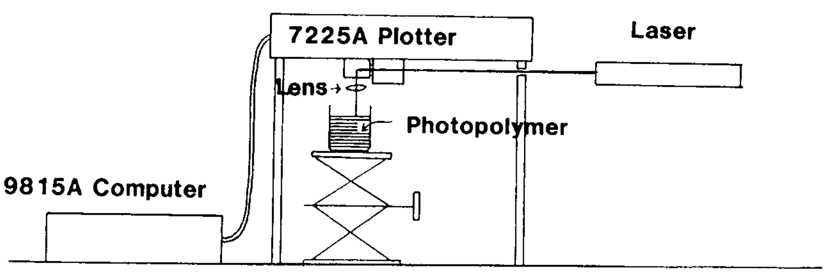


Figure 11: Stereolithigraphy systems of Kodama

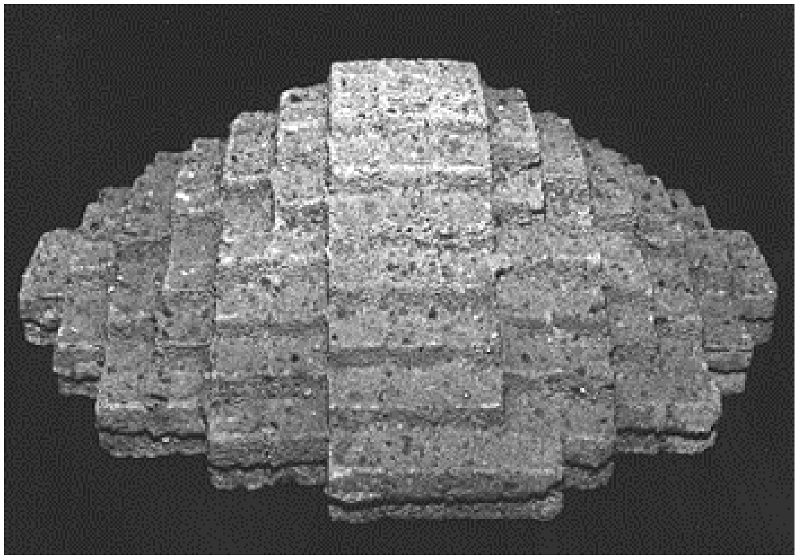
Herbert conducted a second, parallel but independent, effort at 3M (Herbert, 1982). Herbert describes a system that directs a UV laser beam to a photopolymer layer by means of a mirror system on an x-y plotter. (See Figure 12) In Herbert's experimental technique, a computer was used to command a laser beam across a layer, the photopolymer vessel was then lowered (1mm), and additional liquid photopolymer was then added to create a new layer.



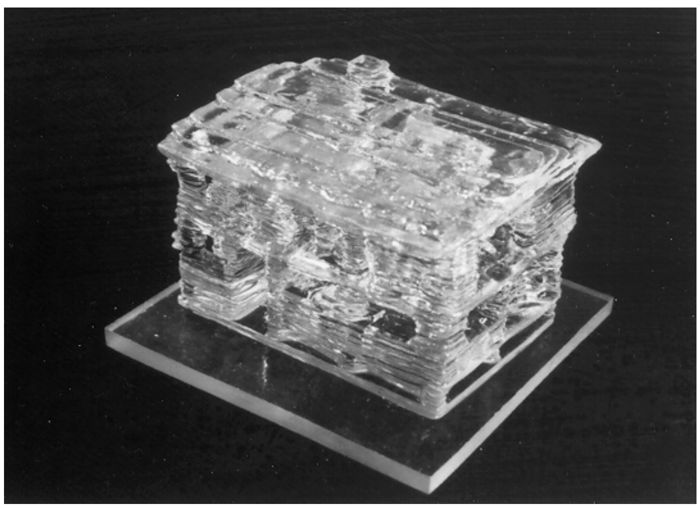
Solid generation apparatus.

Figure 12: Stereolithography system of Herbert

Although we are now accustomed to very intricate parts produced by freeform fabrication equipment, the first parts out of these types of systems required a good deal of faith that improvements would occur. Shown in Figure 13 are three early parts from different systems. The Housholder part was made from an embodiment that includes a grid for separating mold material (concrete and water) from casting material (dry concrete). The Herbert part was created in August 1979. The author does not know exactly when the Kodama and Housholder parts were created.



Housholder



Kodama

Herbert

Figure 13: Early parts by Housholder, Kodama, and Herbert

Commercial Development

In the earliest commercial development, Willème's photosculpture studio was commercially successful from 1861 to 1868 but eventually closed, probably due to the labor involved in hand sculpting with a pantographic (tracing) instrument. The next known commercial attempt was the formation of Formagraphic Engine Co. in 1977 by Swainson. Formagraphic later formed an alliance with Battelle Laboratories and changed its name to Omtec Replication. It appears that this effort was abandoned before a commercial process was developed. Also in 1977, DiMatteo formed a company called Solid Photography, which was spun out of Dynell Electronics Corporation when Dynell merged with United Technologies. As a result, an affiliated retail outlet called Sculpture by Solid Photography was opened in New York City. In this commercial endeavor, a subject was first photographed with structured lighting. From this photograph, a computer was used to create layered cutting paths in order to carve out a rough rendition of the subject which was subsequently smoothed to create a three dimensional likeness. In 1981, Solid Photography changed its name to Robotic Vision. Solid Photography and another company, Solid Copier, operated as subsidiaries of Robotic Vision until 1989 (Lightman, 1996). The following photographs show the process steps.

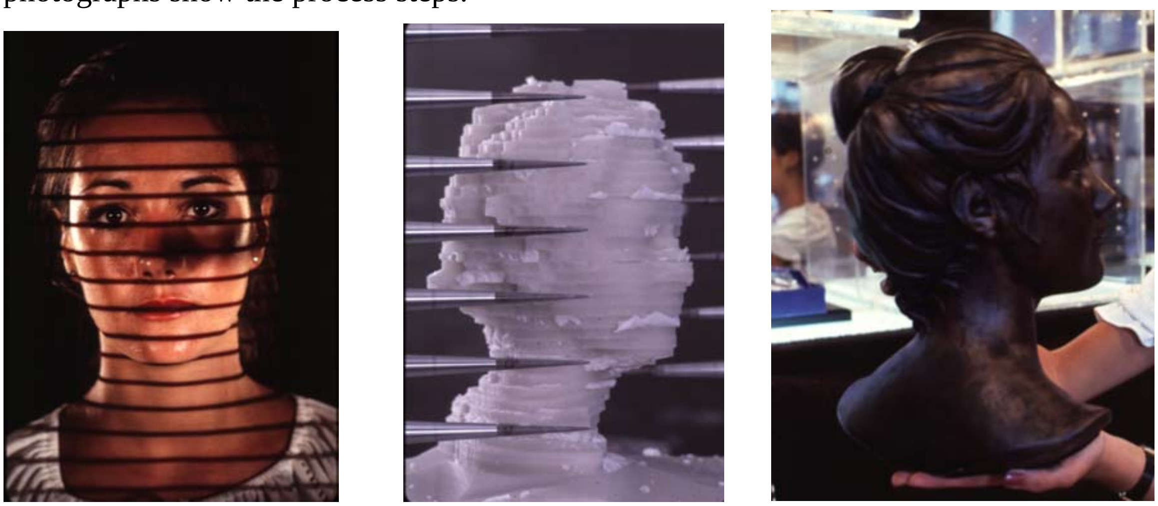


Figure 14: Sculpture by Solid Photography process (No longer in business) (Photos courtesy of SOHO Image Works)

The most important commercial development was the 1st shipment of a stereolithography machine by 3D Systems in 1988. This was the first SFF system that was widely used by customers in a commercial setting.

Summary

Figure 15 displays the overall chronology of Solid Freeform Fabrication. This chronology should not be considered complete; it indicates some (but not all) of the major time events in this rapidly changing field. One glaring omission is the extremely important government funding that was a catalyst for much of the growth in SFF. Of special note were programs at NSF like the Strategic Manufacturing Initiative in 1989, the programs of Dr. Ralph Wachter and Dr. Steve Fishman at ONR and the initiatives of Dr. Bill Coblenz and Dr. Robert Crowe at DARPA.

TOPOGRAPHY

Blanther patent filed	1890
Perera patent filed	1937
Zang patent filed	1962
Gaskin patent filed	1971
Matsubara patent filed	1972
DiMatteo patent filed	1974
Nakagawa laminated fabrication of tools	1979

PHOTOSCULPTURE

1860	Willeme photosculpture
1902	Baese patent filed
1922	Monteah patent filed
1933	Morioka patent filed
1940	Morioka patent filed
1951	Munz patent filed

1968	Swainson patent filed
1972	Ciraud disclosure
1979	Housholder patent filed
1981	Kodama publication
1982	Herbert publication
1984	Maruntani patent filed, Masters patent filed, Andre patent filed, Hull patent filed
1985	Helisys founded Denken venture started
1986	Pomerantz patent filed, Feygin patent filed Deckard patent filed, 3D founded,Light Sculpting started
1987	Fudim patent filed, Arcella patent filed, Cubital founded DTM founded, Dupont Somos venture started
1988	1st shipment by 3D, CMET founded, Stratasys founded
1989	Crump patent filed, Helinski patent filed Marcus patent filed, Sachs patent filed EOS founded, BPM founded
1990	Levent patent filed, Quadrax founded, DMEC founded
1991	Teijen Seiki venture started Foeckele & Schwarze founded, Soligen founded Meiko founded, Mitsui venture started
1992	Penn patent filed, Quadrax acquired by 3D Kira venture started, Laser 3D founded
1994	Sanders Prototyping started
1995	Aaroflex venture started
1997	Aeromet formed, Optomec restarted, Z Corp started
1998	Objet founded
1999	POM founded, BPM closed
2000	Helisys closed, Solidica started
2001	3D and DTM merge

Figure 15: SFF Chronology

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Solidica, http://www.solidica.com/.