Computer Graphics in Rapid Prototyping Technology

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Rapid prototyping has been called "real virtuality" to emphasize its transformation of virtual objects from cyberspace into real objects. It also goes by "3D printing" to highlight the direct realization of a 3D object from an abstract graphics design, in contrast to the more usual 2D plotting of views. "Free-form fabrication" and "tool-less manufacturing" are commonly used descriptive terms. "Desktop manufacturing" and "3D hard copy" are seen in the lay press. Other variants include RPM for "rapid prototyping in manufacturing" and LMT for "layered manufacturing technologies."

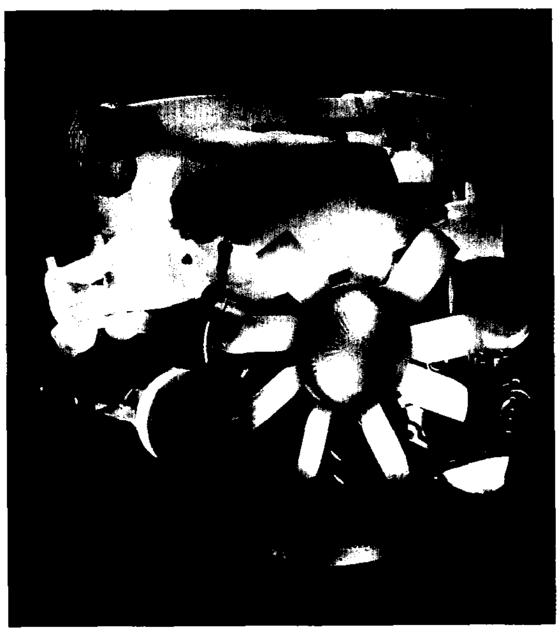
Whatever the name, the evolving use of RP technologies like stereolithography and selective laser sintering to quickly produce parts directly from a CAD surface or solid model is an innovative application area for computer graphics. From a designer's abstract computer model, these technologies now make it routinely possible to fabricate a 3D solid part in a matter of hours or days, rather than the weeks or months conventional production methods can take.

Additive RP technologies

When numerically controlled (NC) machining tools became commonly available in the 1960s, they offered a *subtractive* rapid prototyping process. The new RP technologies offer an *additive* process that in many applications produces complex parts in a single build cycle of layer-by-layer construction from cross-sectional slices. This cumulative process allows for intricate interior structures such as honeycomb chambers, teethed gears, and nested objects.

Briefly, the principal additive RP technologies include

- *Stereolithography*, or *selective photocuring*, which capitalizes on the property of actinic liquid photopolymers to solidify under appropriate light. The light solidifies tiny liquid voxels that are joined in a layer to form a cross-sectional slice of the object being fabricated. The part rests on an elevator that is lowered after each slice solidifies. Then the next slice is laid down until the full 3D part is built up—not unlike the conceptual inverse of an MRI or CT scan that takes an object and slices it into thin layers. Use of a scanning laser with this technique was pioneered by 3D Systems of California with photopolymers from Ciba of Switzerland. Cubital of Israel pioneered masked-lamp curing.
- *Selective sintering*, which scans a laser beam across a thin layer of thermoplastic powder to selectively fuse particles and thereby accrue successive layers of the part. After each layer solidifies sufficiently, an infusion of fresh powder fills any voids and provides a constant thickness from which to make the next layer on top of the layer just completed. DTM Corporation pioneered this approach.
- *Droplet deposition*, which makes each cross-sectional slice by laying down an adhesive liquid in a controlled pattern over a thin layer of ceramic or metal powder. Soligen and Massachusetts Institute of Technology are pioneers of this technique.



Mercedes Benz C Class engine. Stereolithography was used to develop 12 separate engine parts, including cylinder cover, manifold, intake, and cooling fan. Photo courtesy of 3D Systems, 1995.

- *Fused deposition modeling*, which melts a thermoplastic material and feeds it through a nozzle that moves on a robotic arm and deposits the molten material. This material quickly hardens to provide each layer's cross-sectional slice. Stratasys pioneered this method. IBM is also active in this "plastic printing."
- *Laminated object manufacturing*, which employs thin layers of paper. In this approach, pioneered by Helisys, a laser beam cuts the contour outline in each cross-sectional slice. Unwanted areas or scrap portions in each layer are cross-hatched with the laser so that, when finished, the part can be pulled out of the scrap volume. Each layer of paper is glued to those previously shaped, the contour outline is cut, and the scrap is cross-hatched repeatedly until the fully layered part is complete.

Design typically starts with a CAD surface or solid modeler. Alternatively, scanned images can be filtered, chain encoded, and tessellated (triangulated) to realize a surface representation. Input to the various RP systems is, as a de facto standard practice, a file in the .STL format originally proposed by 3D Systems. An .STL file employs surface representations defined by triangles and their outward pointing surface normals.

Fabricated RP parts can be used to verify a design visually—an automobile manufacturer reportedly saved about a million dollars by finding an engine-block design defect this way. RP parts are used to assess the look and feel of a design, to perform wind-tunnel and assembly tests, and to make mold masters—for example, in medical prosthetics, they have been used to make molds for everything from noses to knee joints. Quick casting can be realized by pasting a ceramic coating over an RP plastic model, then hardening the ceramic and burning away the plastic model.

Efficient use of automated additive fabricators requires substantial training. In addition to basic CAD principles, applications that make 3D copies of natural objects, such as bones, require image processing skills. Photopolymerization requires knowledge of thermoplastic properties and other characteristics of the material used in the preferred RP machine. Preparing practical cross-sectional slices and adding any requisite support pillars are skills to be learned. The build parameters of RP apparatuses, such as blade sweeps, pauses, shrinkage compensation, beam intensity, and traversal rate, must also be controlled.

There are many software opportunities to improve usability, robustness, and control of the many parameters necessary to build a part. How much can feasibly be automated or significantly aided is an ongoing question.

The theme articles

In this issue of *CG&A*, authors from four different countries present perspectives on RP technology based on their research and applications experience.

Bailey describes experimental software successfully used for .STL consistency checking and remote RP fabrication of parts over the Internet. He believes the Internet offers great opportunities for making prototype production more cost-effective. Such "telemanufacturing" implies distributed computing and RP processes that can ill afford iterations to correct improper .STL files. At our request, Bailey concentrates on his results rather than his methodology to offer a good introduction to RP technology for the novice. You can contact Bailey directly for technical detail on his methodology.

Bøhn presents an interesting analysis of the problem of correctly declaring a near-zero-volume part to be a true zero-volume part and discusses inherent ambiguities and an automatic repair strategy. While internal walls that represent zero-volume elements are of no consequence mathematically and of little concern in a CAD model, they are a significant problem in actual RP fabrication processes. Tolerancing and experience with variations in finite-precision arithmetic are well treated here.

Sheng and Meier start not from a view of postprocessing an existing .STL file that needs help, but instead from the view of guaranteeing the generation of an .STL file that correctly interfaces surface models to an RP process in the first place. Their robust algorithm first transforms a parametric surface representation into a B-rep solid from which the triangulation for an .STL file is generated free of zero-volume elements, cracks, or other such problems that frequently arise from current CAD systems. Rather than attempt automatic verification, they believe interactive correction of CAD models is the way to go and have implemented their topology analyzer algorithm in C for interactive use by designers.

Chandru, Manohar, and Prakash introduce a voxel-based approach currently under development. Rather than deal with an .STL surface model represented by triangles, they propose to model volumes directly by specifying voxel collections without reference to surfaces. Theirs is a novel approach, worth watching to see how it progresses in the future.

Zollikofer and Ponce de León address the non-CAD use of RP technology to construct models of natural objects from image processing input. They describe two very different applications—fossil reconstruction and computer-assisted surgery. Their extensive development of software tools allows easy manipulation of scanned objects. Their ongoing application of computer graphics to anthropology is especially innovative.

Logitech computer mouse and its stereolithography prototype. It took just seven days to go from CAD design to part using an SLA-250. Photo courtesy of 3D Systems, 1995.

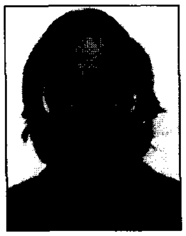
Conclusion

We hope this special issue of *CG&A* enhances your appreciation of this growth application, its successes, and its challenges. Time-to-market is key to successful product introduction in today's fast-paced business world. RP technology will likely play an increasingly important role in shortening the time from concept to product shipment. And better graphics systems will enhance RP capabilities and ease of use. ■

Further reading

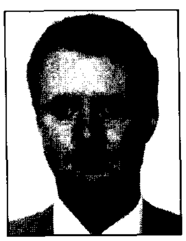
M. Burns, *Automated Fabrication*, Prentice Hall, Englewood Cliffs, N.J., 1993.

P.F. Jacobs, *Rapid Prototyping and Manufacturing; Fundamentals of Stereolithography*, Soc. Mechanical Engineers, Dearborn, Mich., 1992.



Peter Stucki *is a full professor of computer science at the University of Zürich. From 1967 to 1985, he held various research positions with IBM laboratories in Zürich and around the world. His current teaching and research activities address computer graphics, image processing, multimedia systems, and virtual reality. Stucki received his degrees from the Swiss Federal Institute of Technology, Zürich, and the Imperial College of Science, Technology, and Medicine, London.*

Jack Bresenham *is a professor of computer science at Winthrop University. His primary interest is undergraduate teaching. His research focus is graphics algorithms. From 1960 to 1987, he worked at IBM development laboratories in the US, England, and Italy. Bresenham received his PhD at Stanford in 1964. He is an editorial board member of* IEEE CG&A, *a member of Phi Kappa Phi and ACM, and a senior member of IEEE.*



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Rapid prototyping system manufacturers in the US

3D Systems (StereoLithography Apparatus)
26081 Avenue Hall, Valencia, CA 91355
(805) 295-5600, fax (805) 257-1200

DTM Corporation (Selective Laser Sintering)
1611 Headway Circle, Bldg. 2, Austin, TX 78754
(512) 339-2922, fax (512) 339-0634

Helisys (Laminated Object Manufacturing)
24015 Garnier St., Torrance, CA 90505
(310) 891-0600, fax (310) 891-0626

Soligen (Direct Shell Production Casting)
19408 Londelius St., Northridge, CA 91324
(818) 718-1221, fax (818) 718-0760

Stratasys (Fused Deposition Modeling)
14950 Martin Drive, Eden Prairie, MN 55344
(612) 937-3000, fax (612) 937-0070

RP system manufacturers outside the US

CMET, Kamata Tsukimura Bldg., 5-15-8 Kamata,
Oota-ku, Tokyo, 144, Japan
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Note: The source for most of this sidebar information is T.T. Wohlers, "Solid Modeling and Rapid Prototyping," in *Handbook of Solid Modeling*, D.E. LaCourse, ed., McGraw-Hill, New York, 1995, pp. 19.13-19.19.