ROBUST PROTOTYPING

Jana K. Chari
Dr. Jerry L. Hall

Department of Mechanical Engineering
Engel Manufacturing Laboratory
Iowa State University
Ames, IA 50011

Submitted for Publication in
Solid Freeform Fabrication Symposium, The University of Texas, Austin
August 1993

ABSTRACT

This paper presents a new prototyping system consisting of a computer interface based on IGES standard to represent and path plan objects with precise curve and surface definitions and a laser-metal deposition process for the prototype fabrication. The advantage of using the Non-Uniform Rational B-Splines (NURBS) data instead of the traditional triangular data is that it requires fewer data conversions as most standard analytical shapes (like lines, conics, circles, planes and quadratic surfaces) as well as free form curves and surfaces are represented with one common underlying mathematical form. By addressing this issue of improved data representation on the CAD file front-end and an improved processing technique, this research will significantly impact the output of rapid prototyping with functional parts of improved tolerance and surface finish capabilities. A detailed description of the implementation of the computer interface on different hardware platforms and an outline of the fabrication process are presented. We conclude that NURBS interfacing technique is a robust mathematical technique and offers great potential for precise rapid prototyping.

1. INTRODUCTION

Many engineering design and manufacturing situations involve the evolution of a new product and a rethinking of many manufacturing activities. The CAD systems allow designers to routinely develop computer models of parts to be fabricated. When coupled with CAM capability, the part specifications can be down loaded directly to the manufacturing equipment. Currently, several processes such as selective laser sintering, 3D laser cutting of sheet metals, stereolithography and rapid prototyping or solid freeform fabrication use such CAD/CAM systems. One advantage is the speed at which a conceptual design is converted to a form testable prototypes. Robust prototyping is one such challenging fabrication technique to convert conceptual designs to testable functional parts.

2. TECHNICAL BACKGROUND AND LIMITATIONS

The state-of-the-art systems currently available for solid freeform manufacturing perform many of the fabrication functions required. However their limitations include:

1. Metal parts have not been produced rapidly for functional testing.
2. Inaccuracies due to improper CAD representation result in limited application of the fabrication process.

Current prototyping or fabrication systems build three-dimensional shapes by incremental material buildup of thin layers of materials. These prototypes or models are used for form testing only. Functional testing cannot be done due to their fragility. There also seems to be no method available to fabricate metal parts directly using the same principle of successive solidification. NC fabrication of complex geometry remains expensive and time consuming.

These manufacturing systems are also limited in terms of geometric inaccuracies due to the approximation of CAD triangulation. The surfaces of the object are defined as a set of interfacing triangles (many CAD packages use such technique to draw surfaces of on-screen images). The triangles are defined by their vertices and a normal, which identifies which side faces out and which faces in. This planer faceted representation has inherent limitations in terms of its ability to approximate the original part design with acceptable precision.

3. PROBLEM DEFINITION

Although several parts of the problem of providing a computer interface for rapid prototyping have been attempted, there has been no attempt to provide an interface which uses the precise information from the solid modeling system for path planning the laser curing process. At the beginning of this research, the need for such a computer interface was identified. During the development of such an interface based on a CAD representation, a more fundamental understanding of the process of 2D path planning was obtained and this understanding prompted a reexamination of the concepts currently in use. It also seemed clear that the increasing need for functioning prototypes produced through rapid prototyping systems would necessitate more refined methods of geometric representation and advanced material fabrication techniques. The problem addressed in this paper can be defined as:

- **"Given a complete geometric description of the part to be prototyped, design appropriate techniques to retrieve precise cross-sectional information and automatically produce a cross-hatch pattern suitable for the laser post processor and develop methods to fabricate functional parts directly through successive solidification using laser-metal deposition techniques."**

4. OVERALL METHODOLOGY

The 3D computer models created in the CAD system have to be sliced into a stack of 2D cross-sections for laser path planning in rapid prototyping. In commercial systems the object is tessellated (triangulated) before it is sent to the rapid prototyping system and sliced by a special software there. This results in the error/inaccuracy introduced by the triangulation to propagate through the entire process.

The research initiative here is therefore to design and implement a "slicing program" that can be associated with any geometric model. This program can either be an external program or an internal program using the "section cutting" capabilities of the solid modeler. The overall methodology is to provide a system that will help users to extract the information of the cross-sectional profiles based on NURBS data and to then use it for the generation of 2D cross-hatch patterns. The following are the steps in providing such an interface:

1. Design the part using a solid model CAD system and orient it in the way that it would be built.

2. Run the slice program such that the set of cutting planes are defined perpendicular to the build direction. Output all the curves describing the cross-sections in IGES format.
3. Transform these IGES formatted files to the interface software.
4. Obtain the 2D cross-hatch pattern for each cross-section using the intersection algorithm.
5. Verify the correctness of the solution by simulating the laser curing and the part building process using a graphical user interface.

4.1 Obtaining The Cross-sectional Profiles

The cross-sectional profiles are obtained from the intersection calculations between the object and a regularly spaced stack of planar faces. The spacing between these planes can be varied. One or more profiles are created and stored by this operation. The profiles corresponding to a particular cross-section are retrieved and joined together to exactly represent the cross-section of the model. This cross-sectional information is output to an IGES file with the *Rational_B-Spline* option. IGES files are those which conform to the Initial Graphics Exchange Specifications [5].

4.2 Vector Scanning or 2D path planning

The 2D path planning is the task of designing a cross-hatch pattern to move the lase/scanner system over the cross-sectional profiles. This motion involves identifying the solid/hole areas for the laser light to be turned on/off. Normally the motion is specified by assigning a sequence of points between the initial and final points which are termed intersection points. Each of these intersection points specifies whether the light has to be turned on/off. Between these points the motion of the scanning system is defined to be a smooth function. The intersection calculations are based upon the Newton-Raphson method and cross-hatch pattern is generated using the Ray Casting method

4.3 Newton-Raphson Method

Many geometric algorithms include tests for intersection between geometric entities. For example, identification of the interior and skin-fill areas of the cross-sectional profile for laser curing applications involves intersection operations. The intersection between the cross-section and the cross-hatch grid identifies the vectors to be scanned by the laser scanner system. The object boundaries for the laser are quickly found from the perimeter of the cross-sections. Similarly, the grids for the laser path planning are defined by the intersection of the perimeters of the cross-sections with the grid of line segments. A closed form solution for evaluating the surface/curve intersection points is difficult to get. Therefore this problem is solved numerically using the Newton-Raphson method. This algorithm used successive approximations and a general description of this method is given in [Nielson K.L. 1965].

4.4 Method of Ray Casting

Ray casting is a method normally performed by intersecting a ray (a semi-infinite line) against the curve/surface elements of a geometric model. In this case, this method is used to differentiate between solid and hole boundaries. Basically a two dimensional grid of semi-infinite lines are chosen that covers the cross-sectional profile being path planned. A ray (defined by its starting point q and its direction u) is cast along each of the lines on the grid and all the intersections between this ray the cross-sectional profile are obtained.

Having found the intersections points, they are classified as on/off toggle points for the laser scanner system to traverse the cross-sectional contours. Here it is assumed, that the starting point of the ray is outside the cross-sectional profile. Apart from the singular cases when the ray hits the cross-sectional profile in a single point or goes along its boundary curve, it will intersect the cross-sectional profile at an even number of points, denoted by $t_1, t_2, ..., t_n$ in cartesian space. With k = 0, ..., n/2, the ray is within the solid area for the points $t_{2k} < t < t_{2k+1}$ and outside the solid area for the points $t_{2k+1} < t < t_{2k+2}$. When the number of intersections is odd, for k = 0, ..., n-1, the ray is within the solid area for $t_k < t < t_{k+1}$ and outside otherwise. This information is utilized by the laser scanner system to turn on/off the beam according to whether the point is inside the solid area or outside.

5. LASER-METAL DEPOSITION TECHNIQUE

In the current rapid prototyping techniques, CAD models are used to produce parts for iterative design evaluation as well as form and fit testing. The research initiative here is to extend the idea of successive solidification to produce functional metal parts with engineering properties and dimensional tolerances comparable to conventionally produced parts.

The fabrication method involves the sequential buildup of laser melted and subsequently solidified metallic droplets to form continuous, bulk components. The process involves the melting of continuous feed metallic wire under a fiber transmitted laser beam. The movement of the laser beam is controlled by a robot and the substrate on which the laser melt pool solidifies is moved by mounting it on a x-y-z CNC table driven by the CAD data. The subtasks that are being solved are:

- Controlling the melting and flow of metal wire feed
- Controlling the metal transfer mechanism to the substrate - spray, globules or tear drops
- Selecting the nature of the substrate - polymer, metal or ceramic
- Optimizing the laser control parameters.

The metal deposition and post processing are being automated using a robot and fiber optics assembly to control the deposition rate and energy sharing. Automated metal deposition will require the scheduling of the laser parameters and the selection of the robot path. The robotic processing will be enhanced through an off-line trajectory, kinematic and process planner to achieve consistent and predictable performance.

6. EXAMPLE : Model of a Fan and Shroud

An example is provided to explain the CAD interface and how it works with different computer models that have engineering applications. The example is a model of a high performance cooling fan for electronic equipment [figure 1]. The shroud around the fan is modeled from cross-section and are used to "skin" the solid object. This shroud illustrates a classic case of transitioning from a round section around the fan to a square mounting flange. The fan blades were modeled using different surfacing techniques. Seven blades are then combined with the rotor to make the completed fan. Figure 2 shows the cross-sectional profiles created by slicing operation. Figures 3 and 4 show the 2D curing pattern and the part building-up process. These figures also show the ability of the software to vary the mesh size. This is especially useful where a fine mesh is needed for high surface finish.

7. CONCLUSION

Rapid automated prototyping is complete when there exists a system for off-line creation, slicing and path planning of the 2D cross-sectional profiles of objects, and an online laser post processing system with feedback to control the curing process. This research provides a framework on which other interfaces can be built to close the feedback loop and make it completely a CAD based automatic prototyping system. Important contributions by way of this research can be summarized as:

1. Current commercial rapid prototyping systems do not make use of the representational geometry of the solid modeling systems. This research for the first time has implemented a routine that uses the same underlying geometric representation (NURBS) for object creation, slicing and path planning the individual cross-sections.

2. The path planning (2D) is robust mathematical technique to obtain the cross-hatch pattern for the laser post processor and has great potential to be applied in future rapid prototyping systems.

3. Initial attempts are being made with 304 stainless steel wire (0.6mm diameter) with fiber transmitted Nd:YAG laser beam. The ultimate goal of this research is to develop an automated system capable of producing testable metal parts using an integrated CAD/CAM approach where both the geometric and process models share a common precise CAD (NURBS) representation.

8. ACKNOWLEDGMENTS

Funding for this work was provided by the R. A. Engel Laboratory, Department of Mechanical Engineering, Iowa State University and the Iowa Center for Emerging Manufacturing Technology. The authors would like to thank Dr. James Oliver and Dr. Molian for their insightful discussions and advice.

REFERENCES

[1] Agarwal, P.K. 1991, *Intersection and Decomposition Algorithms For Planar Arrangements*, Delmer Publishers Inc., Albany, NY.

[2] Guessel, T. 1989, "Affordable Prototypes Made Without Tooling," *Modern Plastics*, Vol. 66, no. 3, pp. 84-86.

[3] Heller, T. 1990. "Software Enables Laser Stereolithography," *Laser Focus World*, Vol. 7, pp. 57-58.

[4] IDEAS 1991. Solid Modeling User's Guide, SDRC Corporation, Milford, OH.

[5] IGES, 1991. Initial Graphics Exchange Specification, American National Standard, Version 5.1, International TechneGroup Inc., Milford, OH.

[6] McGeough J.A. 1988. *Advanced Methods of Machining* , Chapman and Hall Publishers, New York, NY.

[7] Nielson K.L. 1965. "Methods in Numerical Analysis," The Macmillan Company, New York.

NURBS Based Computer Interface

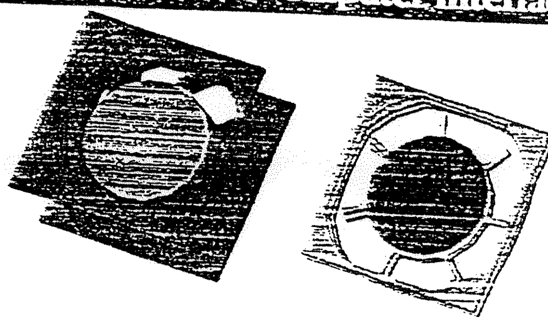
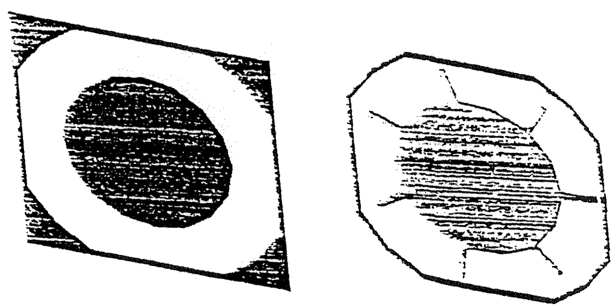


Figure 1: A Model of A Fan and Shroud & sectional profiles stacked together



Engel Laboratory

Figure 2: Cross-sectional Profiles

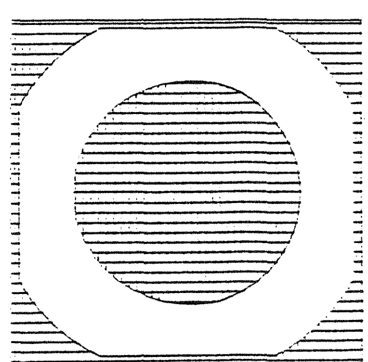


Figure 3: Cross-hatch Pattern of the rotor and the shroud profile

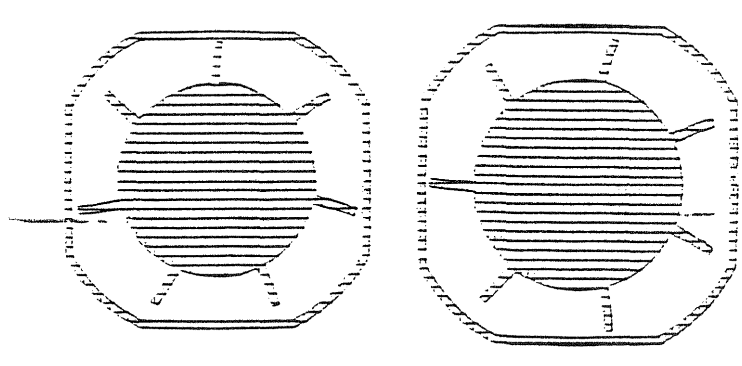


Figure 4: Cross-hatch pattern of the blower and the shroud profile