Adaptive Slicing of Solid Freeform Fabrication Processes

Yong Seok Suh and Michael J. Wozny*
Rensselaer Polytechnic Institute
Troy NY 12180

Abstract

The Solid Freeform Fabrication (SFF) process significantly reduces part specific setup manufacturing lead time. This process has been primarily used in fabricating prototypes for design visualization and verification. However, the major impact of this process on the future of manufacturing technology would be the possibility of fabricating functional parts for end use. One of the obstacles to this goal is the insufficient accuracy of the final physical part produced by the process. From the software point of view, the major sources of the inaccuracy come from the inappropriate data transfer format and the *3D aliasing' or Stair-stepping'* problem.

The `3D aliasing' problem can be reduced by adapting the layer thickness to the geometry of the part. In this paper, the procedure of adaptive slicing from the exact representation of the part model is described. This will improve part accuracy and minimize building time especially for the parts with highly curved surfaces. The procedures are implemented and a comparison to the conventional uniform layer thickness method will be discussed.

1. INTRODUCTION

The primary application of the SFF process has been to fabricate prototypes of new designs for their quick visualization and verification. For this purpose only, high part accuracy is not generally required. However, as the process is improved, fabrication of final functional parts is becoming more interesting. To fabricate functional parts, two major obstacles to the goal must be overcome. The first is the fact that most of the processes build parts made of limited special materials only. The second is an accuracy problem: the process has a relatively loose tolerance, in general, compared to others such as NC machining[1].

In building a part using the SFF process, part accuracy is usually the most important consideration. The major sources of inaccuracy in the process are part shrinkage, approximation of CAD models during data transfer with CAD systems, and the *stair-stepping* or *3D aliasing* problem[2]. A tessellated model is transferred to the SFF process from a CAD system via a file format that stores an unordered list of vertices which comprise triangular facets. Even though a part is modeled with exact geometries in a CAD system, valuable geometric and topological information is lost during the data transfer[3]. The finite thickness of layers of physical material produces 3D aliasing effects that cause the inaccuracy of the final physical part[4]. This is illustrated in Figure 1.

* Currently at National Institute of Standards and Technology

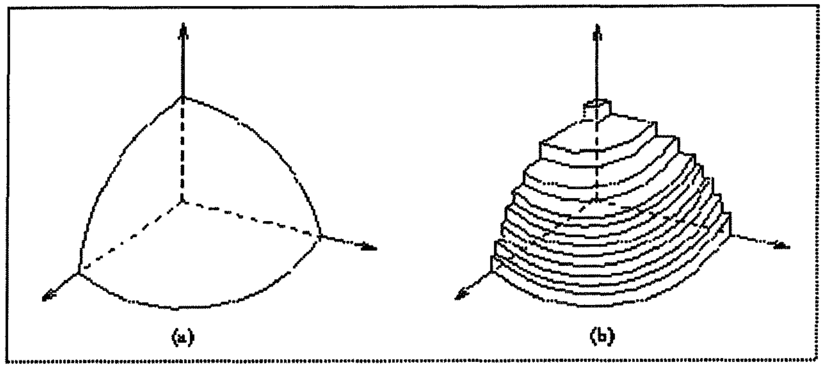

Figure 1. 3D aliasing effect

It is not possible to eliminate 3D aliasing completely because of the process characteristics. However, it can be reduced by varying the thickness of the slices. The thickness must be adaptive to the shape of the surface of the part in order to guarantee that the deviation between the final part surface and the ideal part surface lies within a certain tolerance limit.

In this research, the issue of accuracy is concerned primarily with focusing on reducing the 3D aliasing problem by optimizing the layer thickness. The exact model is transferred from CAD systems through high-level data exchange standards such as STEP/PDES[5].

2. OVERALL SYSTEM ARCHITECTURE

For a fully automated SFF process, a system architecture shown in Figure 2 is currently being developed and tested at Rensselaer Polytechnic Institute. A solid modeling kernel is built as a part of the process software to store model information and perform geometric reasoning. Exact model representation can be exchanged between the kernel modeling system and other CAD systems at the designers' side through a high-level data exchange format such as STEP/PDES. In the near future, the STEP/ACIS Husk[6] being developed at Rensselaer Polytechnic Institute will be integrated for the data transfer. The interface between the modules is via API (Application Protocol Interface) routines to conform to the idea of the standardized application interface[7].

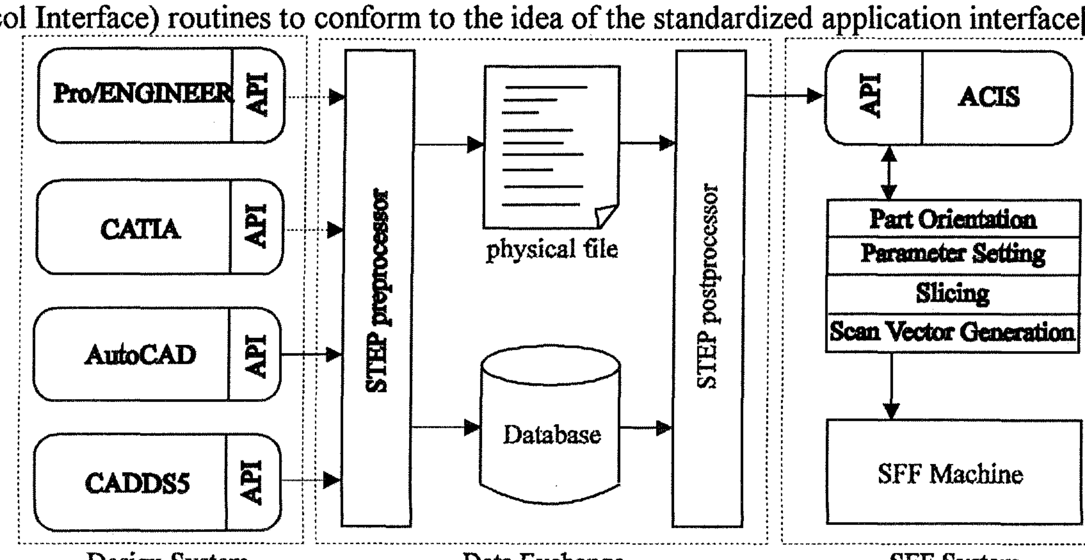

Figure 2. System Architecture

3. ADAPTIVE SLICING PROCEDURE

The purpose of the adaptive slicing is to fabricate geometrically accurate parts. The reference of the part accuracy is the solid model with mathematically defined surfaces. Many attempts have been made successfully to manufacture parts directly from CAD models: the automatic NC machine tool path generation is an example of the attempts.

The 3D aliasing causes the deviation of the part surface from the true surface definition, and the deviation is defined by the maximum gap measured in the normal direction of the surface as shown in Figure 3. The cusp height tolerance is set by designers or SFF process operators based on the functionality of the part to be built. Each surface of a part may be set with different tolerance values according to its functionality. The following subsections will discuss the procedure of adaptive slicing in sequence based on the assumption that a cusp height tolerance and a range of allowable layer thickness are given with a properly oriented part model.

3.1 Finding Slicing Sub-regions

Some special features must be considered when slicing a part for accuracy. Those features include flat areas, peak points and edges, and horizontal edges and the slicing plane must pass through those features for accurate fabrication. The inaccuracies caused by ignoring those features are illustrated in Figure 4. These features will be called *peak features* throughout this paper.

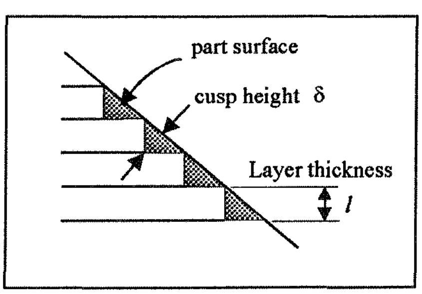

Figure 3. Cusp height

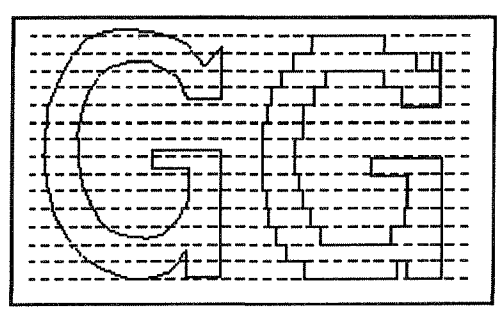

Figure 4. Inaccuracies due to peak features

Once all the peak features are identified in a model, the height of the features is sorted in the order of vertical direction, then the whole part can be subdivided into several sub-regions so that no peak features are within a region except its boundaries. An adaptive slicing algorithm, which will be discussed in the next section, is applied to each subregion. The peak features are identified from the vertices, edges and faces of the model, as described in the following three subsections.

3.1.1 Vertex peak features

All the vertices are basically considered as peak features. However, two types of vertices are excluded from the peak feature list.

- **topological vertex** Some vertices exist only to fulfill the B-rep data structure requirements of a solid modeling system. Several examples are shown in Figure 5. Usually, only one or two faces are adjacent to the topological vertex.

The part orientation is important because it affects the build time, dimensional acccuracy and post-processing complexity.

- **smooth vertex** If a vertex lies on the intersection of surfaces that meet smoothly at the vertex, the vertex is excluded from the peak feature list. Figure 6 shows an example of such vertices.

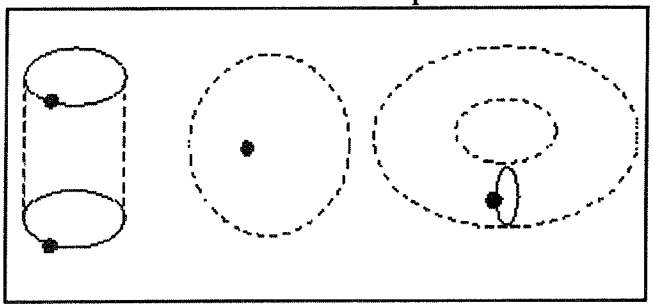

Figure 5. Topology vertices

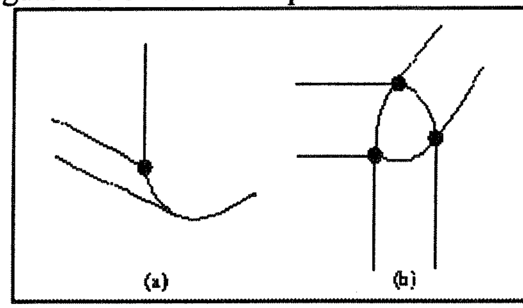

Figure 6. Smooth vertices

3.1.2 Edge peak features

- **horizontal edge** If the geometry of an edge is a planar curve and the edge lies horizontally, the edge is considered as a peak feature as shown in the Figure 7(a). However, if the adjacent surfaces meet smoothly at the edge as illustrated in Figure 7(b), the edge is excluded from the peak feature list.
- **extreme point** If an edge is not linear, the extreme points in the vertical direction must be found to be included in the peak feature list as shown in the Figure 8.

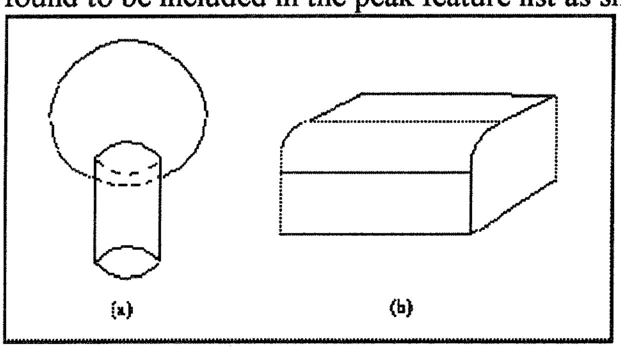

Figure 7. Horizontal edges

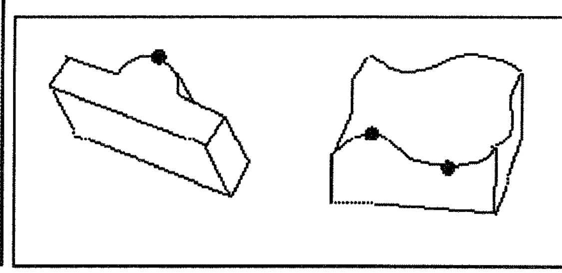

Figure 8. Extreme points

3.1.3 Face peak features

- **horizontal planar face** The slicing plane must pass through the horizontal planar face.
- **extreme point** Extreme points of curved surfaces in vertical direction.

Once these features are found and the part is divided into regions, the procedures in the following sections are applied to each region to generate a series of slicing planes.

3.2 Calculation of the Next Slice Height

Within each slicing region found at the previous section, a set of slicing planes is generated, considering a cusp height tolerance. Let Z^i_L and Z^i_H be the height of the lower and higher boundaries of the i_{th} slicing region respectively, and $Z^i_L < z^i_1 < z^i_2 < \ldots < z^i_j < \ldots < Z^i_H$ be an ordered sequence of height of the slicing planes. The height of a slicing plane, z_{j+1}, is determined from the contours (intersection curves) generated by the previous slicing plane at the height of z_j, based on the geometry of the part.

The procedure is basically similar to that of NC tool path generation for curved surfaces[8,9]. Let C_j be the contour at the height of z_j and C_{j+1} be the next contour to be found. In calculating the next layer thickness, $d = z_{j+1} - z_j$, a set of sampling points are selected along the previous contour, C_j, and the next layer thickness is calculated at each sampling point considering the geometry of the surface at that point. The minimum value is selected as the next layer thickness among those values calculated at every sampling point. The method for selecting a set of sample points will be discussed in the next section.

3.3 Determination of the sampling points

Assume that a sample point, P_i, on a contour curve is obtained. The next sampling point, P_{i+1}, can be calculated from the Figure 9 and Eq.(1). The contour curve is approximated by an arc with the radius of $\rho=1/\kappa$ where κ is the curvature of the curve at the sampling point P_i. The Eq.(1) calculates an arc length to the next sampling point so that the maximum deviation, δ, is less than or equal to the cusp height tolerance.

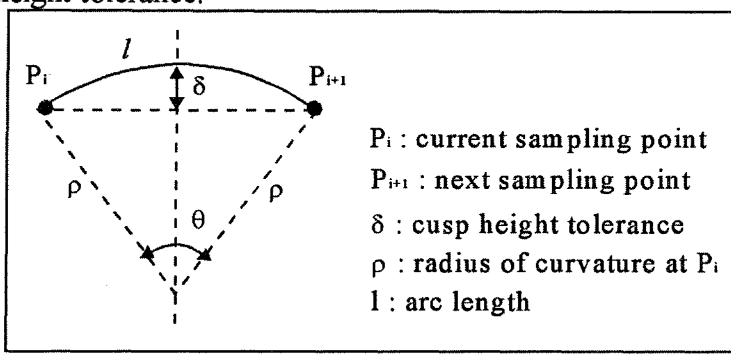

Figure 9. Determination of sampling points

$$l = \begin{cases} \infty & \text{if } \rho = 0 \\ 2\rho\cos^{-1}(1-\rho/\delta) & \text{otherwise} \end{cases} \qquad (1)$$

3.4 Calculation of layer thickness at a sampling point

In this section, a method for calculating the next layer thickness at a sample point will be discussed.

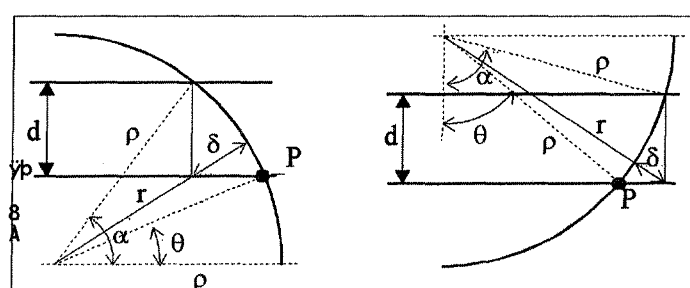

Figure 10. Calculation of next slicing plane

Let ρ be the radius of curvature of the part surface in the vertical direction at the sampling point, P. Then the part surface can be approximated by a sphere with the radius of ρ as shown in Figure 10. This is a good approximation because the layer thickness is much smaller than the radius of curvature of the surfaces of most mechanical parts. The next layer thickness, d, can be calculated from the Figure 10, with the given cusp height tolerance, δ. It is assumed that the laser beam radius is compensated at the border of the part to allow for the laser line width. The cross-sectional shape of a curved line is approximated by a rectangle[2].

If ρ is infinite, the next layer thickness, d, is calculated using Eq.(2),

$$d = \begin{cases} \infty (= l_{\max}) & \text{if } n_k = 0 \\ \delta/\cos\theta = \delta/n_k & \text{otherwise} \end{cases} \tag{2}$$

where n_k is a vertical component of the normal vector of the surface at the point P. Note that the layer thickness, d, must be bounded by the maximum and minimum layer thicknesses, l_{max} and l_{min}.

If r is not infinite, it is required to check the location of the sampling point, P, relative to the center of the sphere. If the point is on the northern hemisphere, the layer thickness, d, is calculated using Eq.(3). The Eq.(4) is for the case where the point is on the southern hemisphere of the sphere.

$$d = -\rho \sin\theta + \sqrt{\rho^2 \cos^2\theta - 2\delta\rho - \delta^2} \tag{3}$$

$$d = \begin{cases} \rho\cos\theta - \sqrt{\rho^2\cos^2\theta - 2\delta\rho - \delta^2} & \text{if } \rho^2\cos^2\theta - 2\delta\rho - \delta^2 > 0 \\ \rho\cos\theta & \text{otherwise} \end{cases} \tag{4}$$

3.5 Layer Contour Generation at Region Boundaries

Care must be taken when generating contours of a layer that pass through a region boundary. All the pathological cases of surface intersection problems may occur because of the peak features. Another concern is the removal of the contours generated by downward planar faces. As pointed out by Dolenc and Makela[10,11], if a slicing plane passes through a down-facing flat surface, the corresponding contour area must be discarded.

These problems can be eliminated by lowering the slicing plane by an infinitesimal amount which is far less than the minimum layer thickness, but greater than the tolerance value used in surface intersection procedure.

4. IMPLEMENTATION AND EXAMPLES

A prototype program has been implemented that includes the features discussed in this paper. Based on the ACIS®[3] solid modeling kernel, the system is built on a Sun Sparc workstation with an X-window based user interface.

To compare the adaptive slicing with the uniform slicing, a sphere with the diameter of 10" is modeled and sliced with various cusp height tolerances as shown in Figure 11. The minimum and maximum layer thickness is set to be 0.001" and 0.020" respectively. The results are summarized in the table below.

Adaptive Slicing		Uniform Slicing
Cusp Height (in.)	Number of Layers	Number of Layers Thick. cusp height
0.006	909	1667
0.007	803	1429
0.008	726	1250

[2] The shape of a cured line is better approximated by a parabolic cylinder 2 .
[3] ACIS is a registered trademark of SPATIAL TECHNOLOGY Inc., Boulder, CO

0.009	669	1112
0.010	626	1000
0.011	593	909
0.012	658	834
0.013	548	770
0.015	533	715

With the cusp height of 0.01", the number of layers is 626. If the uniform thickness method is used, the number of layers is between 500 and 10,000 according to the layer thickness chosen. For the uniform thickness method, the deviation error (cusp height) will vary according to the latitude of the sphere and the maximum error will occur around the north and south poles. For the uniform layer thickness of 0.011", for example, the number of layers will be 909 and the cusp height at the angle of 80 degrees from the equator will be 0.0109", which can be achieved with only 593 layers by using the adaptive slicing method.

From this experiment, we can conclude that, in many parts with highly curved surfaces, a part can be fabricated by using the adaptive slicing method, not only more accurately but also more rapidly. Figure 12 and 13 show more examples.

5. CONCLUSION

The Solid Freeform Fabrication process is a promising new manufacturing method that can fabricate a product with lot size of 1 with minimum cost. In order to serve this goal, however, further development of the process is required. From the software point of view, the part accuracy is the major area to be tackled first. The sources of inaccuracy is identified to be from the approximate model data caused by the data exchange format and '3D aliasing' problem. In this paper, a new system architecture was proposed to exchange exact model representation with CAD systems. And adaptive slicing procedure for reducing the 3D aliasing problem was also discussed.

The procedures has been implemented and tested on several example parts. The results show that the adaptive slicing assures part accuracy and minimizes the number of layers for minimal build time.

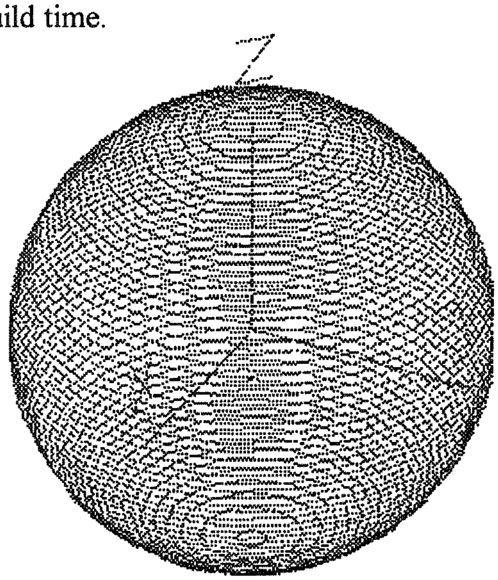

Figure 11. Adaptive slicing of a sphere

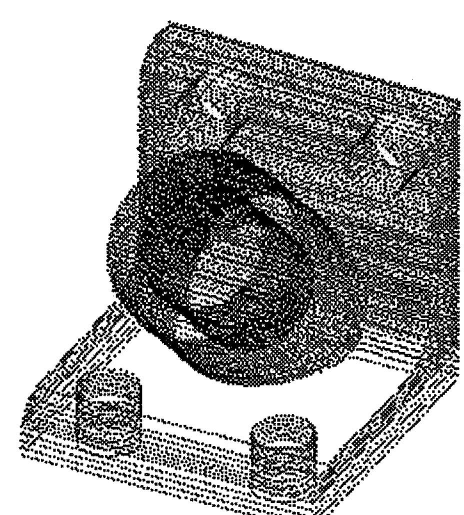

Figure 12. Adaptive slicing of a CAM-I part

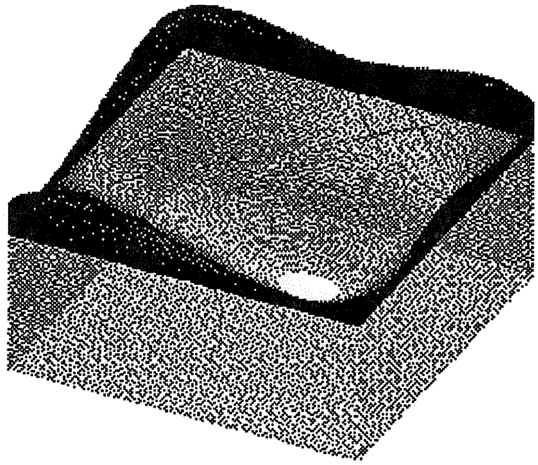

Figure 13. Adaptive slicing of a NURB surface

6. REFERENCES

[1] B. E. Hirsch and H. Muller. "StereoLithography - fields of application and factors influencing the accuracy.", In D. Kochan (Ed), *Complex Machining and AI-Methods,* pages 219-233, Elsevier Science Publishers B.V. (North-Holland), 1991

[2] Paul F. Jacobs, *Rapid Prototyping & Manufacturing, Fundamentals of StereoLithography,* Society of Manufacturing Engineers, first edition, 1992

[3] Marshall Burns, *Automated Fabrication - Improving Productivity in Manufacturing,* PTR Prentice Hall, Englewood Cliffs, New Jersey, 1993

[4] Michael J. Wozny, "Systems Issues in Solid Freeform Fabrication", Technical Report 92023, Rensselaer Polytechnic Institute, Troy, NY 12180, September 1992

[5] *Product Data Exchange Specification (PDES) Testing Draft.* National Institute of Standards and Technology, Gaithersburg, MD, 1988

[6] The STEP/ACIS HUSK, *User's Guide*, STEP Tools Inc., Troy, NY

[7] Spencer P. Magleby and David B. Jackson, "A Standardized Application Interface for Geometric Modelers", in J. Turner, J. Pegna, and M. Wozny (Ed), *Product Modeling for Computer-Aided Design and Manufacturing,* pages 227-243, Elsevier Science Publishers, 1991

[8] I. D. Faux and Michael J. Pratt, *Computational Geometry for Design and Manufacture,* Chichester, England: Horwood; New York: Halsted Press, 1981

[9] Yong Seok Suh and Kunwoo Lee, "NC Milling Tool Path Generation for Arbitrary Pockets Defined by Sculptured Surfaces", *Computer-Aided Design,* 22(5):273-284, June 1990

[10] A. Dolenc, R. Hovtun, and I. Makela, "Better Software for Rapid Prototyping with INSTANTCAM", In G. J. Olling and F. Kimura (Ed), *Human Aspects in Computer Integrated Manufacturing,* pages 449-456, Elsevier Science Publisher B.V. (North-Holland), 1992

[11] A. Dolenc and I. Makela, "Slicing Procedures for Layered Manufacturing Techniques", *Computer-Aided Design,* 26(2):119-126, February 1994