Slicing procedures in layered manufacturing: a review

Pulak Mohan Pandey
N. Venkata Reddy and
Sanjay G. Dhande

The authors

Pulak Mohan Pandey is based at Harcourt Butler Technological Institute, Nawabganj, Kanpur, India.
N. Venkata Reddy and **Sanjay G. Dhande** are both based at the Indian Institute of Technology Kanpur, Kanpur, India.

Keywords

Rapid prototypes, Surface texture, Laminates

Abstract

Layered manufacturing (LM) or rapid prototyping is a process in which a part is produced using layer-by-layer addition of the material. In LM, slicing of the CAD model of a part to be produced is one of the important steps. Slicing of CAD model with a very small slice thickness leads to large build time. At the same time if large slice thickness is chosen, the surface finish is very bad due to staircasing. These two contradicting issues namely reduction in build time and better surface quality have been a major concern in laminated manufacturing. This contradiction has led to the development of number of slicing procedures. The present paper reviews various slicing approaches developed for tessellated as well as actual CAD models.

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1. Introduction

Rapid prototyping (RP) is an important technology as it has potential to reduce the manufacturing lead time of a product up to 30-50 percent even when the relative part complexity is very high (Kai and Fai, 2000). The entire production process of prototyping, by RP, is based on creation of geometric model in a solid modeler, slicing, generation of laser scanning paths or material deposition paths, layer-by-layer deposition and then post processing operations as shown in Figure 1. Time consumption is less to create a solid model or to carry out engineering changes in an existing solid model. A drastic reduction in product launch time to market is a major contribution of RP to integrated design and manufacturing cycle.

In all RP processes, the solid model of a component to be produced is created in CAD environment and is sliced before transferring the data to the RP machine. The procedure followed for transferring the data from the CAD model to RP system is shown in Figure 2. CAD model can be created as a solid model (by using primitive instancing or constructive solid geometry) or a surface model (by using B-rep). A tessellated (.STL) version of the CAD model can then be exported. From Figure 2, it is clear that the slicing of the CAD model can be carried out either directly on a solid or a surface model of the product or on a tessellated model. In slicing, sets of horizontal planes are intersected with CAD model. This results in closed curves or polygons. The space between any two consecutive horizontal planes is referred to as a slice.

Tessellated CAD model (*de facto* standard) has become a standard of RP technology. The tessellated representation of CAD data has a major limitation, as the intent of original design is lost because of first order piece-wise approximation of the surface. The maximum deviation between an original surface of a CAD model and a triangle of tessellated model is termed as chordal error. There is no topological information related to the CAD

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Figure 1 RP process chain

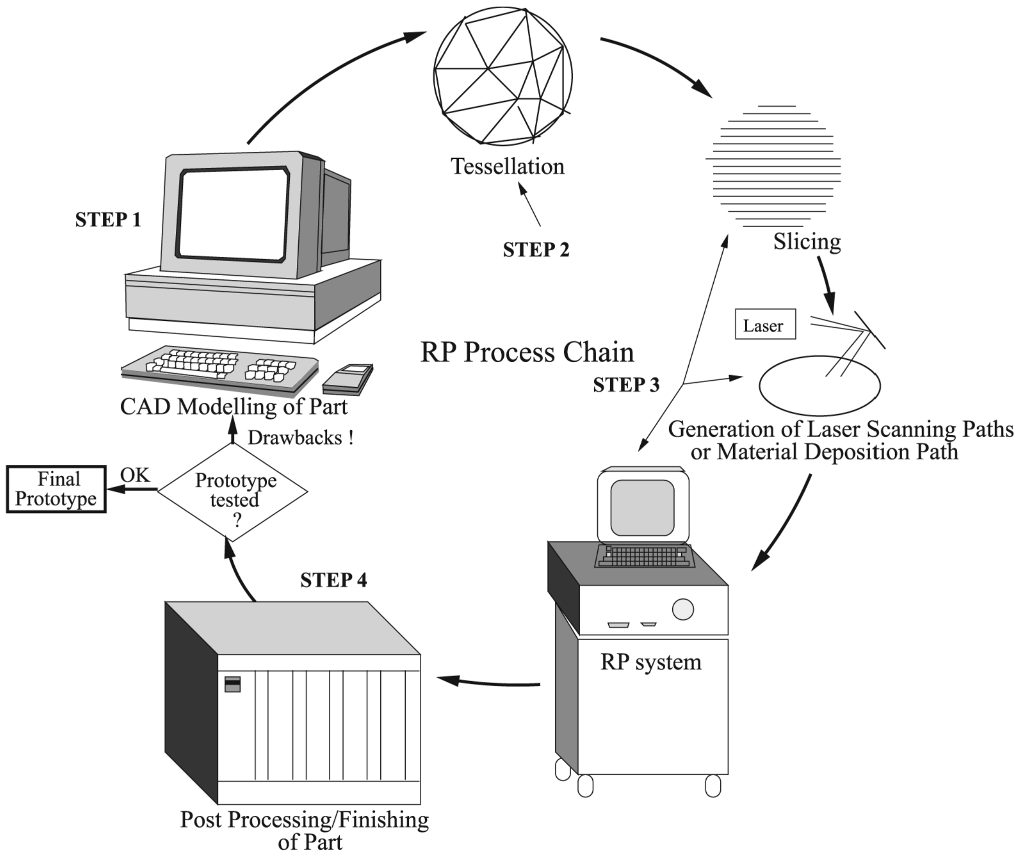
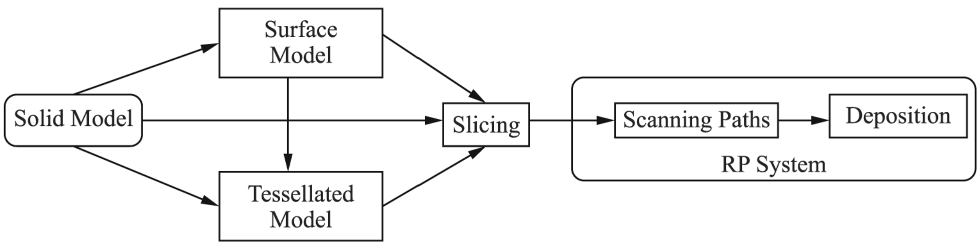


Figure 2 Transfer of CAD data to RP system



model left except the list of triangles and their normals, even though tessellated CAD models have several advantages like implementation of slicing algorithm is easier, ability of orientation of model is better and addition of support structure is simpler. Deposition of sliced layers leads to staircase effect as shown in Figure 3. The staircase effect cannot be eliminated on a RP part completely. Due to the presence of stepped edges, slices may be completely outside or inside the CAD model as shown in Figure 4(a) and (b). In certain circumstances, the slice edges may be inside in certain portion of a CAD model and outside in the other portion as shown in Figure 4(c) and (d). This leads to the distortion of shape and is called containment problem. Hence, one should fabricate the part in such a way that either all edges are inside or outside the CAD model. These two cases are having their own importance as far as the application of the prototype is concerned. The problems of staircase and containment are of major

Figure 3 Staircase effect in RP parts

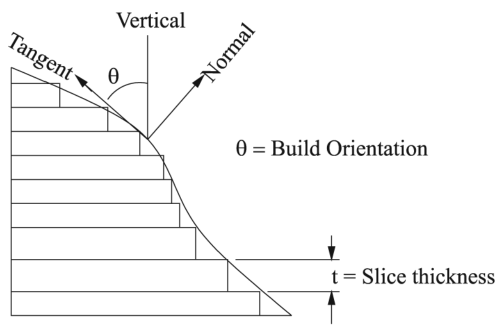
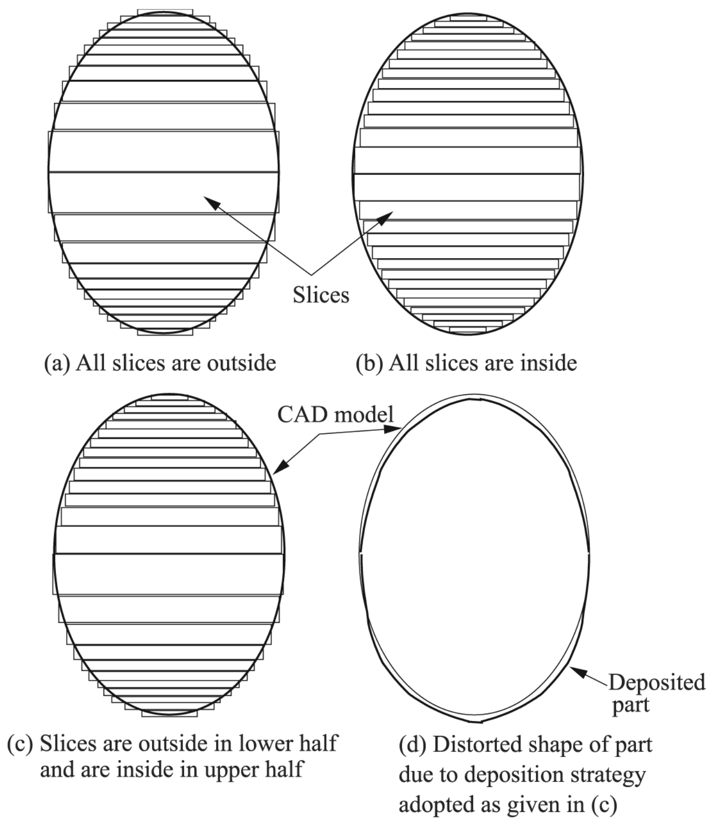


Figure 4 Containment situations in RP parts



concern for engineers as they affect the final quality of the prototype. Refinement of layers improves the surface finish of the part, but it increases the build time. The cost of the prototype is directly governed by the build time. This contradiction between build time and surface finish led to the development of different slicing algorithms. Initially, uniform layer thickness was used to slice the CAD models. Later adaptive slicing procedures which use slices of variable thickness instead of constant thickness were developed and their thickness is governed by the part geometry and RP machine specifications. The different slicing algorithms published can be classified as given in Figure 5. It can be seen from Figure 5 that most of the researchers (Cormier *et al.*, 2000; Dolenc and Makela, 1994; Kulkarni and Dutta, 1996; Lee and Choi, 2000; Sabourin *et al.*, 1996, 1997; Tata *et al.*, 1998; Tyberg and Bohn, 1998) considered rectangular build edges to develop adaptive slicing procedures. Very few researchers considered the build edges to be sloping/trapezium (Hope *et al.*, 1997a, b). Recently, real time edge profile i.e. parabolic in case of FDM (Pandey *et al.*, 2003b) is considered. Any RP system will have the capability of depositing the material between a minimum and maximum thickness with certain intermediate thickness. Most of the RP systems use fixed fabrication thickness for a component to be prototyped to minimize set up time. One cannot change the thickness during the deposition operation in most of the commercial RP systems. The fabrication thickness is selected at the stage of slicing of CAD model. In a typical FDM-1650 system, the orientation is selected and the CAD model is sliced for a constant slice thickness, which depends upon the nozzle tip diameter. To change the slice thickness, the nozzle tip needs to be changed. To have this facility, there is a need for the development of hardware, which is able to deposit these variable slice thicknesses.

This paper presents a detailed overview of slicing procedures comparing with one another. In addition, it deduces some future trends for research.

2. Slicing of tessellated CAD model

In different adaptive slicing procedures, slice thickness is decided based on the geometry of tessellated CAD model for a user specified maximum allowable cusp height or Ra value. In this direction, Dolenc and Makela (1994) introduced the concept of maximum allowable cusp height, which is accepted widely. Different applications of the same concept (Dolenc and Makela, 1994) were successfully attempted by many researchers (Cormier *et al.*, 2000; Sabourin *et al.*, 1996, 1997; Tata *et al.*, 1998; Tyberg and Bohn, 1998). Cusp height is not a standard parameter in design or manufacturing practice to specify surface finish. Therefore, another concept of maximum allowable Ra value is recently introduced by Pandey *et al.* (2003a, b). Present section describes the work done on various slicing approaches using tessellated CAD models as an input.

2.1 Cusp height concept (Dolenc and Makela, 1994)

Cusp height tolerance concept (Figure 6) is introduced by Dolenc and Makela (1994). The layer thickness, t at a point, P is computed based on the cusp height c, within the user specified maximum allowable cusp height, C_{max}. The thickness of the current layer is estimated using the normals around the boundary of the preceding horizontal plane. The normal at any point, P, is given by

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Figure 5 Classification of slicing procedures

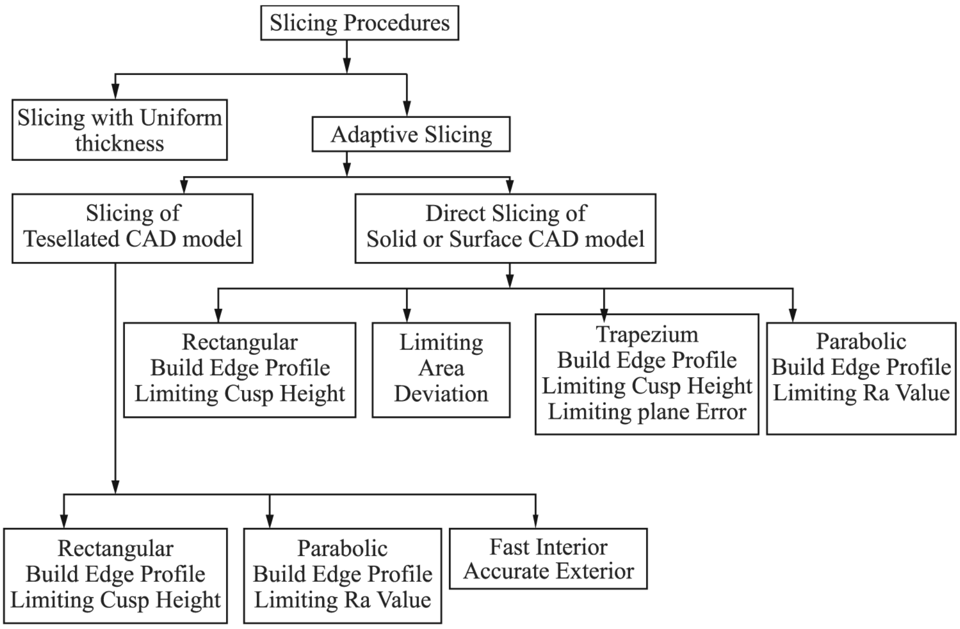
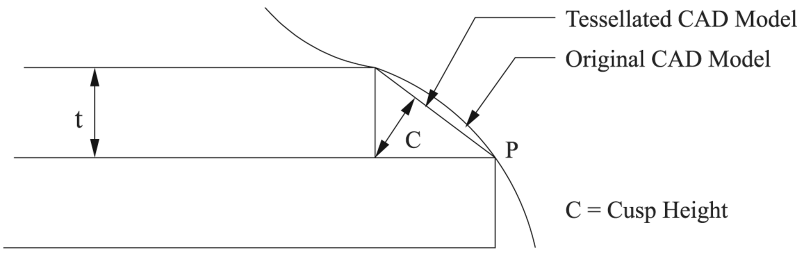


Figure 6 Cusp height



$$N = (N_x, N_y, N_z) \tag{1}$$

and the corresponding cusp vector is given as

$$C = cN \tag{2}$$

where

$$|C| = c \leq C_{\max} \tag{3}$$

The layer thickness t is obtained using the following expression:

$$t = C_{\max}/N_z \quad \text{here} \quad N_z \neq 0 \tag{4}$$

if

$$t_{\min} \leq t \leq t_{\max} \tag{5}$$

otherwise $t = t_{\min}$ if $t < t_{\min}$ and $t = t_{\max}$ if $t > t_{\max}$.

2.2 Stepwise uniform refinement (Sabourin *et al.*, 1996)

Adaptive slicing using stepwise uniform refinement, proposed by Sabourin *et al.* (1996), uses the same concept of limiting cusp height introduced by Dolenc and Makela (1994). Here, tessellated CAD model was first divided into uniform, horizontal slabs of thickness equal to the maximum acceptable layer thickness, $t_{\max}$. Those slabs that do not satisfy the cusp height requirement ($c < C_{\max}$) are further subdivided into finer slabs having uniform thickness. Interpolation is used for slice thickness determination. Specifically, a slab was examined both from its bottom slice looking upward and from its top slice looking downward and the succeeding slice is subdivided. This dual direction examination was less likely to miss high-curvature regions as compared to those procedures, which only examine upward from the current slice.

The basic measure of slice thickness in this work is the same as expression (4). The number of subdivisions (uniform thickness) to be made on a required slab are obtained as

$$\alpha_{\mathrm{slab}} = \mathrm{int}\left[\frac{t_{\max}}{C_{\max}}\max\{N_{z\,\mathrm{bottom}}, N_{z\,\mathrm{top}}\}\right] \quad (6)$$

$$\alpha_{\mathrm{slab}} \in [1, \alpha_{\max}], \alpha_{\mathrm{slab}} = \mathrm{int}\left(\frac{t_{\max}}{t_{\min}}\right) \quad (7)$$

where $N_{z\,\mathrm{top}}$ and $N_{z\,\mathrm{bottom}}$ are the sets of unit normal z components for points P_i across the bottom and top levels of a particular slab, respectively. The resulting uniform layer thickness within a particular slab is therefore given by

$$t = t_{\max}/\alpha_{\mathrm{slab}} \quad (8)$$

2.3 Local adaptive slicing (Tyberg and Bohn, 1998)

Local adaptive slicing of parts uses the same limiting cusp height concept (Dolenc and Makela, 1994), discussed earlier, to determine slice thickness. In this approach, first, individual parts and features in a build are identified and then slicing is carried out independent of one another. It is more often the case for several parts or features to coexist at the same height with different geometries such that each require distinct layer thickness to meet the tolerance conditions. Here, a tessellated CAD model is first sliced into uniformly thick slabs using the maximum thickness available in a RP system. The resulting contours belonging to the slab's top and bottom slices are then matched using topological information to form a set of sub-slabs. Finally, each sub-slab is independently divided into a distinct number of thinner layers based on the vertical slope of its surface or surfaces, measured along the contours. Different tests namely orientation, multiple part, proximity, direct, indirect and virtual tests are carried out to establish vertical connectivity between the two contours.
The sequence of different tests carried out is shown in Figure 7. After sub-slabs identification, each one is further subdivided independently into an integer number of uniform layers using the stepwise uniform refinement procedure (Sabourin *et al.*, 1996). They implemented local adaptive slicing on FDM-1600 RP system. Increase in extrusion temperature to prevent de-lamination when thin layers were built and revision of calibration tables were needed to fabricate the part (Tyberg and Bohn, 1999).
Figure 8 shows typical parts sliced by this method. It can be seen from Figure 8 that the first build consists of a single part (Figure 8(a)), containing a base which branches into three different features of varying curvature. The second build also consists of a single part (Figure 8(b)), having vertical surfaces and three different features. The build shown in Figure 8(c) is a combination of builds shown in Figure 8(a) and (b). Each build was sliced and fabricated with the three-layer thickness. These layer thickness are shown in Figure 8 with different shades. It is concluded by them that the build time can be reduced up to 73, 42 and 55 percent for build shown in Figure 8(a)-(c), respectively, using local adaptive slicing.

2.4 Accurate exterior and fast interior (Sabourin *et al.*, 1997)

In this procedure, a precise exterior is built with regular thin layers (using adaptive layer thickness). At the same time, the interior is built with thick and wide material application. Here, the interior layers are not of the same thickness as the exterior layers, but several times thicker as shown in Figure 9.

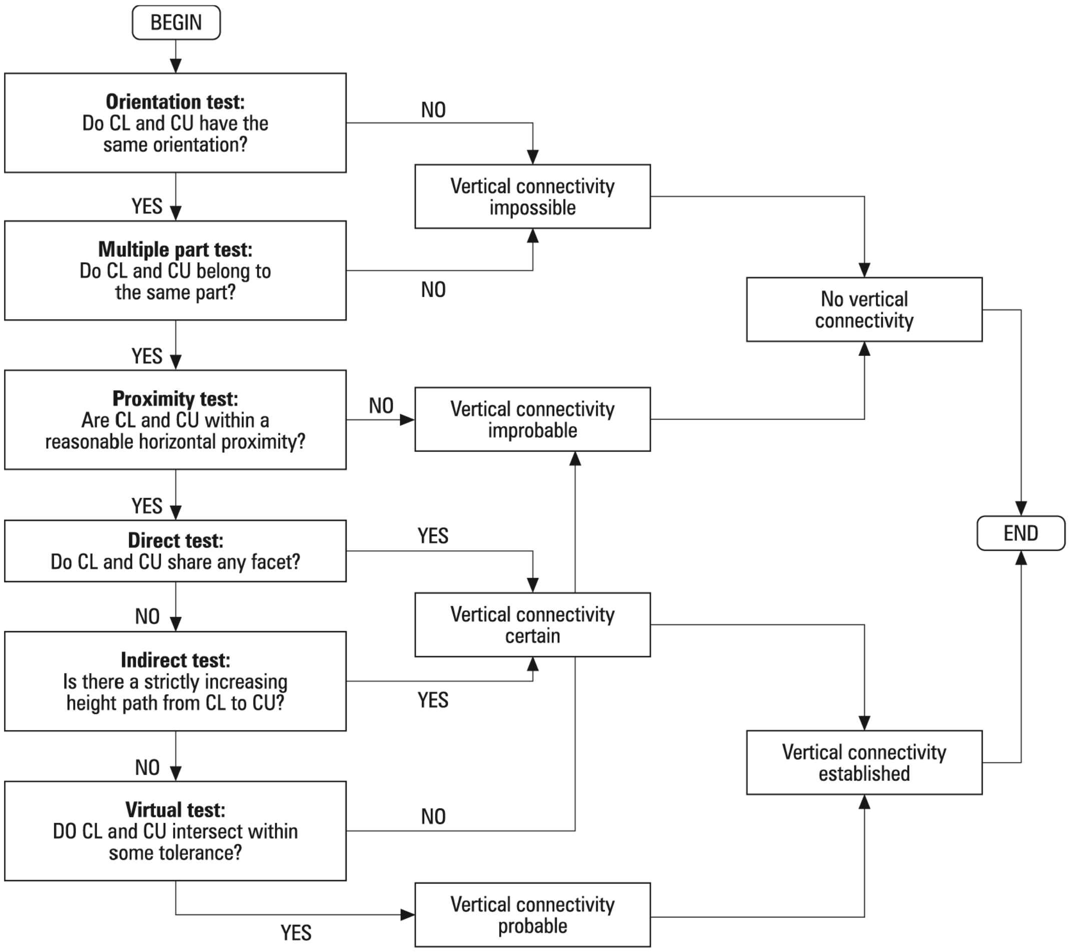
The process of fabrication in 3D space using thick and thin layers is coordinated by first slicing the tessellated CAD model into thick horizontal slabs of uniform thickness. These slabs are then processed from the bottom to the top of the part and the contours on the top and bottom of each slab are offset inward (shown in Figure 10) into the part in the horizontal plane to form a new set of contours that separate the exterior and interior regions within the slab. These two sets of regions can be built in a sequence. First, the exterior region is built with thin layers and then the interior regions are backfilled with thick layers to complete the fabrication of the part. Accurate exterior and fast interior slicing procedure is important as it could reduce the build time of the prototype from 50 to 80 percent.

2.5 Efficient slicing method (Tata *et al.*, 1998)

Tata *et al.* (1998) demonstrated that the productivity of the layered manufacturing (LM) processes can be significantly improved by upgrading the slicing software. The slicing procedure developed by them has four key constituents and are as follows.

- *Facet processor*. The function of facet processor is to arrange the triangular facets in the .STL file into groups based

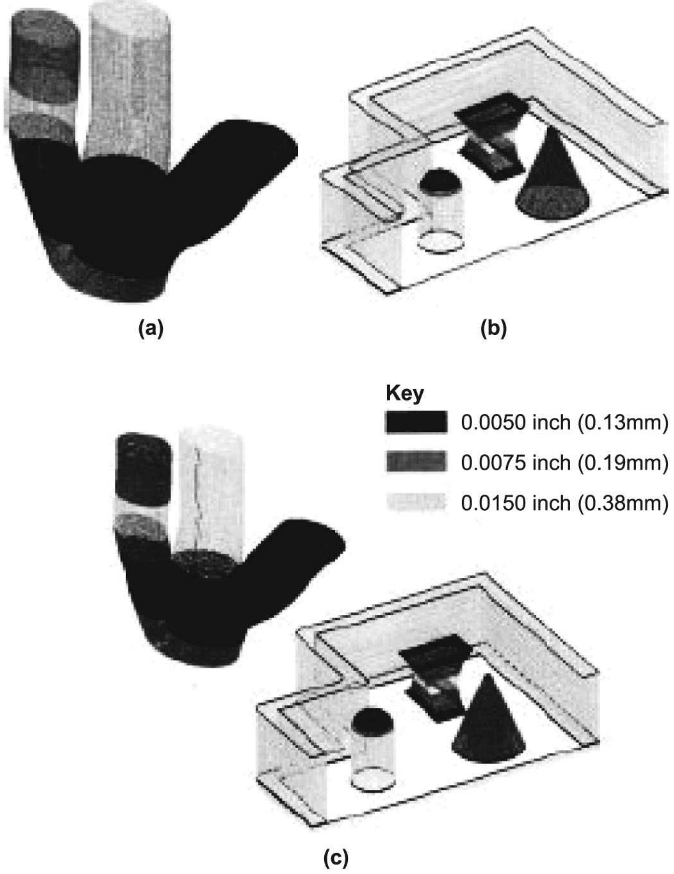
Figure 7 Establishment of vertical connectivity of contours in the implementation of local adaptive slicing (Tyberg and Bohn, 1998)



on their location with respect to the base of the model. Unordered collection of triangular facets in .STL file is the prime reason for the inefficiency of slicing algorithms. Facet grouping is performed by sorting the coordinates of vertices in ascending order of the z direction. This grouping is utilized for feature recognition in the later stages as shown in Figure 11.

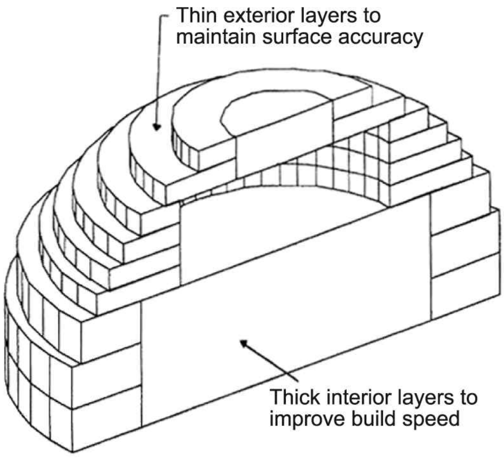
- *Key characteristic identifier*. It is a module which is based on the rules of simple geometric and engineering principles, with an aim to recognize the base faces (horizontal surfaces, pointed edges and pointed ends), type of features (protrusions or depressions), geometric shapes and orientation of features.
- *Thickness calculator*. This module calculates the slice thickness based on the geometrical complexity of the surfaces of the part. Complexity of a surface is defined as $S = \tan|\theta|$, where θ is the acute angle between the slice axis (z) and its projection on the surface. The layer thickness for *zero complexity surface* is chosen such that the fastest build time can be achieved i.e. the maximum allowable fabrication thickness for a RP system. For complex surfaces having nonzero complexity the *criterion of maximum deviation* i.e. $t \times \tan\theta$ and *chord length* ($t/\cos\theta$) are considered as constrains for slicing. Maximum deviation criterion is expected to be useful when it is necessary to contain the deviation of a layered model within the predetermined value. Chord length as a criterion is expected to be useful, when the deviation of a layered model is compared with the original CAD model. A fourth criterion based on the *volumetric error* was also considered. A layered model can lose or gain volume over the tessellated model based on whether the layer error is positive or negative. The volumetric error is a function of perimeter (p), layer cross sectional area (A), layer thickness (t)

Figure 8 Typical parts sliced by local adaptive slicing



Source: Tyberg and Bohn (1998)

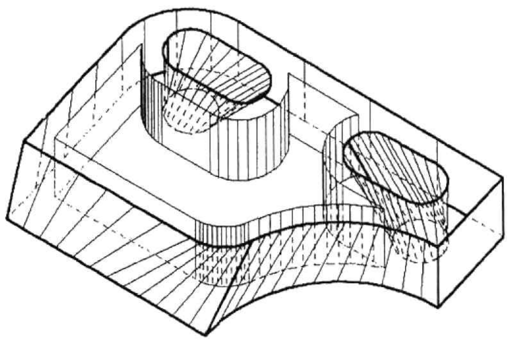
Figure 9 Concept of accurate exterior and fast interior slicing



Source: Sabourin *et al.* (1997)

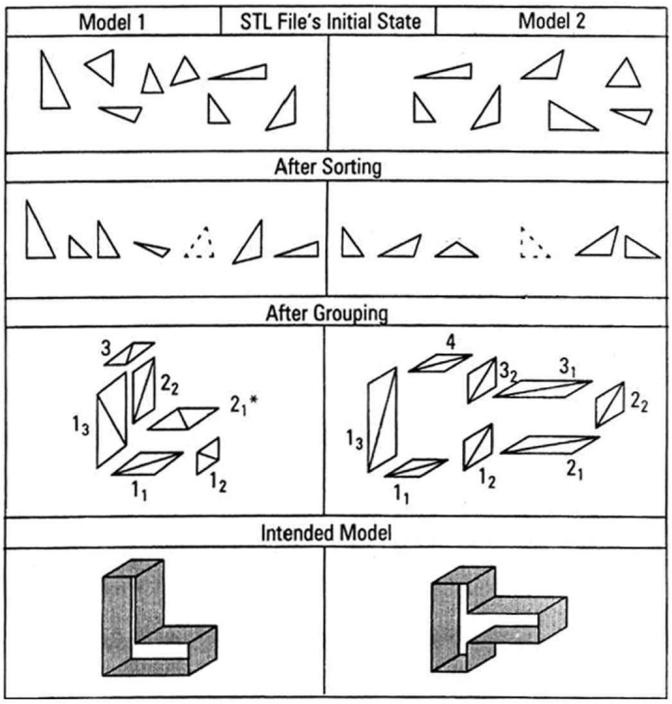
and surface complexity (S). It is not possible to maintain the volumetric error constant between layers because of the possible variations in the perimeter from layer to layer. Therefore, volumetric error per unit length is maintained as constant.

Figure 10 Contours offseted inward to implement accurate exterior and fast interior slicing procedure



Source: Sabourin *et al.* (1997)

Figure 11 Grouping of facets and feature recognition



Source: Tata *et al.* (1998)

Backtracking is introduced to meet the sudden changes in surface complexity levels.

- *Slicer*. Two-dimensional contours are created in this step by computing plane-triangle intersections at any height. Intersections are calculated marching from one triangle to its adjacent triangle. The advantage of the marching algorithm is that the intersection points are always calculated in the correct sequence. In addition, shape and orientation of any contour can be obtained by joining the points in order.

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2.6 Nonuniform cusp heights (Cormier *et al.*, 2000)

Most of the adaptive slicing algorithms presented earlier assume a maximum allowable cusp height, which applies to the entire part. As far as the application of the part is concerned, it may not have uniform cusp height requirement everywhere. Some faces of the part are required to be smooth while other faces are relatively unimportant.

This procedure uses tessellated CAD model as an input. The edges are found by edge finding algorithm and grouping of facets is carried out. The facet model of the part to be sliced is rendered. Designer has the option of specifying the maximum allowable cusp heights for different faces as per the functional requirement of the part.

2.7 Consideration of parabolic build edges (Pandey *et al.*, 2003b)

There have been a number of attempts to develop adaptive slicing procedures for tessellated CAD models and the slice edge profiles are implicitly assumed rectangular. Recently, a slicing algorithm based on the realistic edge profile of fused deposition modeling (FDM) is proposed by Pandey *et al.* (2003b). In this work, Ra value is used as a user specified parameter instead of the cusp height. The major advantage of using Ra value in the place of cusp height is that Ra value is most commonly used in integrated design and manufacturing. In real practice, the edge profiles of a layer manufactured part using FDM is found to be parabolic as shown in Figure 12. A stochastic model is developed for surface roughness (Ra value) prediction. The Ra value of the part is found to be dependent on the layer thickness (t) and build orientation (θ) i.e.

$$\mathrm{Ra}(\mu\mathrm{m}) = (69.28 - 72.36)\frac{t(\mathrm{mm})}{\cos\theta} \qquad (9)$$

for a 99 percent confidence limit. They studied the effect of radius of curvature on Ra and concluded by using a neural network model that the radius of curvature effect on surface roughness can be thought of independent as it varies within 5 percent over a wide range of curvature values.

The layer thickness for a maximum specified Ra value on the part surface is calculated using the following expression:

$$t(\mathrm{mm}) = \mathrm{Ra}(\mu\mathrm{m})\cos\theta/70.82 \qquad (10)$$

A typical part sliced by this method is given in Figure 13. The procedure is implemented using C and OpenGL. Average part surface quality in terms of standard Ra value is also predicted in the developed procedure.

3. Direct slicing of CAD model

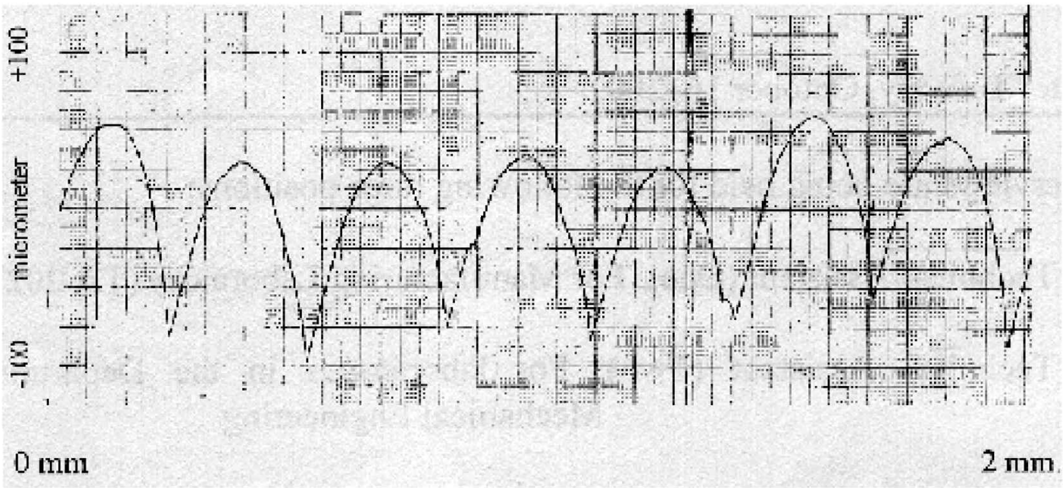
Even though tessellated CAD data format has number of advantages still it has several limitations. The exported .STL file is sometimes larger than the original CAD file because it has high degree of redundancy since each triangle is individually recorded and shared ordinates are duplicated. Tessellated CAD data files generally carry defects like gaps, overlaps, degenerate facets etc. hence, repair software is needed. Sometimes it is not possible to get back the original CAD model through the .STL interface successfully. Slicing of large .STL file may take long time. The slicing error (real error) is quite high as compared to chordal error due to tessellation (given error) as shown in Figure 14.

Planar closed curves (contours) result, when a horizontal plane is intersected with CAD model during slicing. These contours may either be produced by a three-dimensional CAD model, reverse engineering technique, coordinate measurement machine or by computer tomography. Direct slicing may prove most useful for RP users, who produce large axisymmetric or spherical geometries because they suffer the disadvantages of large tessellated files. The direct slicing has potential in terms of reduced file size, greater model accuracy, reduced RP post processing time and elimination of repair software. However, there are some limitations with direct slicing. The implementation of program for adding support structure is not easy. The ability to orient the model is minimum as CAD model is stored in the form of analytical surfaces or mathematical definitions instead of coordinates of points as in the case of tessellated models. Therefore, more designer knowledge is needed (Jamieson and Hacker, 1995) as software support is not readily available. In the present section, different direct slicing procedures for CAD models are reviewed.

3.1 Area deviation method (Jamieson and Hacker, 1995; Zhao and Laperriere, 2000)

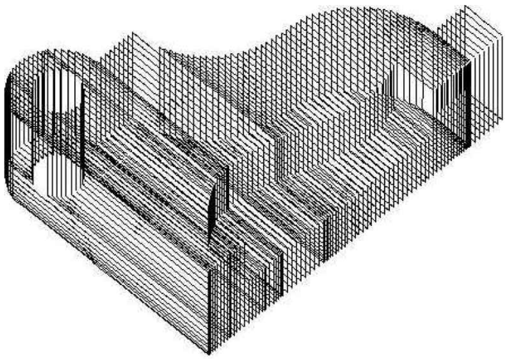
Direct slicing of CAD models with uniform slice thickness was implemented first using *Parasolid* CAD software and user defined

Figure 12 Edge profiles of FDM part surface, $\theta = 45°$, $t = 0.254$ mm



Note: Reprinted from *Journal of Material Processing Technology*, Vol 132 No 1, Pandey *et al*., "Improvement of surface finish by staircase machining in fused deposition modelling", pp. 323-331, © 2003, with permission from Elsevier

Figure 13 Typical part sliced by limited Ra value method



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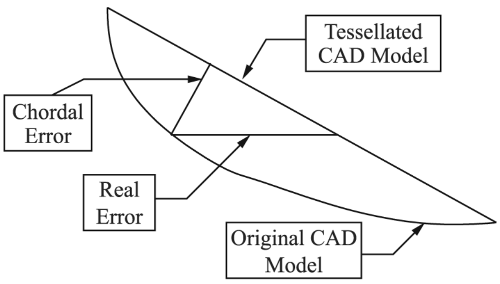
Source: Pandey *et al*. (2003b)

Figure 14 Slicing error and chordal error



Source: Jamieson and Hacker (1995)

routines in C (a solid modeling kernel of Unigraphics) by Jamieson and Hacker (1995). Parts were modeled using boundary representation method. These models had non-manifold problem which was avoided by giving tolerance to the sectioning plane in the positive or negative Z-direction.

The slicing algorithm starts with the finding of the highest and lowest points of a part. The slicing direction is chosen as the Z-direction. The slicing of the part is achieved by, consecutively calling the function for one slice and then putting the tags of the slice together in an assembly.

An optional adaptive slicing approach is provided which was based on the limited area deviation. The area deviation is defined as

$$\sigma = \left| \frac{A_{i+1} - A_i}{A_i} \right| \leq \delta \qquad (11)$$

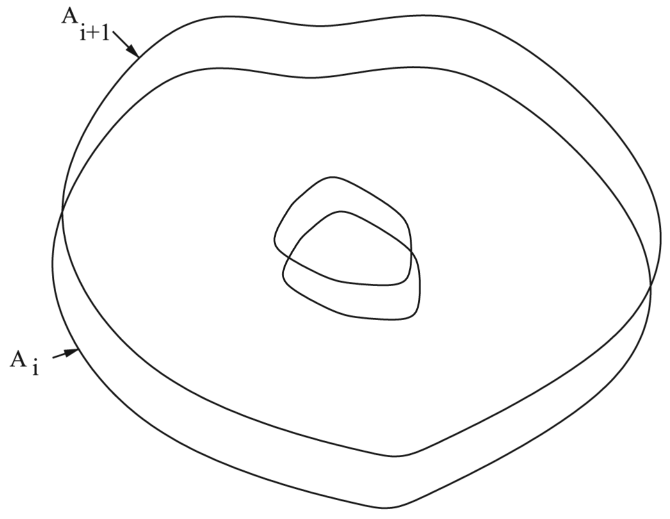
where A_i and A_{i+1} are areas of two consecutive slices as shown in Figure 15. In this work, δ is considered as 5 percent. The thickness of a layer always remains between the maximum and minimum fabrication thickness available in the RP system.

Zhao and Laperriere (2000) also carried out the adaptive slicing of solid models using the same concept of limited area deviation, but implemented the procedure using AutoCAD Run Time Extension (ARX) and C++.

3.2 Accurate slicing procedure (Kulkarni and Dutta, 1996)

The effect of containment and staircase on the final product accuracy and surface quality was studied by Kulkarni and Dutta (1996). Vertical normal curvature and normal vector at any point P of a CAD model is computed.

Figure 15 Areas of two consecutive planes in area deviation method



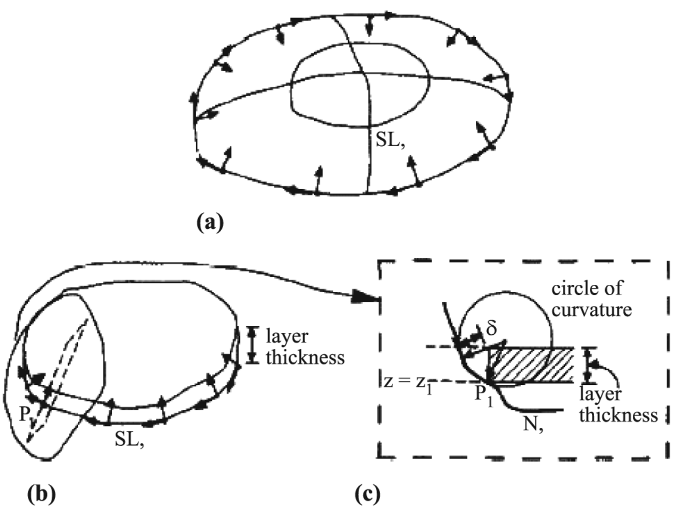
The normal section at that point P is approximated as a circle as shown in Figure 16. This approximation results into 12 expressions, when the different possible geometrical conditions and containment requirements are considered. Slice thickness at a point P is given by

$$t = f(\rho, \theta, \delta) \tag{12}$$

where ρ is the vertical normal curvature, θ the angle between the horizontal and normal vector and δ the allowable cusp height. Two approaches used for finding the slice thickness are as follows.

Maximum curvature approach:

Figure 16 Vertical normal curvature and approximation as circle. (a) Object showing the vertical and horizontal directions; (b) a layer of the object; and (c) normal vertical section at P_1 (Kulkarni and Dutta, 1996)



Note: Reprinted from *Computer-Aided Design*, Vol 28 No 9, Kulkarni and Dutta, "An accurate slicing procedure for layered manufacturing", pp. 683-697, © 1996, with permission from Elsevier

$$\text{maximize}\{\kappa_n(u, v)\} \tag{13}$$

subject to:

$$z(u, v) = \text{constant} \tag{14}$$

Minimum layer thickness approach:

$$\text{minimize}\{t(u, v)\} \tag{15}$$

subject to:

$$z(u, v) = \text{constant} \tag{16}$$

The minimum layer thickness approach is reported to yield better results compared to maximum curvature approach. Sequential quadratic programming (SQP) algorithm (MATLAB) is used to solve the optimization problem. The procedure of slicing was carried out in two steps. In the first step, the model was divided into distinct sectors so that sharp features were not missed as the circular approximation of a vertex may yield erroneous results. In the second step these separated sectors were sliced based on the specified cusp height.

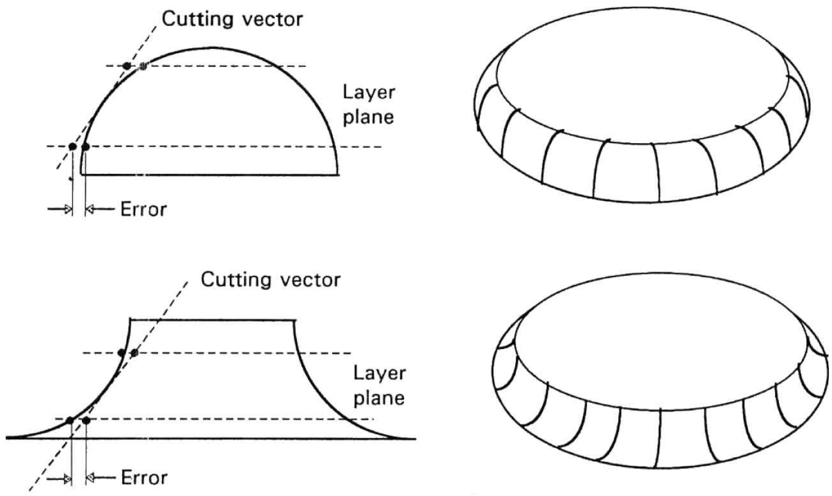
Adaptive slicing of an arbitrary object, which has many bounding surfaces, is carried out by extracting their geometrical definition. These surfaces are then converted into parametric splined surfaces and then slicing is performed.

3.3 Sloping surface consideration (Hope *et al.*, 1997a, b)

In all the earlier approaches presented above, the build edges considered to be rectangular. Hope *et al.* (1997a, b) used sloping build edges instead of rectangular edges for the better approximation of surface of the part. The main advantage achieved is improved surface finish and decreased build time as thick layers can be used. In this work, multiple B-spline surfaces from IGES format were used to define a part. They sliced the model by tracing surface contours, and computing the cutting direction at a number of points as specified by the user. These points and corresponding cutting vectors are used to generate computer numerical control (CNC) code to machine the slices. Figure 17 shows the error between the CAD model, cut layers and cutting vectors.

Adaptive slicing with sloping surface is also proposed by Hope *et al.* (1997b) to further reduce the build time. Two types of errors namely cusp height and maximum difference in the plane layer are introduced as shown in

Figure 17 Error between CAD model, cut layer and cutting vector



Source: Hope *et al.* (1997a)

Figure 18. The expression for cusp height (δ) and for maximum difference in the layer plane (ε) (Figure 19)

$$\delta = \left[\left(\frac{t}{2\cos\alpha}\right)^2 + R_c^2\right]^{\frac{1}{2}} - R_c \qquad (17)$$

$$\varepsilon = (\delta + R_c)\cos\phi - \left[\{(\delta + R_c)\cos\phi\}^2 - \left(\frac{t}{2\cos\alpha}\right)^2\right]^{\frac{1}{2}} \qquad (18)$$

where

$$\phi = \alpha \pm \arctan\left\{\frac{t}{2R_c\cos\alpha}\right\} \qquad (19)$$

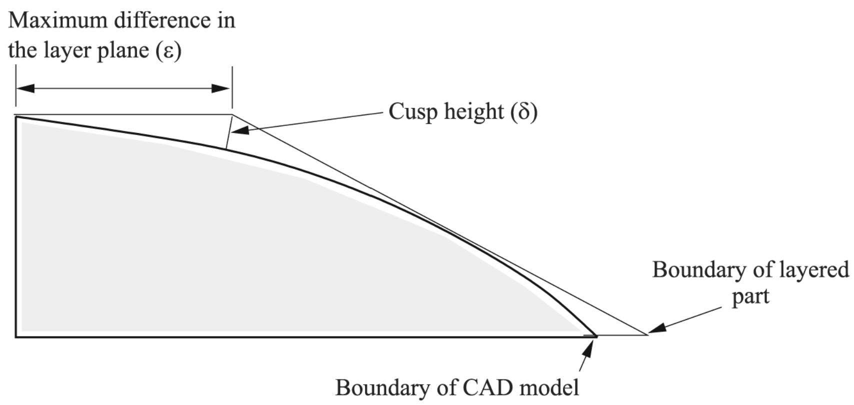
here R_c is the radius of curvature, t is the layer thickness and α is the angle between the horizontal and normal. They have provided a choice between using the cusp height (δ) and maximum difference in the layer plane (ε) as the measure of error. In adaptive slicing, module slicing is performed and the CNC code is generated to machine them. These slices are glued together to form the prototype.

3.4 Region-based adaptive slicing (Mani *et al.*, 1999)

Many researchers implemented fixed cusp height restriction on the entire part. Flexibility of imposing different cusp heights on the different surfaces of the model was implemented by Mani *et al.* (1999). Similar concept of specifying nonuniform cusp heights on different faces of a model is also implemented by Cormier *et al.* (2000) for tessellated CAD models. Difference between traditional adaptive slicing and region-based adaptive slicing is shown in Figure 20.

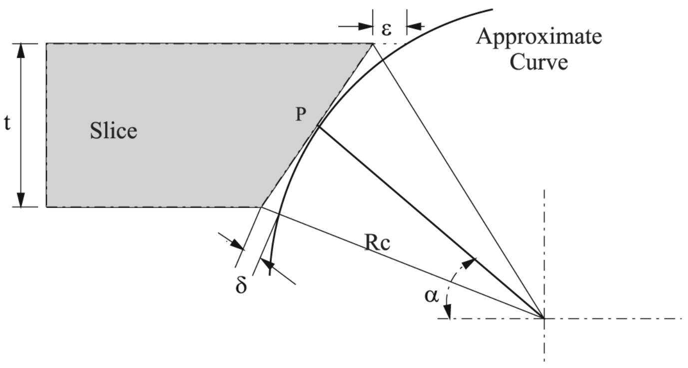
The region-based slicing procedure was

Figure 18 Errors in sloping surfaces consideration of build edges



Source: Hope *et al.* (1997b)

Figure 19 Geometrical computation, sloping surfaces



Source: Hope *et al.* (1997b)

implemented in four steps. In the first step, critical surfaces are identified for cusp height requirements, spatial decomposition of the model into adaptive layer thickness and the common interface layer region is then carried out. Common layer region (region C, Figure 20) is built with maximum possible fabrication thickness on RP system and adaptive layer thickness region (region A, Figure 20) is sliced based on the geometry and cusp height requirement. The process of decomposition of the model into two regions is almost similar to fast interior and accurate exterior implemented by Sabourin *et al.* (1997). Finally, the sequence of layer deposition is decided.

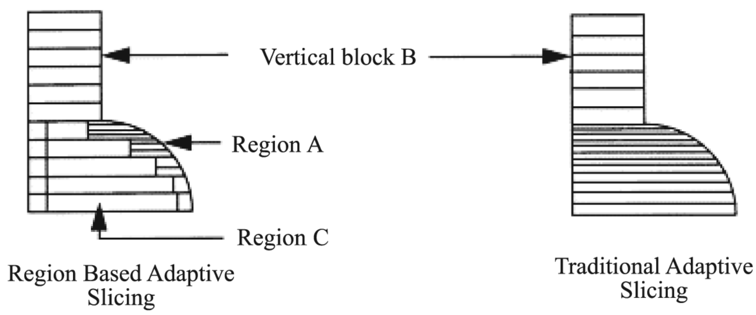
3.5 Adaptive slicing and selective hatching (Weiyin and Peiren, 1999)

An adaptive slicing procedure with selective hatching is implemented for slicing of non-uniform rational B-spline surfaces (NURBS) by Weiyin and Peiren (1999). First, extreme points of the CAD model are identified. Then the model is subdivided along the z-direction into several slabs to preserve sharp features. These slabs are then subdivided based on the containment and a pre-specified cusp height requirement. Here, the slice thickness is a function of vertical normal radius of curvature (ρ), cusp height (δ) and n_z (similar to expression (12) of Kulkarni and Dutta (1996)). The slice thickness is obtained by minimization problem as given by expressions (15) and (16). Selective hatching procedure is implemented by the computation of skin contours. This is carried out by offsetting the contours in the interior of CAD model, which corresponds to maximum fabrication thickness of RP system. The region between original and offset contours forms the skin of the part. The skin region is deposited with finer layers calculated by adaptive slicing method to ensure better part surface quality. The internal space is filled with the thickest layers to reduce the build time.

3.6 Optimization by sampling of points for fast computing (Lee and Choi, 2000)

Lee and Choi (2000) combined the work of Dolenc and Makela (1994) for polyhedral features and Kulkarni and Dutta (1996) for freeform features. The computing time is reduced by introducing the concept of sampling points at $z =$ constant for solving the optimization problem to determine the perpendicular distance between two consecutive slices projected on the same x-y plane. In place of minimum slice thickness, they minimized the perpendicular distance between the two consecutive slices projected on the same x-y plane. They were able to reduce the computational time further by introducing the concept of vertical character line i.e. the curve that connects the optimum sampling points, P_k, where the perpendicular

Figure 20 Difference between traditional and region-based adaptive slicing



Note: Reprinted from *Computer-Aided Design*, Vol 31 No 5, Mani *et al.*, "Region-based adaptive slicing", pp. 317-333, © 1999, with permission from Elsevier distance between the two contours C_i and C_{i+1} is maximum. The character line, therefore passes through the points where the slope of the model is most moderate for each slice as shown in Figure 21. It is important that the optimum sampling point is found out rapidly and exactly (by taking thicker slabs in the beginning) in this adaptive slicing procedure and character line is established. If the optimum sampling points are located on or close to the character line, their locations can be predicted in advance.

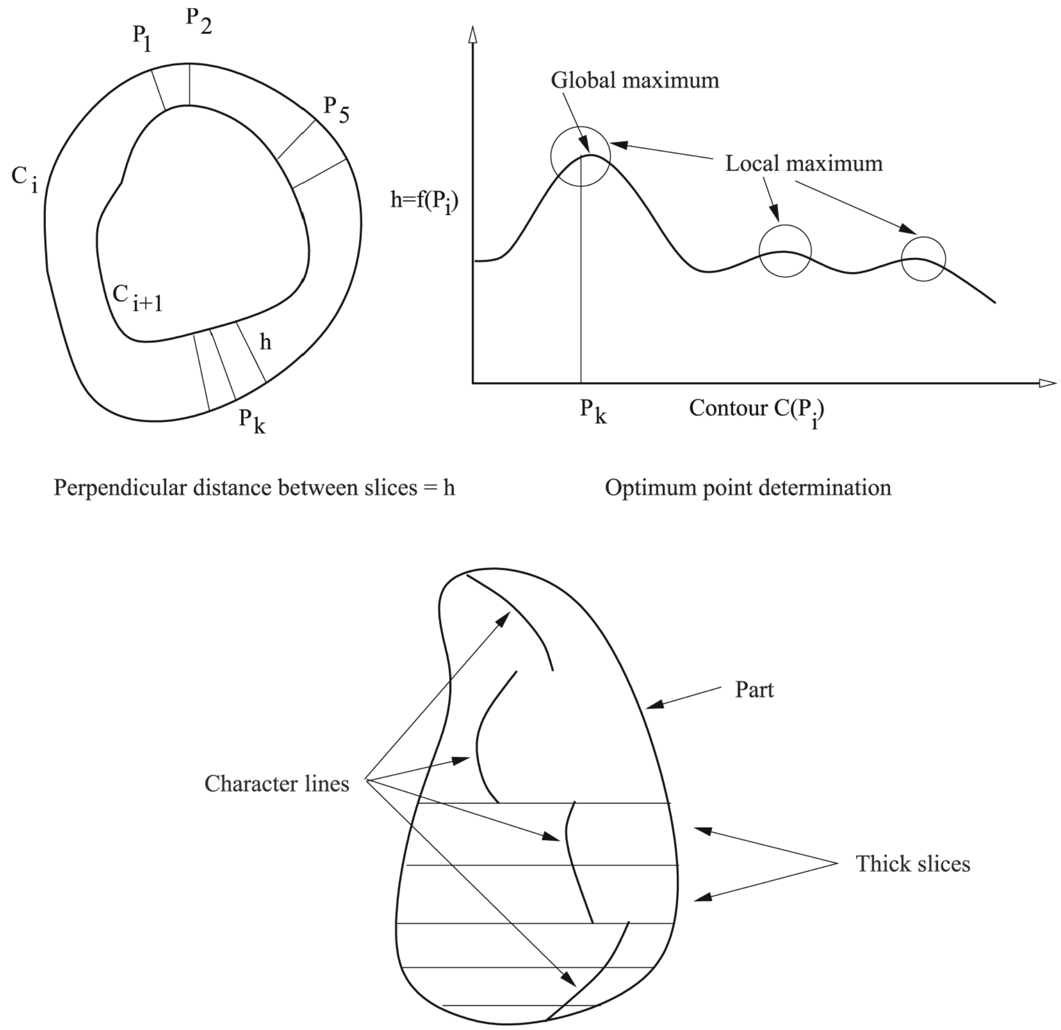
3.7 Consideration of parabolic build edges (Pandey *et al.*, 2003b)

Direct adaptive slicing of axisymmetric parts is also implemented by Pandey *et al.* (2003b). Slice thickness was calculated using expression (10). The average part surface quality in terms of standard Ra value is predicted in their work. The direct adaptive slicing software also gives cusp height (Dolenc and Makela, 1994) and relative area deviation (Jamieson and Hacker, 1995; Zhao and Laperriere, 2000) for two consecutive slices. They have drawn conclusion that for most of the RP process, the Ra value is proportional to $t/\cos\theta$. The constant of proportionality will be different for different RP processes. Therefore, this procedure can be used for different RP systems.

4. Discussion

It is evident from the literature that the slicing algorithms can be broadly classified as slicing of tessellated CAD models and direct slicing. Adaptive slicing of CAD models is a solution to handle the contradicting situation of enhancement of surface finish of the part and reduction in build time. Adaptive slicing is implemented by Dolenc and Makela (1994) by introducing the concept of limited cusp height for polyhedral parts. Different versions of the same concept like stepwise uniform

Figure 21 Sampling of points and vertical character lines



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refinement (Sabourin *et al.*, 1996), local adaptive slicing (Tyberg and Bohn, 1998) and non-uniform cusp height at different faces (Cormier *et al.*, 2000) of a solid as per functional requirement are developed which have their individual importance and use as in accordance with the geometry of the part. These procedures assume the build edge profile of the deposited layers as rectangular. Proper material deposition strategy is required to develop fast interior and accurate exterior (Sabourin *et al.*, 1997) slicing method. The slicing of exterior region is also carried out by assuming build edges as rectangular. Assumption of build edges as parabola (Pandey *et al.*, 2003b) is quite closer to real time situation in case of FDM RP system. Introduction of standard measure of surface quality i.e. Ra value is important as it is widely accepted in engineering design and manufacturing practice.

In direct adaptive slicing, first attempt is made by introducing maximum allowable deviation in area as a key to decide layer thickness (Jamieson and Hacker, 1995; Zhao and Laperriere, 2000). The limitation of this procedure is that it does not take surface geometry in consideration. Direct slicing developed by Kulkarni and Dutta (1996) is based on cusp height concept. It is useful when the CAD model is defined as the analytical surface or combination of surface patches. In this procedure, the build edges are assumed as rectangular. Sloping build edge consideration and direct slicing were implemented by Hope *et al.* (1997a, b). Assumption of sloping build edges can lead to better results in terms of approximating the geometry and reduction of build time, but its application is limited to larger objects only. The development of procedure, which has fast computational ability by introduction of character line concept (Lee and Choi, 2000) along with direct slicing, is useful for larger parts. The direct slicing, considering actual build edges (parabolic build edges) is more realistic and is implemented for axisymmetric components by Pandey *et al.* (2003b). Although build time is not estimated by them, it can be expected to reduce further as the surface is approximated by realistic edge. Implementation of direct slicing of a surface with a planar surface is recently reported (Jun *et al.*, 2001). This approach is based on finding the points of topology transition of a surface. Seven types of topology transition points of a surface and algorithms to identify these points are described. Algorithm to calculate the resulting contour is also presented, which may prove suitable to implement direct adaptive slicing for a general component.

5. Conclusions

Different published slicing algorithms are presented and classified into two major categories. Many researchers implemented adaptive slicing and used cusp height as limiting parameter assuming build edge profiles as rectangular. Very few adaptive slicing algorithms are implemented considering build edges as sloping. Limited area deviation between any two consecutive slices is also attempted without considering the surface geometry of the part. An adaptive slicing algorithm, based on real time edge profiles, using limited Ra value as a criterion to determine slice thickness for FDM is recently implemented for direct slicing of axisymmetric parts and tessellated CAD models. Average part surface quality in terms of standard Ra value is predicted in this procedure.

It is realized to develop slicing procedures based on actual build edge profiles for different RP processes. It is clear that direct slicing certainly increases the accuracy of a RP part. Most of the RP machines present can only be driven by line vectors; therefore, output of direct slicing i.e. closed curves cannot be used as an input to these machines. These curves must therefore be broken up into short segments and put into the file format so that the RP machine can understand. There is a need for modification in hardware that can drive the slides or scan laser for curing within a closed curved resulting from direct slicing.

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