ADAPTIVE SLICING WITH SLOPING LAYER SURFACES

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ABSTRACT

An adaptive slicing procedure for improving the geometric accuracy of layered manufacturing techniques is presented. Unlike previous procedures, the present method uses layers with sloping boundary surfaces that closely match the shape of the required surface. This greatly reduces the stair case effect which is characteristic of layered components with square edges. Two measures of error are considered and a method of predicting these measures for sloping layer surfaces is outlined. To cater for different manufacturing requirements, a method to produce parts with either an inside or outside tolerance, or a combination of both, is presented. Finally, some problems associated with surface joins, vertices, and inflection points are considered and some solutions proposed.

INTRODUCTION

The work presented here is an extension to the TruSurf system, which was initially proposed in Hope et al. (1995) and (1996), and further detailed in Hope et al. (1997). TruSurf is a Rapid Prototyping (RP) system for building solid objects from layers with sloping surfaces that closely match the designed surface shape. Jacobs (1992) describes stereolithography, the most widely used RP system, and gives an overview of other RP systems that are available or in development. TruSurf obtains the definition of the required surface from IGES files (U.S. Standards, 1988) exported from a CAD system. IGES stores descriptions of solids and surfaces as Non-Uniform Rational B-spline Surfaces (NURBS), and TruSurf uses these NURBS because they enable direct calculation of surface slope and curvature. NURBS use the same geometric definitions for surfaces as the original CAD model, thus accuracy is maintained, unlike the faceted approximations used by most RP systems. The TruSurf project aims to address the problems of build time and accuracy for large prototypes where the volume of the prototype is of the order of one cubic meter or greater.

For TruSurf, and most other RP systems, build time is mainly dependent on the number of layers used and can be reduced significantly through the use of thicker layers. Both the accuracy and surface finish of parts are degraded as layer thickness increases, so the choice of layer thickness is a compromise between build time and accuracy. TruSurf makes use of sloping layer surfaces, instead of the stepped square edges used by commercial RP systems, as a way of improving accuracy, while allowing thicker layers to be used. However, parts have varying degrees of detail and, if constant layer thicknesses are used the accuracy will also vary. To account for this, models can be built from layers where the thickness varies depending on the required accuracy. This procedure of adapting the layer thickness to suit the geometry of each layer has become known as adaptive slicing (Suh & Wozny, 1994).

In adaptive slicing, the user selects a maximum allowable error and the layer thickness for each slice is then determined by the local surface geometry and the specified error. To calculate the appropriate layer thickness a method to determine the error must be established. For general surfaces, the error can not be easily found and an approximation is used. The method presented here, to approximate the error, is based on previous work by Kulkarni and Dutta (1996), and is adapted for sloping layer boundaries. The validity of this method is checked by using it on simple revolved surfaces where the actual error can be easily found.

SLOPING LAYER SURFACES

Commercial RP systems that are currently available build three dimensional objects from layers which are essentially two dimensional cross sections with some thickness. This creates a stepped effect on planar surfaces inclined to the build direction and curved surfaces. To produce an acceptable surface on parts, very thin layers are generally used. Recently a number of groups have worked to improve the surface finish and accuracy of parts by using sloping surfaces on layer boundaries. To achieve this more axes of control are needed, and the sloping surface path has to be obtained.

Stratoconception (Barlier et al. ,1995) uses a macro script within the CATIA CAD software to produce "twisted profile layers". De Jager (1996) presents a method of determining the sloping surface path by interpolating two contours of a NURBS surface with an isoparametric line. This method works well for simple surfaces created from a rotational sweep, but can not be used for more complex surfaces. A similar method used in the Shape Maker II (Thomas et al. 1996) and CAM-LEM (Zheng and Newman, 1997) attempts to recreate the surface from contour curves. This method relies on the two cross sections of a model, used to define a layer, having the same number of curves and each curve being topologically connected to a corresponding curve on the other cross section. If this criterion is satisfied the topologically connected curves are subdivided into an equal number of points and the points connected by lines to form ruled surfaces. If the criterion is not satisfied the method fails.

TruSurf (Hope et al. ,1995, 1996, and 1997) derives the sloping surface path from the vector cross product of the surface normal and tangent at a series of points around the layer. At surface edges the edge tangent is included in the path to ensure they are reproduced correctly. This method will work for any shape.

A different approach is taken in Shape Deposition Manufacturing (SDM) (Weiss & Prinz, 1995) where sloping layer surfaces are produced by CNC machining the edges of deposited 2D layers. This may produce a surface quality similar to that achieved by the methods above, but requires an extra machining stage.

ADAPTIVE SLICING

Adaptive slicing has already been performed for layers with edges square to the layer plane, and these will be covered briefly. Dolenc and Makela (1994) present a method to control the staircase effect. They worked with faceted surfaces, and use the angle of the surface normal to predict a cusp height. The cusp height is the maximum deviation from the layered part to the CAD surface measured in the direction normal to the CAD surface, as shown in figure 1. Their slicer selects an appropriate layer thickness from a given range, to ensure the cusp height is within a user-specified tolerance. Sabourin et al (1996) approach adaptive slicing by first subdividing the CAD model into slabs of uniform thickness equal to the maximum available. The slabs are then subdivided using the same measure of cusp height as by Dolenc and Makela (1994). The main difference in their approach is that they examine both the top and bottom of each slice to guard against sudden changes in curvature above the base of the layer.

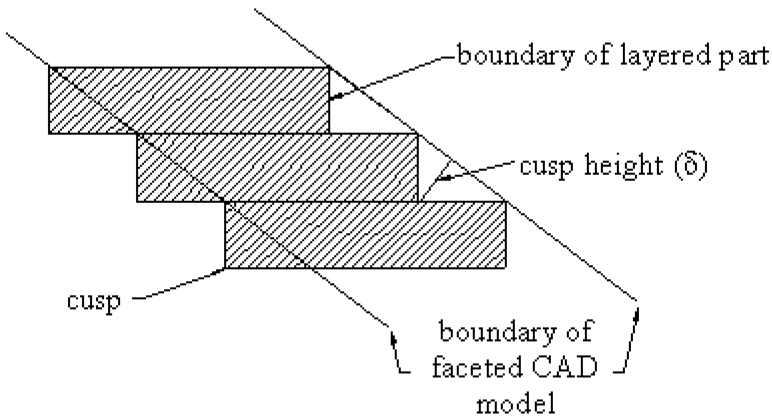


Figure 1. The cusp height on faceted surfaces as used by Dolenc and Makela (1994).

Jamieson and Hacker (1995) performed direct slicing of CAD data by creating algorithms to interact with Parasolid, the solid modelling kernal of Unigraphics. In their slicing algorithm they included a basic adaptive slicing option that would attempt to use a thicker layer if the current slice had the same geometry as the previous one. This situation would only occur when all the surfaces of the slice are planar and in the build direction.

Kulkarni and Dutta (1995) and (1996) address the problem of determining adaptive slicing for a surface from its analytical representation. They also use a cusp height to quantify the error associated with the staircase effect, as shown in figure 2. Instead of selecting a layer thickness from a given range of thicknesses, they determine a maximum allowable thickness for each layer. In their earlier paper they use a "maximum curvature" approach where they find the point (P) on a slice at which the normal curvature in the vertical plane is maximum. They then approximate the vertical section at P with a circle to determine the layer thickness. In their later paper they identify that the cusp height at a point P is a function of the angle that the surface normal makes to the horizontal, as well as the radius of vertical normal curvature of the surface at that point.

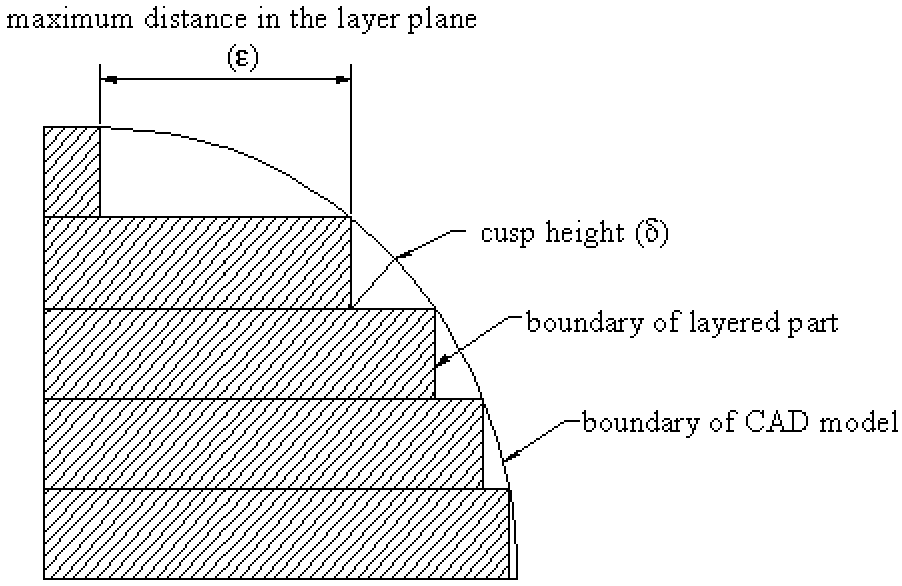


Figure 2. The cusp height, and maximum distance in the layer plane on an analytical surface.

Although cusp height is the most commonly used measure of error, another measure of the error is the maximum distance in the layer plane between the boundary of the original CAD model and the boundary of the layered part. This measure of error has also been used by Novac et al (1997) and is indicated in figure 2. When the normal to the CAD surface is in the plane of the layer, the two measures of error produce almost the same result. This can be seen in the bottom layer of the diagrams. The difference between the two measures increases with the angle between the normal and the layer plane, and is greatest when the normal to the CAD surface becomes perpendicular to the layer plane. At and near this point the validity of using the cusp height to measure the error becomes questionable. Consider the top two layers in figure 2. The cusp height for these two layers is fairly similar, but the maximum difference in the layer plane for the top layer is more than twice that of the layer below. This raises the question as to what the measure of error is trying to represent. Should it represent the volume difference or the smoothness of the layered surface. In this case the maximum difference in the layer plane gives a more accurate representation of the volume missing from the layered part, while the cusp height better represents the surface smoothness.

These two measures of layer error can be transferred to layers with sloping boundaries. Figure 3 shows the same CAD surface used in figure 2 with the resulting part as built with sloped layer surfaces. In this case the differences between the layered part and CAD model are smaller for both volume and smoothness measures. To view the error, figure 4 shows a close up of the top layer of the part. For sloped layers, the difference between the two measures of error is least for small angles between the surface normal and the layer plane. When the normal to the CAD surface becomes close to perpendicular to the layer plane, the maximum distance in the layer plane becomes very large compared to the volume difference. At this point the cusp height gives a better representation for both volume difference, and surface smoothness.

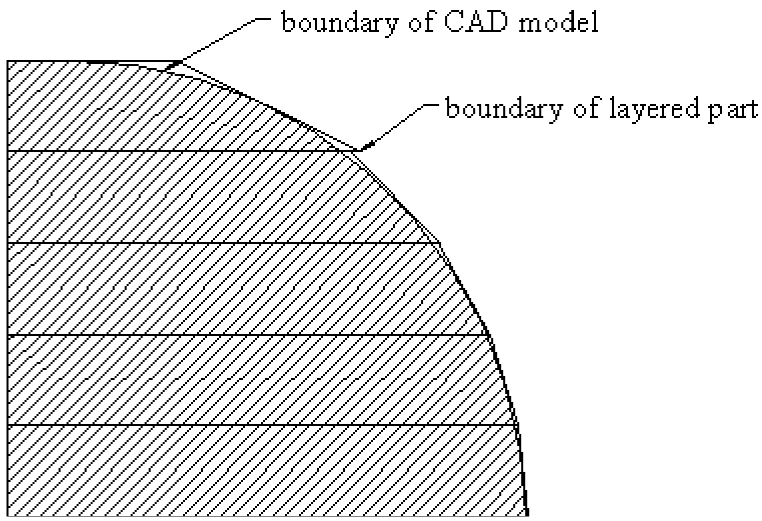


Figure 3. Using sloped layer surfaces eliminates the staircase effect.

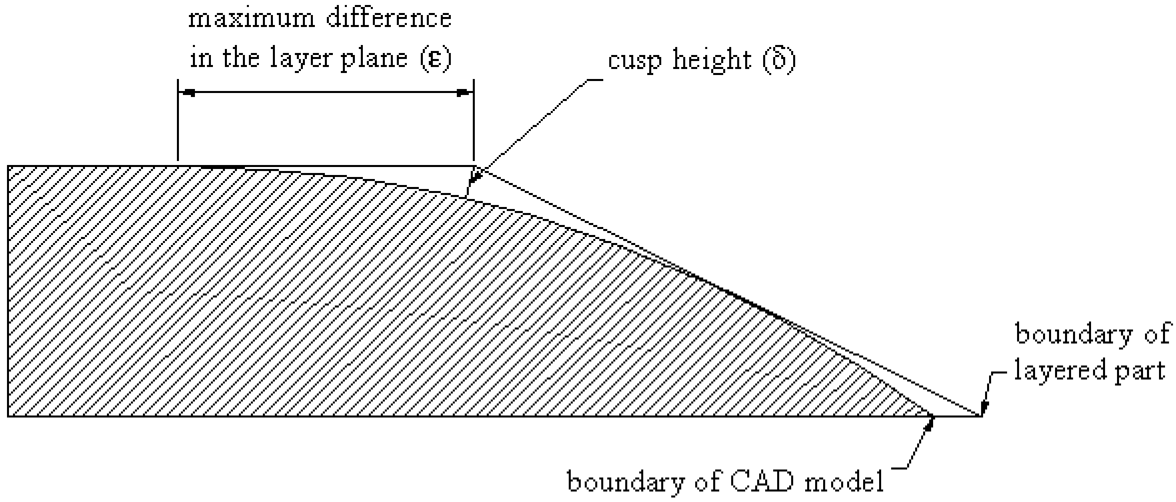


Figure 4. Cusp height and maximum difference in the layer plane, for layers with a sloping boundary surface.

The other essential part of an adaptive slicing procedure is a method to estimate the layer error. The method used here is adapted for sloping layer boundaries from Kulkarni and Dutta (1996) in which the surface section at point P is approximated locally as a circle. The radius of surface curvature (Rc) and the angle of the surface normal to the layer plane are used to calculate the cusp height and the maximum distance in the layer plane. Figure 5 illustrates one layer of a part with the local surface approximated by the circle through point P. The surface normal and radius of curvature are both calculated at P, which is chosen to be half way between the top and bottom of the layer. Cusp height is the same at the top and bottom of the layer, and can be found from,

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

, the maximum difference in the layer plane, is then

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

where $\phi = \alpha \pm \tan^{-1}\left(\frac{t}{2R_c\cos\alpha} \right)$ (3)

The two values for () give the maximum difference in the layer plane at the top and at the bottom of the layer.

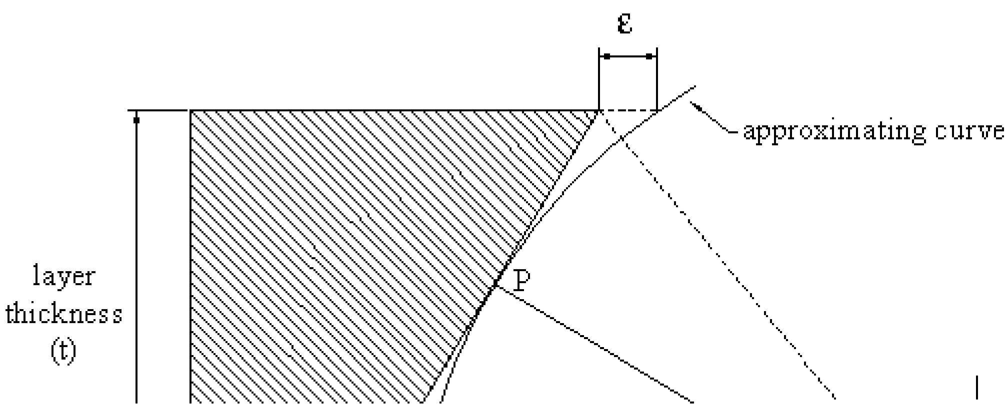


Figure 5. To calculate d and e, the surface at point P is locally approximated as a circle. The radius of surface curvature (Rc), and the angle of the surface normal to the layer plane (a), are used in the calculations.

CALCULATING RADIUS OF CURVATURE

The radius of curvature in the direction of the cutting vector (see figure 6) is the inverse of the normal curvature in the same direction. For a surface represented in parametric form by s(u,v) = {x(u,v), y(u,v), z(u,v)} the normal curvature (is given by the following formula (see for example Hosaka, 1992).

$$\kappa = \frac{L(\mathrm{d}u)^2 + 2M\,\mathrm{d}u\,\mathrm{d}v + N(\mathrm{d}v)^2}{E(\mathrm{d}u)^2 + 2F\,\mathrm{d}u\,\mathrm{d}v + G(\mathrm{d}v)^2} \quad (4)$$

Where E, F and G are the fundamental magnitudes of the first order, and are obtained from the dot product of the partial derivatives of the surface.

$$E = \vec{s}_u \cdot \vec{s}_u, \qquad F = \vec{s}_u \cdot \vec{s}_v, \qquad G = \vec{s}_v \cdot \vec{s}_v \quad (5)$$

Similarly L, M and N are the fundamental magnitudes of the second order, and are obtained from the dot product of the unit normal , and the second partial derivatives of the surface.

$$L = \hat{n} \cdot \vec{s}_{uu}, \qquad M = \hat{n} \cdot \vec{s}_{uv}, \qquad N = \hat{n} \cdot \vec{s}_{vv} \quad (6)$$

At a point on the surface, the values of the fundamental magnitudes are fixed, but the normal curvature has different values depending on the direction of the normal plane through the point. The direction depends on the ratio dv/du, and if both the numerator and denominator of equation 4 are divided by du2 an expression for the normal curvature in terms of dv/du results.

$$\kappa = \frac{L + 2M\frac{\mathrm{d}v}{\mathrm{d}u} + N\left(\frac{\mathrm{d}v}{\mathrm{d}u}\right)^2}{E + 2F\frac{\mathrm{d}v}{\mathrm{d}u} + G\left(\frac{\mathrm{d}v}{\mathrm{d}u}\right)^2} \quad (7)$$

TruSurf uses a cutting vector orthogonal to both the surface normal and the surface tangent. Figure 6 illustrates how the cutting direction is obtained by showing a single layer of a model. Solid contours represent the path that would be cut by the cutting vector. These may or may not lie on the B-spline model surface. The dashed line is the contour calculated from the B-spline surface model, and is located midway between the top and bottom surfaces of each layer. This position was chosen to give the average slope over the layer. At points around the contour, the direction of the cutting vector is found by computing the cross product of the surface normal and the tangent vector. For a more detailed description of TruSurf's layer slicing method see Hope et al (1997).

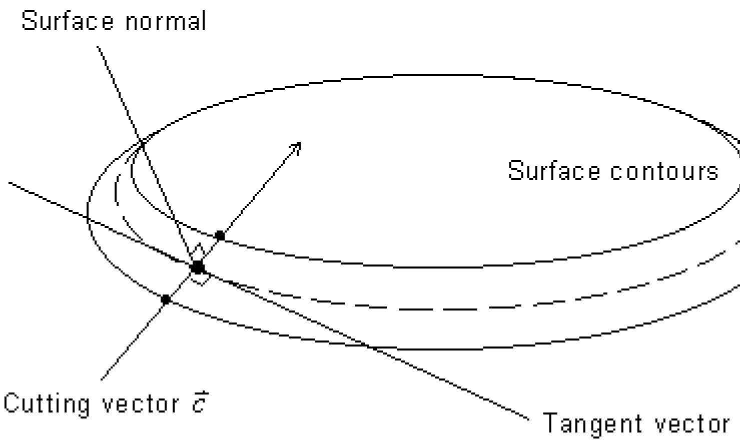


Figure 6. TruSurf uses a single interpolated contour, and the surface normal and tangent to calculate the cutting vector .

Since the cutting vector , and the partial derivatives of the surface and are known in three dimensional space, the value of dv/du can be found by solving the following vector equation

$$\vec{c} = \vec{s}_u du + \vec{s}_v dv \quad (8)$$

MATERIAL TOLERANCE

In many cases the boundaries of a prototype will need to be either fully inside, or fully outside, the boundaries of the original CAD model. For example, if finishing procedures remove material from the prototype surface, it is best to have cusps of extra material. Conversely if a coating, or filling material, is to be applied to the surface of the prototype it would be desirable to have cusps of missing material. TruSurf traces contours, and determines the direction and slope of the cutting vector, at the mid point of a layer. In doing so, the cutting vector always meets the CAD model at the mid point of each layer. When a concave CAD surface is sliced, extra material is removed from the top and bottom of the layer, while for a convex surface extra material is left on the manufactured object.

The slicing positions TruSurf would normally use for a CAD surface with a concave and a convex section is shown in Figure 7(a). Figure 7(b) shows the case when the prototype surface is to be always outside of the original CAD surface. Here the outside tolerance is the specified cusp height, and the inside tolerance is zero. This is the same as OUTTOL in the APT (Automated Programming Tool) language (IBM, 1972). Figure 7(c) shows the case when the prototype surface is to be always inside of the original CAD surface. Here the outside tolerance is zero, and the inside tolerance is the specified cusp height, INTOL in APT. Figure 7(d) shows a slicing method that positions the cutting vector midway between the positions in figure 7(b) and 7(c). In this case both the inside and outside tolerances are equal to half of the specified cusp height, resulting in the cutting vector being closer to the CAD model and minimising the error.

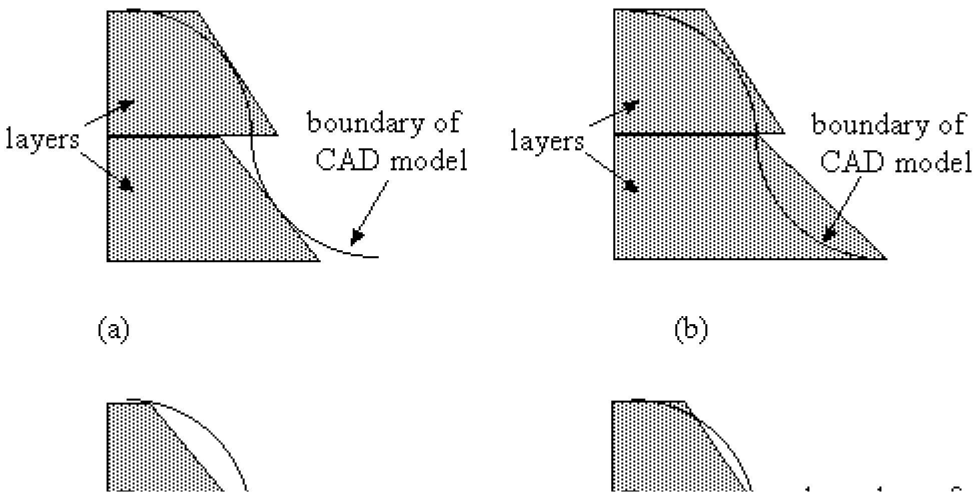


Figure 7.

(a) Normal slicing position.

(b) Tolerance all outside (OUTTOL).

(c) Tolerance all inside (INTOL).

(d) Combination of inside and outside tolerance resulting in minimum error.

To achieve these other slicing methods, TruSurf uses the predicted maximum difference in the layer plane to adjust the position of the cutting vector. For the outside tolerance condition and a concave surface, the cutting vector is moved out by a distance equal to the maximum difference in the layer plane. Conversely for the inside tolerance condition, the cutting vector is moved in when the surface is convex. For the minimum error condition the cutting vector is moved in, or out, by half of the maximum difference in the layer plane, depending on the sign of the curvature. The direction of adjustment is given by the component of the surface normal in the layer plane.

SOFTWARE IMPLEMENTATION

The TruSurf system was implemented in C++ as a stand alone program and operates independently from a CAD system. It can handle multiple surfaces from the one IGES file to define a part. First, TruSurf reads the IGES file and stores the B-spline surfaces in memory. It checks the surfaces to find their maximum and minimum dimensions in each of the x, y, and z directions. This information is displayed to the user, and they may select the orientation of the slicing plane with respect to the CAD model. If adaptive slicing is to be used, a choice between using the cusp height or difference in the layer plane as the measure of error is offered. The maximum allowable layer error can also be specified. TruSurf slices the model by tracing surface contours and computing the cutting direction at a number of points, specified by the user, around the contour. These points and corresponding cutting vectors are used to create Numerical Control (NC) code for the machine that will be used to cut the layers.

When adaptive slicing is used the curvature is also calculated at each point and an estimate of the error is determined. If this error is greater than the maximum specified, the layer thickness is reduced and the contour is traced at the new height. Similarly if the error is less than that specified, the layer thickness is increased and another estimate of error is made. Since TruSurf performs its calculations at the mid-height of a layer, the point of calculation changes with the layer thickness. Thus, the error can only be predicted for the current layer thickness and, if it is unacceptable the thickness must be changed and the error recalculated at the new level. TruSurf does not select a layer thickness to exactly produce the given error, but rather uses a database of layer thicknesses matching the modeling material available to the user. The choice is determined as the largest layer thickness that will produce an error less than the specified maximum.

SURFACE JOINS AND VERTICES

For a CAD model consisting of more than one surface, the surface joins have to be treated as special cases. Vertices and distinct changes in surface curvature are often present at the transition from one surface to another, and at these points, the local circular approximation of the surface is not unique. Figure 8 shows a vertex with the circular approximation at point P. The curvature at point P would lead to a layer thickness of t being selected (as shown). However, this thickness produces an unacceptable error.

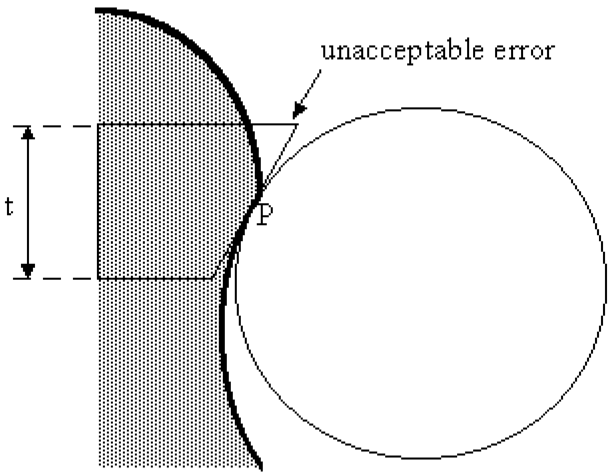


Figure 8. Thickness t produces an unacceptable error due to the presence of a vertex near P.

Kulkarni and Dutta (1996) rectify this problem by slicing the model so that the surface joins coincide with layer joins. This works for their slicing procedure because they have not limited themselves to any specific layer thicknesses. For TruSurf a layer thickness from the database, or combination of layer thicknesses, may not exist to exactly match the surface join. If the closest combination of layer thicknesses is used, it has to be accepted that a larger error than that specified may occur. Alternatively a special piece of layered material would need to be made to the exact thickness.

Another problem with trying to match the surface and layer joins is that in a large number of cases the surface joins are not in the layer plane. Hence for these cases there is no one thickness that will meet with the surface join at all points. Consider a bolt with a simple triangular thread. Since the threads are angled across the layer plane, vertices will be present in the layer no matter what thickness is used. Using the curvature to estimate error does not work in this case, as the triangular threads have zero curvature. For situations such as this, there appears to be no simple way to accurately approximate the error and it will be necessary to calculate the error exactly. This will require a more detailed calculation of the intersection curve between the surface and the vertical normal plane and, although this will increase the accuracy of adaptive slicing, it will also significantly increase the time taken by a computer to slice a CAD model.

CASE STUDY

To investigate the performance of adaptive slicing, and the accuracy of the error approximation, some example objects were tested in TruSurf. Figure 9 shows a symmetrical part consisting of three surfaces of revolution, with a total part height of 200 mm. The bottom surface is a revolved spline curve, the middle surface is conic, and the top surface is a hemi-sphere. A rotated shape was used so that the actual difference in the layer plane could be easily calculated. For a surface constructed from a rotated curve one of the B-Spline parameters remains constant along that curve. Thus for this type of surface, at any point P on the surface contour, all the other points in the normal section have a constant B-Spline parameter. Using this fact, the points where the normal section intersects the layer on the top and bottom can be calculated and then compared to the points where the cutting vector intersects the layer. The difference between these points is the actual difference in the layer plane. The reason this actual measure of error is not normally used in TruSurf is because it is designed to handle more general shapes, where the actual difference in the layer plane can not be calculated so easily and an approximation must be made.

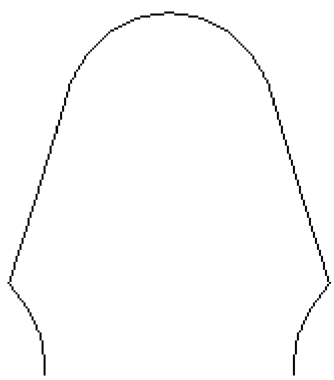
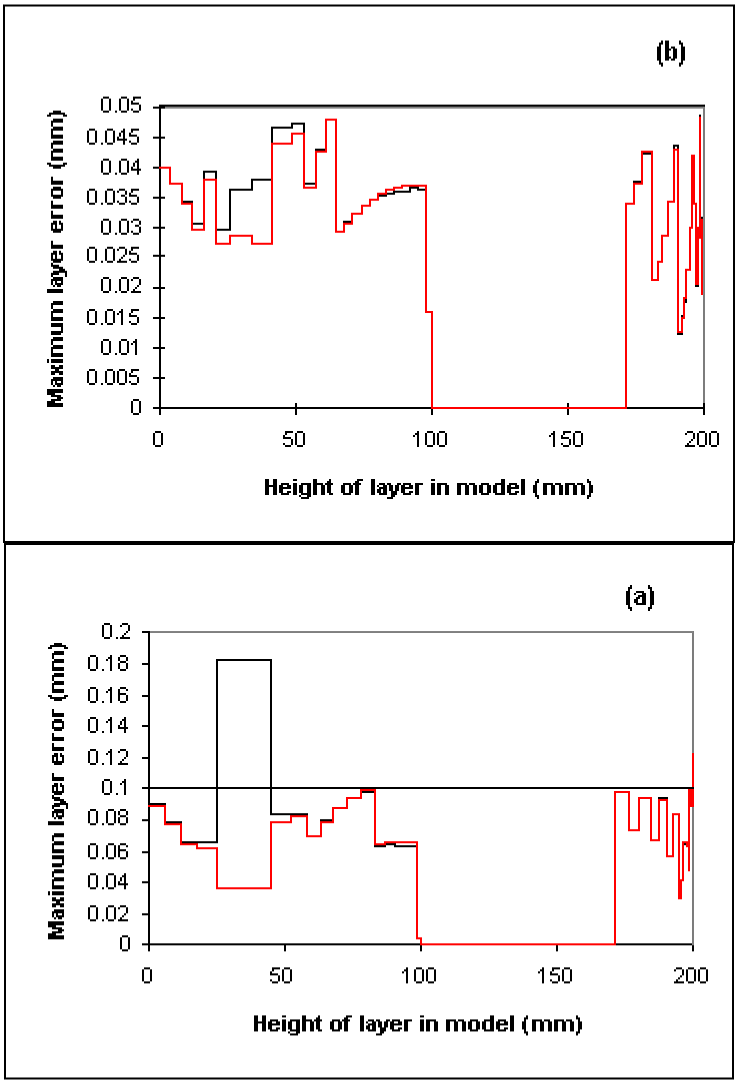


Figure 9. Sample part tested in TruSurf.

Due to the difficulty of calculating the actual cusp height, only the difference in the layer plane was used to make a comparison between the predicted error and the actual error. The graphs in figure 10 compare the predicted and actual difference in the layer plane for three different settings of the maximum allowable error. As expected, the number of layers required to build the part increases as the maximum allowable error is decreased. The number of layers used will also depend on the range of thicknesses in the database. This raises the question of what constitutes a good selection of layers. The answer will depend on part geometry, and probably be restricted by what is commercially available. For simplicity only one database was used in all three cases, and it had layer thicknesses ranging from 0.2mm to 70mm. It should be noted that surfaces such as the conic region, with zero curvature in the cutting direction, can be generated perfectly regardless of layer thickness. In this case the maximum available layer thickness (70mm) was used.



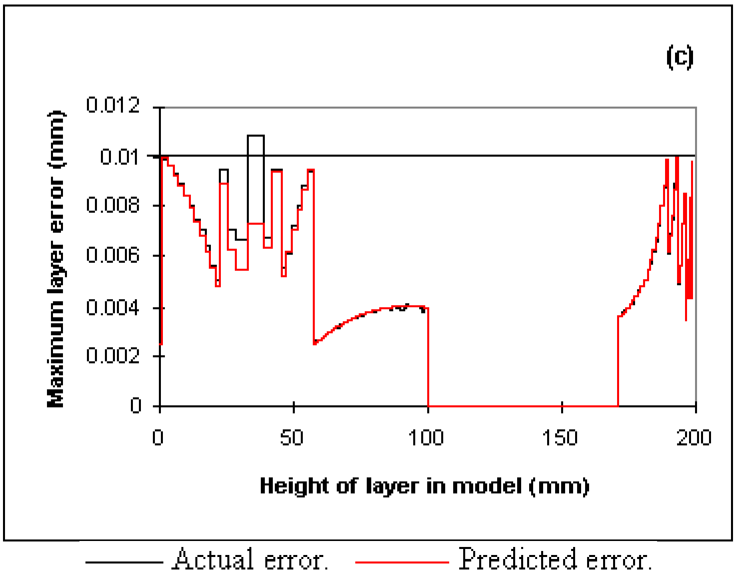


Figure 10. Maximum predicted and actual errors resulting from the body of revolution in figure 9 being tested in TruSurf.

(a) maximum allowable error set to 0.1mm, 34 layers used.

(b) maximum allowable error set to 0.05mm, 49 layers used.

(c) maximum allowable error set to 0.01mm, 113 layers used.

For most of the part the predicted error is a very good approximation. In fact for the conical and spherical regions the error is predicted exactly. In the first three graphs there is a section just below the 50mm level where the measured error is significantly greater than the predicted error. This corresponds to an inflection point on the model where the curvature changes sign. The difference is greatest in 10(a), with the measured error almost twice that allowable. In 10 (b) the measured error does not exceed the limit, and in 10(c) the limit is only slightly exceeded. However the fact that the actual error is significantly greater than the predicted error indicates that the method of predicting the error breaks down near inflection points. This is because the curvature is zero at the inflection point and very small nearby, but becomes larger further away. Thus when the curvature is calculated in the middle of the layer, the presence of an inflection point will cause the value of the curvature at the outer edges of the layer to be greater than those in the middle.

To further investigate the effect of inflection points, the surface model shown in figure 11 was tested in TruSurf, with the maximum allowable error set to 0.1mm. This surface has ten inflection points, all at a different rate of change of curvature. The predicted and actual layer errors for the part are shown in figure 12(a). From the graph it can be seen that the actual error exceeded the maximum allowable error on four layers. There were also six other occasions where the actual error was about twice that predicted, but still remained below the allowable level. On comparing these layers with the original CAD model it was confirmed that an inflection point occurred within all the layers. It was also noted that the actual error only exceeded that allowable when the predicted error was greater than half the allowable level.

Figure 11. Surface model tested in TruSurf to investigate the effect of inflection points.

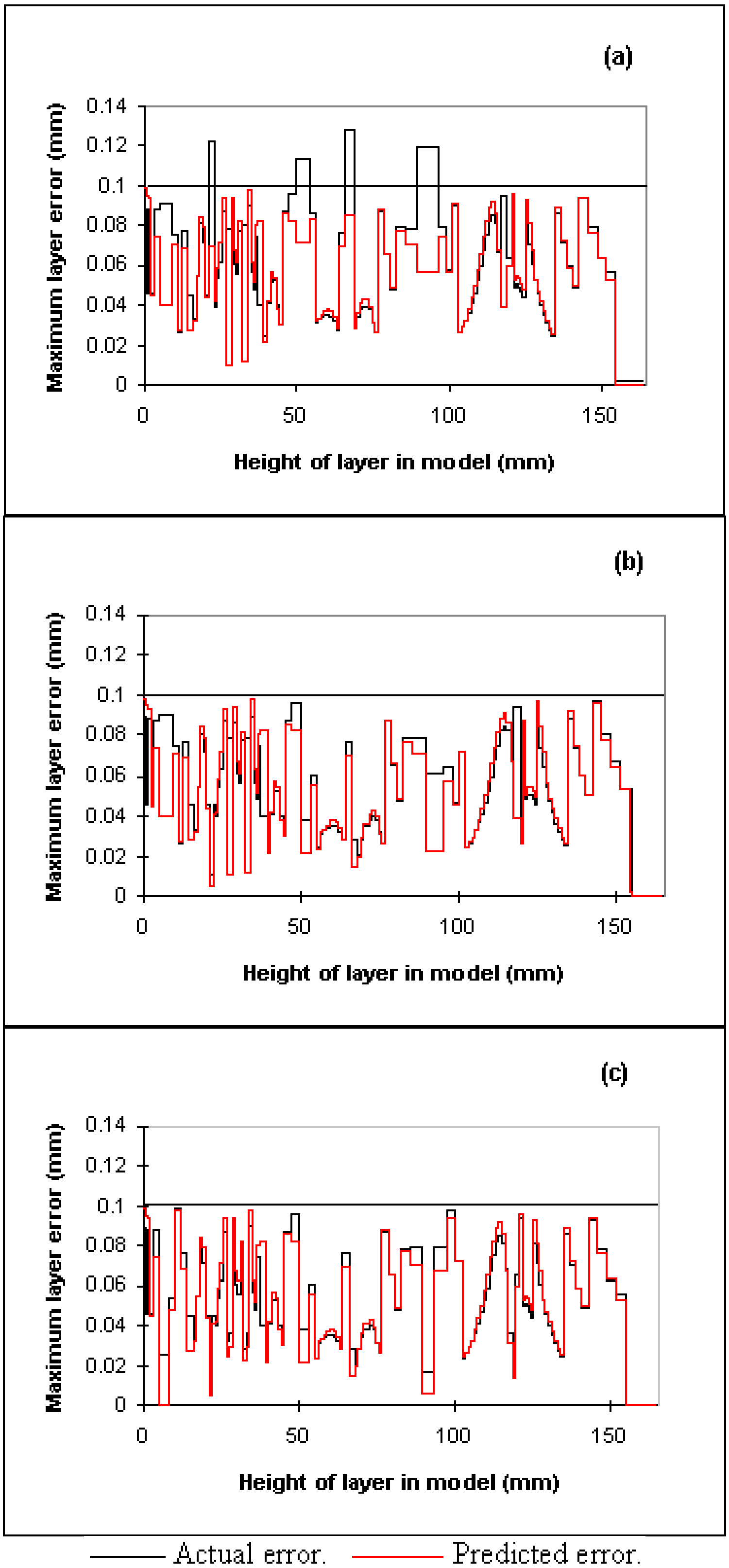


Figure 12. Maximum predicted and actual errors resulting from the surface model shown in figure 11 being tested in TruSurf, with the maximum allowable error set to 0.1mm.

(a) no adjustment made at inflection points, 109 layers used.

(b) allowable error halved where inflection points occur, 113 layers used.

(c) curvature checked at the top and bottom of the layers where inflection points occur, 116 layers used.

A simple solution to this problem is to identify when an inflection point occurs within a layer and to reduce the allowable error for that layer. In TruSurf, inflection points on the surface model can be identified by noting the change in sign of the curvature. This was implemented in TruSurf, and the CAD model shown in figure 11 was tested again. For this trial it was decided to halve the allowable error where inflection points occurred. The results are shown in figure 12(b). It can be seen that this time the actual error remained below the allowable level for every layer. This simple solution will work in most cases, and further reducing the allowable error at inflection points will decrease the chances of unacceptable errors occurring. However, it is not a robust solution as it does not guarantee the error will remain below the given limit.

A more robust solution is to calculate the curvatures at the top and bottom of the layer as well as in the middle. The error can then be estimated from the maximum of the three curvatures, which will be furthest away from the inflection point. This would only be done if an inflection point occurs within the layer. If it were done for all layers, the slicing time would be more than doubled. This procedure was also implemented in TruSurf, and the CAD model shown in figure 11 was tested once more. The results are shown in figure 12(c). As with figure 12(b) the actual error remained below the allowable level for every layer, but this time the predicted error was generally closer to the actual error. Due to the error being estimated from the maximum of the three curvatures, sometimes thinner layers than could have been used were selected when inflection points occurred within a layer. This resulted in three more layers being used than in figure 12(b).

CONCLUDING REMARKS

A method, based on surface curvature and angle of the surface normal, was developed to predict the difference between a sliced model and the original CAD model when the layers have sloping boundary surfaces. This was used in an adaptive slicing procedure to optimise the building of layered parts for both speed and accuracy. Provisions were also made to allow parts to be produced with either an INTOL, OUTTOL, or a combination of both to reduce overall error.

Inflection points were found to cause the predicted difference to be significantly less than the actual difference. Two procedures were trialed to account for the presence of inflection points. In the first, the allowable error was halved for layers where they occurred. In the second the curvature was calculated at the top, bottom, and middle of layers where they occurred, and the maximum of the three used to determine the layer thickness. The first procedure was seen to work in most cases, and the second procedure was found to be a more robust solution to the problem.

It was noted that joins between two or more surfaces can cause the error approximation to give incorrect results. For cases when the surface joins are in the same plane as the layers this problem can be solved by slicing the part so that the surface joins coincide with layer joins. However in many cases where a part is defined by two intersecting surfaces, the intersection curve is not in the layer plane. No simple solution was found for this situation. It appears that further work is required to enable a more detailed calculation of the intersection curve between the surface and the vertical normal plane. This will enable the measures of error to be calculated exactly, but will also significantly increase the time taken for models to be sliced by computer.

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