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REVIEW PAPER: ANALYSIS OF DATA TRANSFORMATION IN RAPID PROTOTYPING TECHNOLOGY

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Abstract

Layered manufacturing (LM) machines use stereolithography (STL) files to build parts by creating continuous slices on top of each other. An STL file approximates the surface of a part with planar triangles. This results in geometric errors being introduced in the part surface during the conversion from the CAD model to the STL file format, which in turn leads to errors in the LM manufactured part. CAD packages have built-in export options to reduce this CAD to STL conversion error. However, this is applied to the entire part geometry which leads to an increase in the file size and pre-processing time in LM machines. This paper presents a new approach to locally reduce this CAD to STL translation error. This approach, referred to as vertex translation algorithm (VTA), compares an STL facet to its corresponding CAD surface, computes the chordal error at multiple points on the STL surface, and translates the point with the maximum chordal error until it lies on the design surface. This translation results in the reduction of the chordal error locally without unnecessarily increasing the size of the STL file. In addition, a facet isolation algorithm (FIA) has also been developed and presented in this paper. This isolation algorithm extracts the STL facets corresponding to the surfaces and features of the part that have to be modified by the translation algorithm. The VTA is applied in conjunction with the FIA on a sample service part to reduce the form and profile error of critical features of the part in order to satisfy the tolerance callouts on the part.

Keywords: layered manufacturing (LM), STL file, vertex translation algorithm (VTA), facet isolation algorithm (FIA), chordal error, form error, profile error

1. Introduction

RP process belong to the generative (or additive) production processes unlike subtractive or forming processes such as lathing, milling, grinding or coining etc. in which form is shaped by material removal or plastic deformation. In all commercial RP processes, the part is fabricated by deposition of layers contoured in a (x-y) plane two dimensionally. The third dimension (z) results from single layers being stacked up on top of each other, but not as a continuous z-coordinate. Therefore, the prototypes are very exact on the x-y plane but have stair-stepping effect in z-direction. If model is deposited with very fine layers, i.e., smaller z-stepping, model looks like original. RP can be classified into two fundamental process steps namely generation of mathematical layer information and generation of physical layer model. Typical process chain of various RP systems is shown in figure 1. It can be seen from figure 1 that process starts with 3D modeling of the product and then STL file is exported by tessellating the geometric 3D model. In tessellation various surfaces of a CAD model are piecewise approximated by a series of triangles and co-ordinate of vertices of triangles and their surface normals are listed. The number and size of triangles are decided by facet deviation or chordal error as shown in figure. These STL files are checked for defects like flip triangles, missing facets, overlapping facets, dangling edges or faces etc. and are repaired if found faultyDefect free STL files are used as an input to various slicing softwares. At this stage choice of part deposition orientation is the most important factor as part building time, surface quality, amount of support structures, cost etc. are influenced. Once part deposition orientation is decided and slice thickness is selected, tessellated model is sliced and the generated data in standard data formats like SLC (stereolithography contour) or CLI (common layer interface) is stored

***Rapid Prototyping Processes*:**Rapid Prototyping (RP) technologies such as Stereolithography (SLA), Selective Laser Sintering (SLS), Laminating Object Manufacturing (LOM), Three Dimension Printing (3D printing), etc have been developed since mid 1980s. It is a technology that directly generates physical objects from CAD databases. They have a common important feature: the prototype is produced by adding materials rather then removing materials. This simplifies the 3D object producing process to a 2D layer adding processes such that an object can be produced directly from its computer model . An object is first designed by a CAD system like solid modeler, and then the solid model built-in tessellation algorithm creates a simple boundary representation that covers the surface of the solid with triangles. This structure is named .STL file format. Each triangle is described by an outward normal vector and the coordinates of three vertices. Such triangular meshes stored in STL format are used as definitions of geometry of real solids for several industrial applications, and also for RP and manufacturing. A mesh is then sliced into a series of parallel layers. The layers can be manufactured by different techniques . After slicing solid model to layers, RP machines start to build the part. Because of the nature of Some RP methods, these methods need support structure such as SLA. Some STL files have errors in triangle tessellation such as facet missing, incorrect normal vector, gaps, non- manifold and other errors will be described in the latter section

2. Literature Review

The STL file format is the standard input to all LM machines. However, the STL file is prone to several drawbacks, such as missing geometry, redundant information, and lack of manufacturing data. Several researchers have studied ways to eliminate the STL file errors and this section presents some of the relevant research carried out in this area. The errors in the STL file together with the staircase effect lead to profile and form errors in LM manufactured parts. The calculations of profile and form errors have also been researched before and some of the published research has been presented here.

2.1 STL File Format Errors and Modification: The STL format approximates the design surface by a series of triangular facets. It lacks any topological information and can exist in both binary and ASCII formats. Although the STL file format is an accepted industry standard, it may suffer from certain shortcomings, such as gaps, missing and overlapping facets and non-manifold topology conditions. Leong et al. [10] studied these problems and provided a geometric solution to correct the missing facets. van Niekerk and Ehlers [11] divided STL errors into structural and geometrical errors and developed a mathematical approach to check the problems in an STL file and corrected them. They considered the errors in file structure, overlapping triangles, violation of vertex to vertex rule, incorrect direction of surface normal and violation of Euler's rule. Stroud and Xirouchakis [12] presented approaches towards improving the free form fabrication procesby using approximation control parameters and use of STL extensions. According to their study, STL format redundancy, incomplete description of geometry, coarse approximation method and inability to include manufacturing information were the main shortcomings of the STL file format. Fadel and Kirschman [9] explained the issues involved in tessellation and convex boundary error. Errors, such as missing lines, truncation errors, and reversa of normal direction due to incorrect order of vertices were explained. Lee et al. [13] proposed a methodology for generating an STL file from measured data points using a Delaunay triangulation approach. Lee and Kim [14] presented a methodology to obtain a deformed model from an STL model based on a user defined error criteria. They introduced a new STL data structure that involves searching and splitting the facets using Euler operators. The STL file was deformed on the basis of a certain user defined error criteria evaluated from the given constraints of the shape. To date, researchers have not looked into selectively modifying the existing STL format to minimize the CAD-STL translation errors associated with the different surfaces of the part. The current paper is an extension of the study on STL file modification by Navangul et al. [7,8] and presents a new algorithm which will seek to improve the STL file quality by locally modifying the STL facets in order to satisfy and minimize the chordal errors specified on the part.

3. Errors occurs in STL files:

When a CAD model is too complex then the number of facets in .STL file increases many enormously. Also, CAD systems may generate incorrect .STL files that do not obey the two rules described above, so it may cause a RP machine not to function properly and may cause an interruption in making the solid model. Several problems plague .STL files and they are due to the very nature of .STL files as they do not contain topological data. The most common occurring errors in STL files are as follow :

A) Incorrect normal vector

Tessellation of surfaces with large curvature can result in the wrong orientation of facets which in turn means not obeying the facet orientation rule.

B) Gaps (missing facets)

Tessellation of surfaces with large curvature can result in errors at the intersections between such surfaces, leaving gaps or holes along edges of the part model as shown in bold lines in Figure 1.

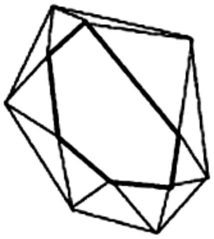


Fig 1: Missing facet example

C) Degenerate facets

A geometrical degeneracy of a facet occurs when all of the facet’s edges are collinear even though all its vertices are distinct. This might be caused by stitching algorithms that attempt to avoid shell punctures (Figure 2).

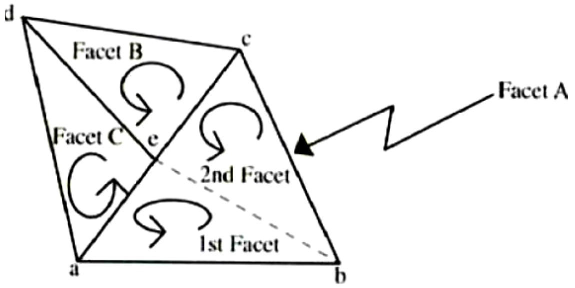


Fig 2: degenerate facets

D) Overlapping facets:

Overlapping facets may be generated due to numerical round-off errors during tessellation. The vertices are represented in 3-dimensional space as floating point numbers instead of integers. Thus the numerical round-off can cause facets to overlap if tolerances are set too liberally (Figure 3)

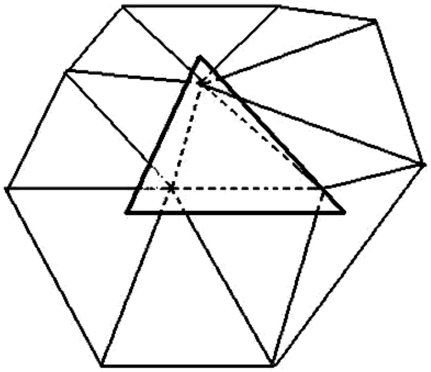
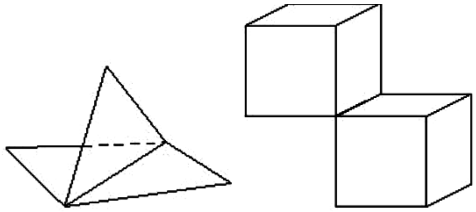


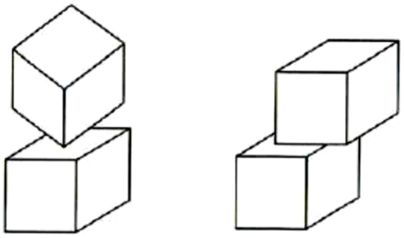
Fig 3: overlapping facets

E) Non-manifold conditions

When two parts of a model are tangent (as shown in figure 4) , some CAD systems will export an STL file with non-manifold facets, one edge of which will be shared by more than two adjacent facets .



(a) one edge adjacent to 3 facet



(b) (left)non-manifold vertex- (right) non-manifold facet

Fig 4: Non manifold facets

4. Problem Definition

Layered manufacturing (LM) is an emerging technology for manufacturing highly complex precision parts by creating contiguous slices on top of one another. The inputs that are required for manufacturing a part by the LM process are STL file, part orientation, slicing, support structures, tool path planning and materials . The stereolithography (STL) file format is the standard input for all LM machines and approximates the skin of the part using planar triangles. This approximation leads to geometric errors in the STL file when the part consists of curved surfaces. These geometric errors are propagated downstream in the manufacturing process and lead to surface inaccuracies and errors in LM parts. Although, alternate file formats and methodologies have been proposed to improve LM part accuracy , LM machines still use the standard STL file format as their input. Therefore, there is a definite need to improve the quality of the existing STL file format in order to minimize the loss of part information during CAD to STL conversion. This paper presents a new algorithm to selectively and locally modify the STL file to reduce the CAD-STL conversion errors with a view to achieving profile and form tolerances specified in the part design.

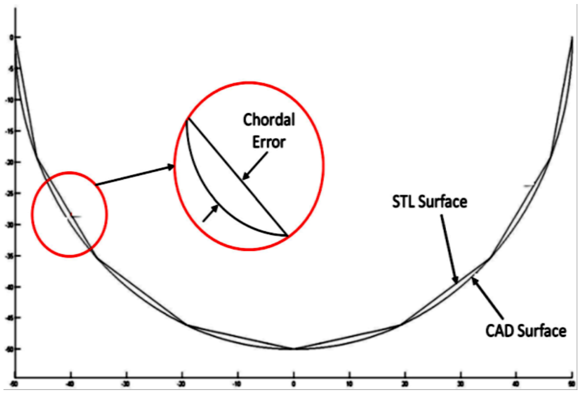


Fig. 1 Chordal error in an STL file

The CAD-STL translation error has been generally defined by LM researchers as a chordal error .which is the Euclidean distance between the STL facet and the CAD surface as shown in Fig. 5 Mathematically,

$$E_{ch}=\|P_{STL}-P_{CAD}\| \text{ ……………..…(1)}$$

Where, P_{STL} is a point on the STL facet and P_{CAD} is the corresponding point on the CAD surface. In the algorithm presented in this report, the chordal errors for multiple points on the STL facets are calculated and the point on an STL facet with the maximum chordal error is translated to coincide with the CAD surface. [2]

5. Methodology

The objective of the problem defined can be achieved

4.1 Vertex Translation Algorithm: The conversion of the CAD model to an STL file leads to surface errors due to the approximation of nonplanar surfaces by planar triangles [3,4,6]. This approximation, defined as chordal error, leads to the development of form, profile and volumetric errors in LM parts built from the STL file. This section introduces a new vertex translation algorithm (VTA) for reducing the chordal error of an STL file.

VTA Methodology: For developing the VTA, the surface is first modeled using any standard CAD package (in this case NX 7.5 from Siemens PLM) and then exported into two file formats, initial graphics exchange specification (IGES) and STL. IGES is a neutral file format that is widely used in the industry and can be used for extracting information about part surfaces stored within the native CAD file. In the IGES file, all surfaces whether they are planar or curved are stored as a NURBS surface. A NURBS surface can be written mathematically as

$$\mathbf{S(u,v)}= \frac{\sum_{i=0}^{m}\sum_{j=0}^{n} N_{i,p}(u)\, N_{j,q}(v)\, w_{i,j}\, CP_{i,j}}{\sum_{i=0}^{m}\sum_{j=0}^{n} N_{i,p}(u)\, N_{j,q}(v)\, w_{i,j}} \text{ ……..(2)}$$

where ,(u,v) are the parameters of the NURBS surface, (m,n) is the order of the NURBS surface, Ni,p and Nj,q are the basis functions, CPi,j are the control points, and $w_{i,j}$ are the weights. This NURBS surface is considered as the design surface in this paper and the STL file is compared with this NURBS surface for calculating the chordal error. The chordal error is calculated for an STL file and if the error is more than a certain user specified threshold, the VTA is applied on the STL file. The algorithm is applied iteratively on the STL surface until the chordal error threshold is satisfied. The algorithm is explained in detail in the following sections.[2]

1) Overall Methodology: The first step in the algorithm is to calculate the chordal errors at multiple points within an STL facet and then compute the maximum chordal error within the STL facet.

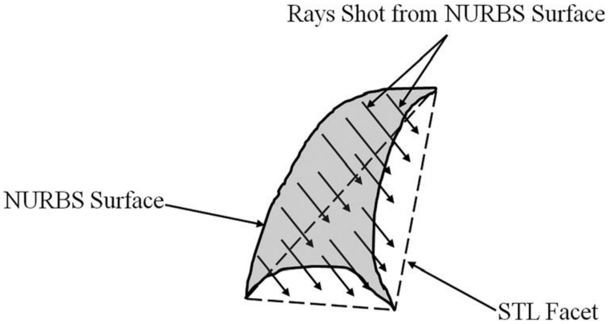


Fig. 6 Rays shot from NURBS surface to STL facet

The calculation of chordal errors at multiple points can be carried out as follows

1. Divide the STL triangle into multiple points, PSTL.
2. From each point on the STL facet, shoot rays along the direction of the normal of the facet.
3. Find the point of intersection of these rays with the NURBS design surface. This provides the points on the design surface, PCAD in 3D Euclidean space.
4. Calculate the Euclidean distance between PSTL and PCAD from Eq. (1) which provides the chordal error at the points PSTL on the STL facet.

However, the calculation of the point of intersection between a line and an NURBS surface, as required in step 3 above, is not straightforward. Therefore, in this paper, an alternate method has been adopted in which instead of shooting rays from the STL facet to the NURBS surface, the rays are shot from multiple points on the NURBS patch towards their corresponding points on the STL surface. The overall steps involved in this alternate method are

(1) Find the NURBS patch corresponding to an STL facet; this step is explained in detail in the next section.

(2) Divide this NURBS patch into multiple points, PCAD.

(3) Shoot rays from these points towards the STL facet parallel to the direction of the normal of the STL surface as shown in Fig. 6.

(4) Calculate the points of intersection of the rays with the STL facet, PSTL.

(5) Calculate the chordal error at the point PSTL from Eq. (1).

2) Calculating the Corresponding NURBS Patch: For calculating the NURBS patch corresponding to an STL facet, the u; v values of the three STL vertices are first calculated. In an STL file, the three vertices of the triangular facets always lie on the design NURBS surface , as shown in Fig. 6.

The Euclidean distance between any triangle vertex and its corresponding NURBS design point is ideally zero. Thus the problem of finding the u; v values for the triangular facet vertices that lie on the NURBS surface can be formulated as an unconstrained nonlinear optimization as shown below

$$\mathbf{Min\ f\ (u_i,v_i) = \left\| S(u_i,v_i)-P_i(x_i,y_i,z_i) \right\|}$$

$$\mathbf{0 \leq u_i \leq 1}$$

$$\mathbf{0 \leq v_i \leq 1 \qquad \ldots\ldots\ldots\ldots\ldots\ldots..(3)}$$

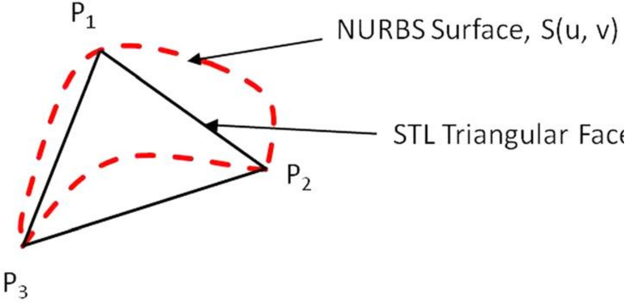


Fig. 7 STL vertices and CAD surface

Table 1. Lookup table for coarse optimization

X	**Y**	**Z**	**U**	**V**
50.33	**10.23**	**41.41**	**0.2**	**0.4**
65.00	**6.56**	**40.24**	**0.6**	**0.2**
45.78	**3.00**	**21.63**	**0.8**	**0.6**
-	-	-	-	-
-	-	-	-	-

where P_i (x_i,y_i,z_i) i=1,2,3 are the vertices of the triangle facet and $S_i(u_i,v_i)$ are the NURBS design points for the vertices. The optimization model in Eq. (3) is a nonlinear optimization and the final optimal solution depends upon the initial starting point for the optimization. Also, the time required for solving the optimization is effected by how close the initial guess is to the final optimal solution. Therefore, for ensuring a correct and fast solution, a coarse optimization is first performed to bring the initial starting point within the neighborhood of the probable optimal solution. In the coarse optimization step, the starting solution for the optimization model in Eq. (3) is calculated by using a lookup table.[2] The lookup table is generated by discretizing the u; v space of the CAD surface into finite number of values to form a grid and calculating the x; y; z Cartesian coordinates for each of these u; v values using Eq. (2). A sample lookup table is shown in Table 1. After the lookup table has been generated, the x; y; z coordinates in the lookup table closest to each STL vertex are chosen and the corresponding u; v values in the lookup table are selected as the starting solution for the fine optimization step. This optimization provides the final u; v parameter values for the three vertices of each STL facet and these u; v values describe the boundary of the NURBS surface patch corresponding to each STL facet.

3) Calculating Maximum Chordal Error in an STL Facet: Once the NURBS patch corresponding to the STL facet has been calculated, chordal errors at multiple points on the STL facet are calculated. The chordal errors are calculated by shooting rays from discrete points on the NURBS surface patch corresponding to an STL facet, as shown in Fig. 8. The discretization of the NURBS surface patch is performed using the following steps:

(1) Calculate the NURBS u; v parameters of the three vertices using the methodology described in Sec. 3.1.2. These u; v values form an analogous triangle in the u; v parameter space as shown in Fig. 10 (a) with vertices $S_1(u_1,v_1)$, $S_2(u_2,v_2)$ and $S_3(u_3,v_3)$

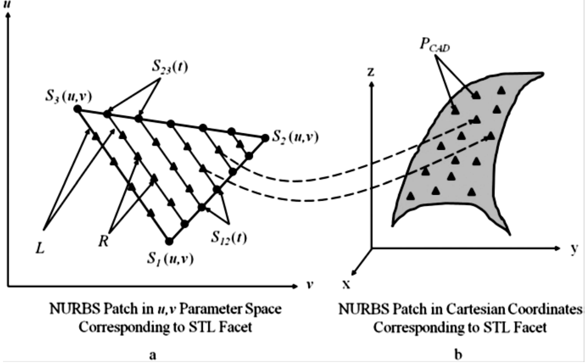


Fig. 8 (a) Division of the u; v triangle and (b) mapping to Cartesian coordinates

(2) Divide any two edges of the triangle into an equal number of points using the following formulas:

$$\mathbf{S_{12}\ (t) = S_1 + t.(S_2-S_1)}$$

$$\mathbf{S_{23}\ (t) = S_2 + t.(S_3-S_2)}$$

where t is varied between 0 and 1, i.e., t (0, 1). The values of the parameter t determine the number of points into which the edges will be divided and can be varied by the user according to his/her preferences.

(3) Connect the corresponding points on both the edges, S12 and S23 , and join these points to form connecting lines, L. These lines, L are then further

divided into points to obtain the point set R in the u; v parameter space using the formula

$R(s,t) = S_{12}(t) + s.(S_{23}(t) - S_{12}(t))$

where s is varied between 0 and 1, i.e., s (0,1). The value of the parameter s depends on the length of the line L and is varied such that the distance between any two points in the point set R remains constant.

(4) Calculate the points, P_{CAD} , on the NURBS patch in the Cartesian space corresponding to the discretized points R in the u; v space. The mapping of the points R in the u; v space to points P_{CAD} in the Cartesian space is shown in Fig. 10(b).

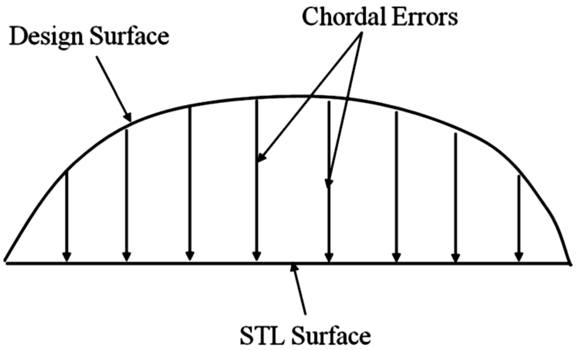


Fig. 9 Chordal errors at different points in an STL facet

Rays are then traced from these discretized NURBS points P_{CAD} parallel to the direction of the normal of the STL triangle until they intersect the STL facet. The points of intersection are denoted as P_{STL} and their Euclidean distances from the corresponding design points P_{CAD} provide the chordal error for the multiple points on the STL facet, as shown in Fig. 9. However,

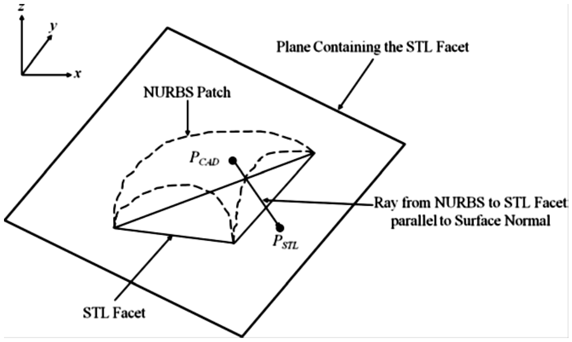


Fig. 10 Point of intersection outside the STL facet

There may be cases when the rays from the NURBS surface inter- sect the plane containing the STL facet outside the boundary of the STL triangle, as shown in Fig.12. These cases are eliminated by using a simple point in a polygon test .

After the chordal errors for different points in an STL triangle are calculated, the maximum chordal error ε_{ch-max} is chosen for the facet and the point on the STL facet with the maximum chordal error, PSTL _max is found. The Cartesian point on the NURBS surface corresponding to the maximum chordal error (PCAD_max) is also calculated.

4) Dividing the STL Facet: The average chordal error ε_{ch-avg} for the STL file is then calculated. The average chordal error is defined as the mean of the chordal errors of all discrete points on all triangular facets within the STL file. Mathematically, the average chordal error can be written as

$$\boldsymbol{\varepsilon_{ch-avg} = \frac{\sum_{i=0}^{nt}\sum_{j=0}^{n_i}(\varepsilon_{ch})_{i,j}}{\sum_{i=0}^{nt} n_i}}\ldots\ldots\ldots\ldots\ldots\ldots(4)$$

Where, $(\varepsilon_{ch})_{i,j}$ is the chordal error for the jth point on the ith triangular facet, n_i the number of points in the ith triangular facet, and n_t is the total number of triangular facets in the STL file corresponding to the NURBS surface or feature. If this average error is less than the user specified threshold chordal error specified for the surface ε_{ch-avg} , then the STL file is not modified.

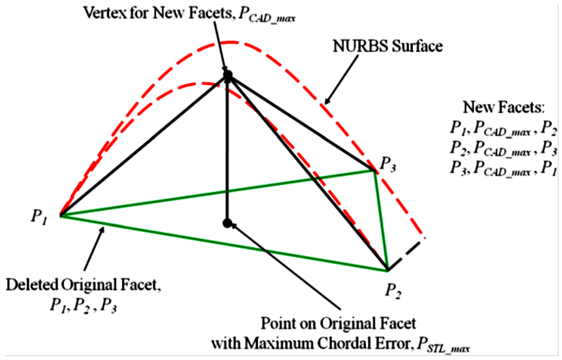


Fig. 11 Vertex translation to create new facets

Otherwise, for each facet in the STL file, the point within the facet which has the maximum chordal error, $P_{STL-MAX}$, is translated parallel to direction of the normal of the facet until it coincides with its corresponding design point, $P_{CAD-MAX}$, on the NURBS surface. Thus the point $P_{STL-MAX}$ forms the common vertex for three new STL triangles which are generated due to this translation, as shown in Fig13. . The original facet is deleted after the translation which results in a bottomless tetrahedral structure, i.e., the original facet P1 P2 P3 is replaced with three new triangles, P1 PCAD max P2 , P2 PCAD max P3 , and P3 PCAD max P1 . This translation results in the reduction in the maximum chordal error for the three new triangular facets as compared to the original triangle, as shown in Fig. 14. The original vertices and edges of the existing triangles are not removed which ensures that the connectivity of the new triangles with the neighboring triangles is not affected.

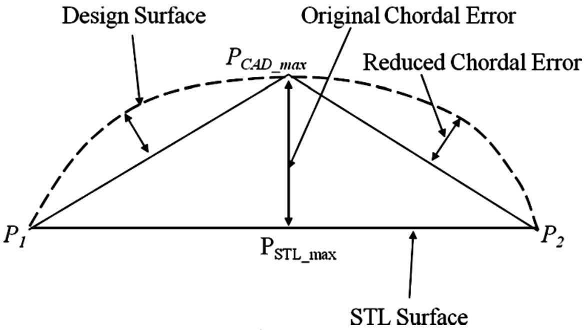


Fig. 12 Reduction of chordal error due to VTA

A special case may arise when the point with the maximum chordal error occurs on the edges of the STL facets. If such an edge point is translated to the CAD surface, the original edge of the triangle will be broken. This may create connectivity problems if this triangle facet is shared by two neighboring surfaces of the part. Since in this research, the edge connectivity between original and modified facets is kept unchanged, such edge points are discarded. Effectively, this means that any point in the set PSTL lying.

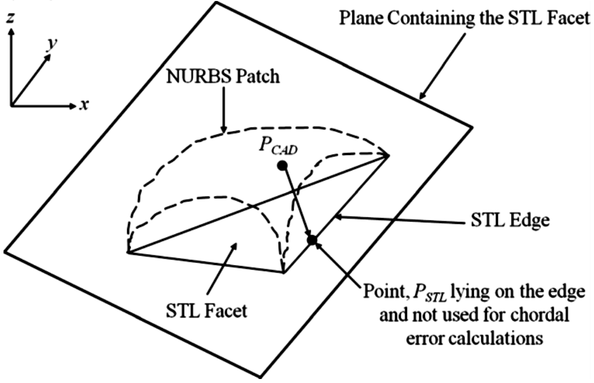


Fig. 13 Point with maximum chordal error lying on the edge of the STL triangle

On the STL triangle edges is not used in the chordal error calculations (as shown in Fig. 13) and only those points which lie within the boundary of the triangular facet are considered. This is a limitation of the current algorithm but does not seem to have any significant impact on the final results, as presented in later sections.Once the facets are modified by the VTA, they are combined to form a new modified STL file. The algorithm is applied iteratively until the average chordal error for the surface is less than the threshold chordal error. The next section presents two cases where the VTA was successfully applied to minimize the chordal error of two test surfaces.

6. Scope

Future work may involve modifying the slice contours by comparing the STL and NURBS slices to reduce the error locally at the slice level and rebuilding the modified STL files from the slice contours. Incorporating LM machine errors while modifying the STL file by the VTA can be another approach for minimizing the errors on the final part manufactured by the LM machine. Current STL files approximate the curved surfaces of a part with planar triangular facers. If these planar facets can be replaced wholly or partially by spherical or Bezier triangles, the chordal errors and by extension, form and profile errors, can be minimized drastically (VTA) modifies the STL file based on the chordal.

7. Conclusion

In this paper, a new algorithm for localized STL file modification has been presented. The algorithm named as the vertex translation algorithm error requirements by translating the point on each STL facet with the maximum chordal error to its corresponding design points. A facet isolating algorithm (FIA) was developed which isolates the STL facets corresponding to the surfaces being analyzed. The facets extracted from the FIA along with the specified error are used as an input to the VTA. The translation algorithm was applied successfully on two test surfaces and was able to reduce their chordal errors by 91.6% and 95.39%. In addition to the chordal error, the VTA was also applied to reduce the form and profile errors on critical features of a service part manufactured using an LM process. The VTA was able to reduce the cylindricity errors of a cylindrical feature by about 73.43% and the profile errors of two freeform surfaces by approximately 48% and 14%. The methodology developed in this paper will provide LM engineers a method for selectively modifying the STL file quality for achieving the required tolerances specified on the part features. This will eliminate the manufacturing of defective parts and reduce the time associated with producing parts in the LM process, thereby leading to reduced material expenditure and lower costs.

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