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I, Wentao Zha , hereby submit this original work as part of the requirements for the degree of Master of Science in Mechanical Engineering.

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Geometric Approaches to Input File (STL) Modification for Part Quality Improvement in Additive Manufacturing

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Geometric Approaches to Input File (STL) Modification for Part Quality Improvement in Additive Manufacturing

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ABSTRACT

Additive manufacturing (AM) machines use the Stereolithography (STL) file as standard input file format to build parts. STL model is a triangular faceted approximation of a CAD model which represents a part with less accuracy than the CAD model. Commercial softwares have the ability to convert a CAD file into an STL file based on a user defined threshold value to uniformly convert the entire part body into triangular facets. Increasing the geometric accuracy of STL models is typically accomplished by decreasing the user defined threshold value, which results in an increase in STL file size. In this research, a Surface-based Modification Algorithm (SMA) that adaptively and locally increases the facet density of an STL model is presented. The Surface-based Modification Algorithm is an error minimization approach to modify the STL facets locally based on chordal error, cusp height and cylindricity error for cylindrical features and is typically able to achieve a smaller file size compared to uniform export option. A novel bounding box based algorithm is developed to calculate cusp height error from the point cloud generated from the part by slicing the STL facets or from the CAD surface. Final results show a distinct improvement in the part error of the STL model using Surface-based Modification Algorithm (SMA) when compared to the original STL file.

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CHAPTER 1   INTRODUCTION

1.1   <u>Introduction</u>

Additive manufacturing (AM) refers to the manufacturing of parts by building thin slices and layering the slices on top of each other, as shown in Fig. 1. The Z axis is usually considered the build direction. AM machines use the Stereolithography (STL) file [1] as an input file format to build parts by different additive manufacturing processes.
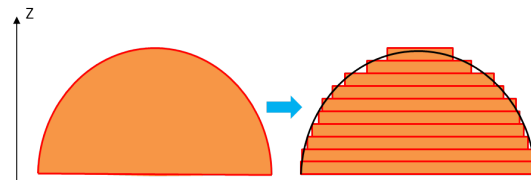
Figure 1: Slicing and part building in additive manufacturing.

Generally, three main stages exist in the additive manufacturing process planning. Modeling takes place in the first stage in which the geometric features of the part to be built are created and finalized virtually. The actual manufacturing process takes place in the second stage while the third stage concentrates on final finishing and post processing of the manufactured part such as external machining, hot isostatic pressing and heat treatment.

1.2   <u>Research Motivation</u>

Despite the reporting of modified STL file formats with curved-edge triangles [2] and recently introduced Additive manufacturing File format (AMF) [3], current commercial AM machines still use STL files as standard input file. The STL file has planar triangles tessellated from the CAD surface which introduces an approximation error, known as chordal error. Parts manufactured with STL file may also not satisfy Geometric Dimensioning & Tolerance (GD&T) requirements due to the approximated geometry. To increase the accuracy of CAD to STL conversion, there is a need to improve the quality of the existing STL file formats. Existing CAD packages export an STL file by globally increasing the density of STL file facets to reduce the CAD to STL approximation error. The denser STL facets leads to

a substantial increase in the overall STL file size, resulting in more computational burden, more pre-processing time and unnecessary increase in accuracy of some unimportant features. In order to minimize the CAD-STL approximation error, increasing the density of STL facets selectively and locally will result in minimizing geometric errors without unnecessary increase of file size.

This paper presents an approach to densify STL facets in areas that have critical GD&T error values, based on new patterns of facet formation that replaces the original STL facets. The modified STL file is then used to virtually build the part and verify that the part errors have been minimized per the GD&T callouts. The GD&T improvement is verified by collecting the point cloud data from the virtual build based on the modified STL file after the application of SMA.

CHAPTER 2 LITERATURE REVIEW

2.1   Additive Manufacturing

Additive manufacturing (AM), more commonly known as 3D Printing, refers to the manufacturing process which evolved from Rapid prototyping (RP) techniques [4]. The fundamental principle of additive manufacturing process is creating parts by generating contiguous layers on top of each other. An STL file generated from a CAD model is used as an input file for building a part during the AM process.

2.2   STL file format

The STL file format is supported by many software packages and is a standard input format for contemporary AM machines. STL file consists of triangular facet data (three vertices and an associated normal), which represents the 3D surface geometry of an actual CAD model. The basic rule used to check the correctness of the STL file is to ensure that each edge of a triangular facet is shared by only two facets at most [5].

(a)   (b)
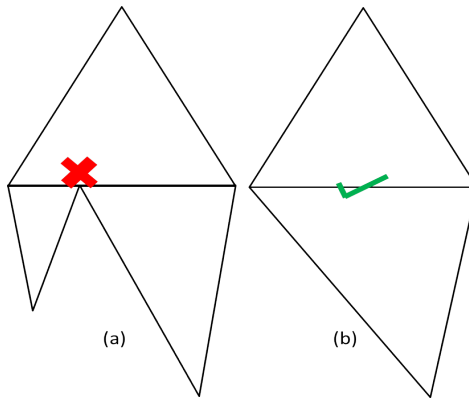
Figure 2: (a) Invalid STL and (b) valid STL facets (adapted from [5]).

As we can see, in Fig. 2a, one edge of the upper facet is shared by two lower facets at the same time, depicting an invalid STL model while Fig. 2b represents a valid STL model. The modified STL models generated using the Surface-based Modification Algorithm (SMA), introduced in later section, are always valid STL models.

The STL part model is sliced by slicing planes that are perpendicular to part build direction and manufactured layer by layer by AM machines [6].

2.3   Geometric error generated in CAD-STL conversion
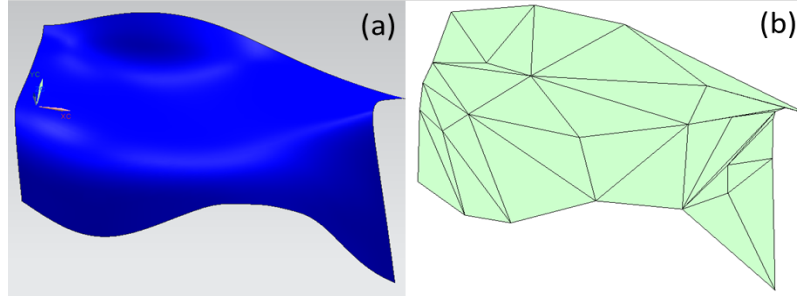
Figure 3: (a) The original CAD model and (b) exported STL model.

Fig. 3 shows the difference between a surface defined by the original CAD file and the converted STL file using Siemens NX 8.5 and with a 0.3 error threshold. The CAD-STL conversion error is defined as chordal error [7-9], which is the Euclidean distance between a point on the STL facet and the CAD surface along the direction of the normal of the STL facet [10], as shown in Fig. 4. The length of the black arrows on the right side of the figure represents chordal error of the point.
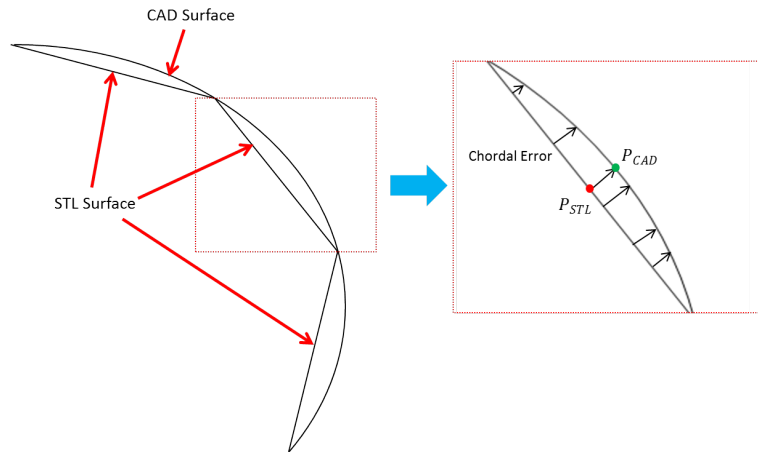
Figure 4: CAD-STL conversion error.

If P_{STL} is a point on the STL facet, $\overline{n_{STL}}$ is the normal to the facet and P_{CAD} is the corresponding point on the CAD surface based on the normal direction of P_{STL}, then the chordal error can be written as [11]:

$$\varepsilon_{ch} = \|P_{STL} - P_{CAD}\|$$

2.4   Previous STL File Local Modification Approach

Previously a Vertex Translation Algorithm (VTA) [10,11] was proposed to selectively modify the STL format part model with the goal of reducing chordal error of certain STL facets. For each facet, the Vertex Translation Algorithm (VTA) finds a point on the CAD surface with the largest value of chordal error from the facet and then replaces the original facet with three new facets based on the point, as shown in Fig. 5.
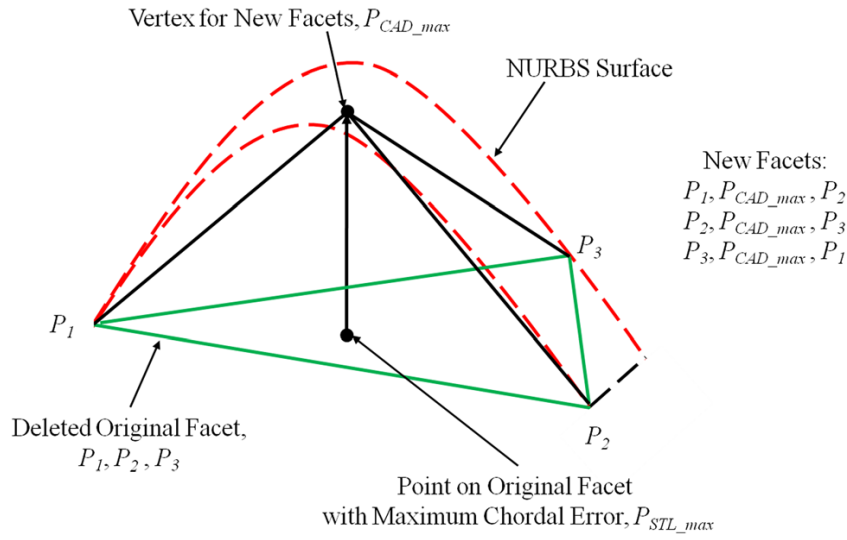
Figure 5: Vertex translation to create new facets [10].

The Vertex Translation Algorithm (VTA) was able to reduce the CAD-STL conversion error. Each iteration of VTA will reduce the error compared to the last iteration. However, quite a few iterations are usually required to satisfy some of the desired GD&T parameters and each iteration requires significant amount of computation time and results in increased file size.

The STL facetization pattern developed in Surface-based Modification Algorithm (SMA) performs better in decreasing GD&T errors and increasing overall part accuracy with lesser STL file size when compared to VTA.

CHAPTER 3   METHODOLOGY

The application of SMA file modification algorithm is based on evaluation of average cusp height and average chordal error (and cylindricity error for cylindrical features) of individual STL surfaces.

In Section 3.1, a bounding box based cusp height calculation method is introduced. Section 3.2 introduces the method of obtaining average chordal error of an STL surface and the illustration of Surface-based Modification Algorithm (SMA).

3.1   Cusp height calculation using a bounding box method

Cusp height is the staircase error generated in additive manufacturing process due to the 2.5D nature of layers (represented by the blue lines in Fig. 6). Cusp height also correlates with layer thickness.
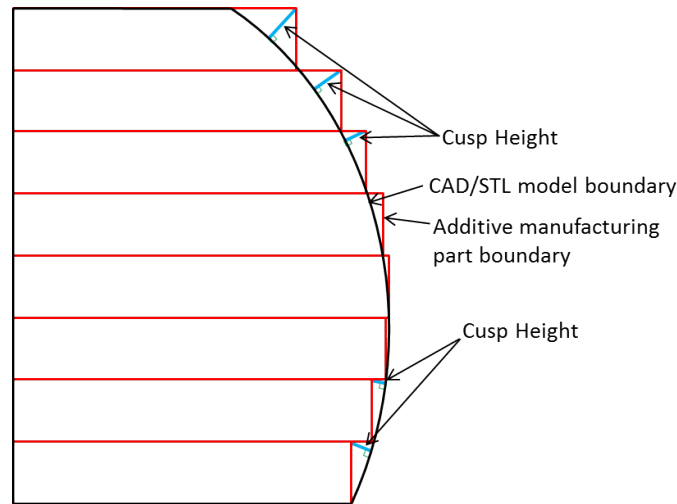
Figure 6: Cusp height error illustration.

A new cusp height calculation approach is presented that accurately reflects the geometric deviation of the manufactured part from the original model (either in CAD or STL format) at each slice level. The widely accepted cusp height calculation method [12] considers the angle between the STL facet normal and build axis to obtain the approximate cusp height. However, the value obtained is only approximate and will deviate from the actual cusp height value if the layer thickness is greater than the size of any of the facets in the STL model.

The proposed bounding box method utilizes point cloud from either the surface of the STL or the CAD model. If the point cloud is generated from CAD model, the cusp height calculated will represent a more accurate geometric deviation of the manufactured part from the original model since it bypasses the CAD-STL conversion stage.

The following are the detailed steps for calculation of cusp height using the bounding box approach:

Step 1: Evenly generate a point cloud based on the whole body surface of the STL model or CAD model (Fig. 7). All points generated will not only have Cartesian coordinate information, but also contain normal information that is perpendicular to the model surface and facing outwards.
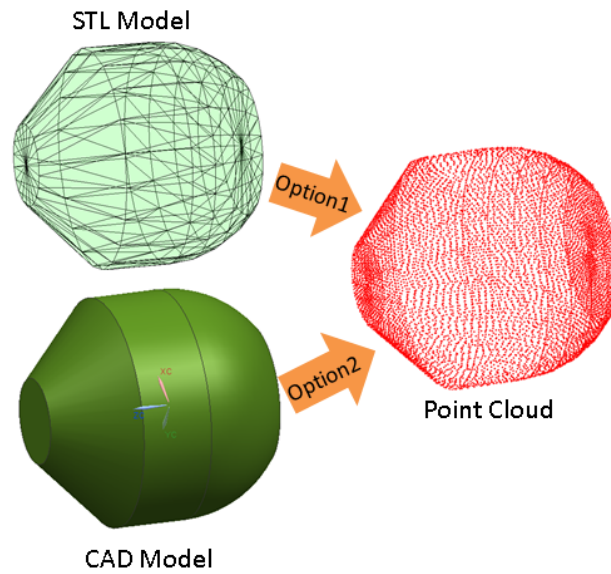
Figure 7: Generation of point cloud data.

Step 2: Slice the STL model perpendicular to the build orientation using the chosen slice thickness (Fig. 8). Each slicing plane intersects with multiple STL facets, resulting in two (or more) intersection points between each facet and the slicing plane.
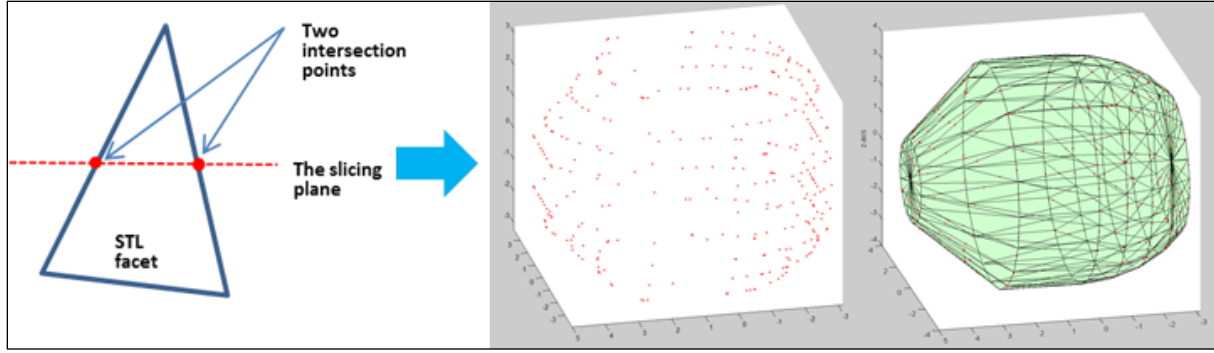
Figure 8: Intersection of slicing plane with STL facets.

Step 3: Create two bounding boxes based on the two intersection points P_1 and P_2 as shown in Fig. 9.

Two situations arise after creating the bounding boxes, as shown in Fig. 10. In the first case, the right bounding box will contain points generated from step 1 while the red one on the left is empty. In the second case, the left bounding box will contain points generated from step 1 while the red one on the right is empty. Thus, there is a need to always create two bounding boxes for the two intersection points between the slicing plane and an STL facet.
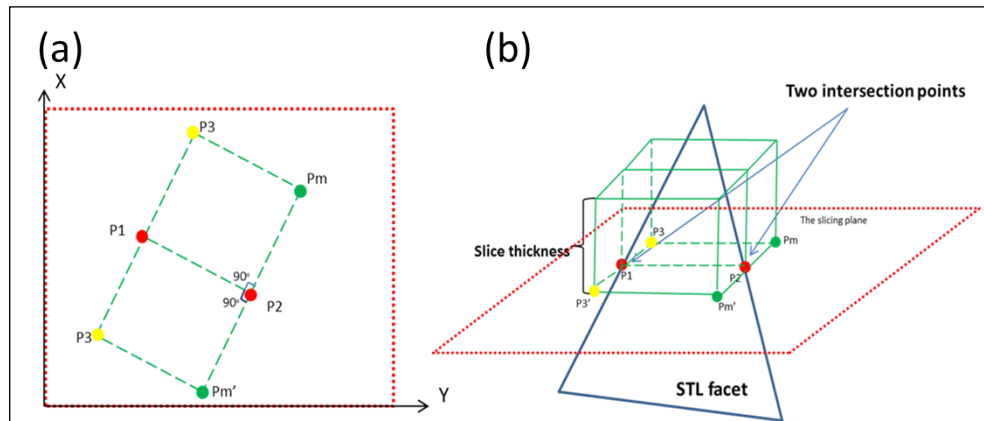
Figure 9: Creation of bounding boxes on slicing plane. (a) Top view and (b) Isometric view.

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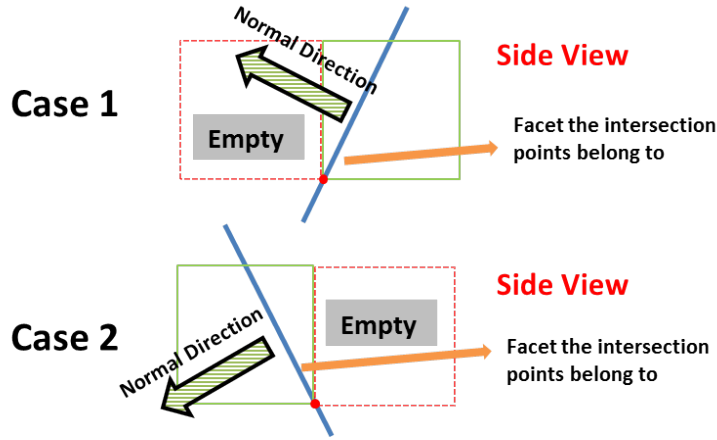
Figure 10: Creating of two bounding boxes on the slicing plane.

In Figure 9, based on P_1 and P_2, find a point P_m such that: (1) P_1P_2 and P_2P_m are perpendicular to each other. (2) The length P_2P_m is equal to slice thickness.

For each point P_m and $P_m{}'$, find the fourth point P_3 (or $P_3{}'$) such that $P_1P_2P_mP_3$ (and $P_1P_2P_m{}'P_3{}'$) form a rectangle.

For each of the two 2D rectangles, $P_1P_2P_mP_3$ and $P_1P_2P_m{}'P_3{}'$ in the XY plane, form a 3D bounding box by extruding it by the length of slice thickness in the Z direction, which simulates a slice in the AM process. Thus, two bounding boxes will be created every time a slicing plane intersects an STL facet.

Step 4: In this step, the cusp height calculation based on the bounding box is performed (Fig. 11).
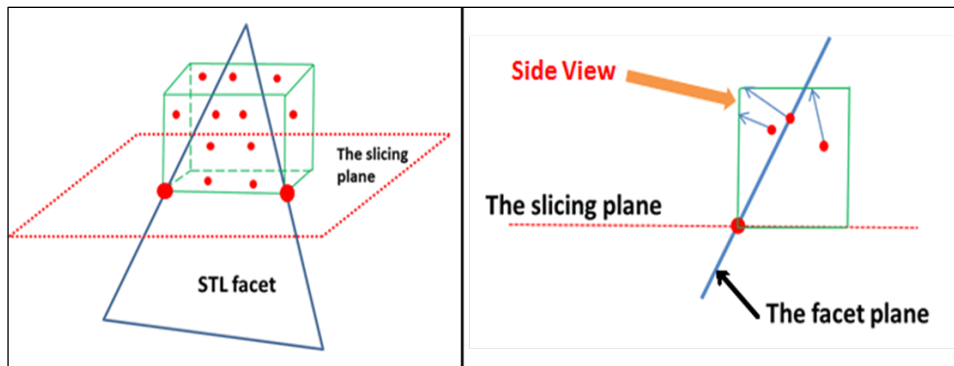
Figure 11: Cusp height calculation using the bounding box. (a) Isometric view and (b) side view.

For each bounding box, check if there are points from the point cloud generated in step 1 within it. If any, for each point, shoot a ray either in the normal direction or the reversed normal direction of the facet that the point belongs to, and calculate the distance between the point and the intersection point on the boundary (either face or edge) of the bounding box.

Sometimes, the normal direction for the point may be pointing in the opposite direction of cusp height. In this case, a reversed normal direction is required. Two of the four cases in Fig. 12 depict the need for reversed normal direction; cases 2 and 4 will need reversed normals.
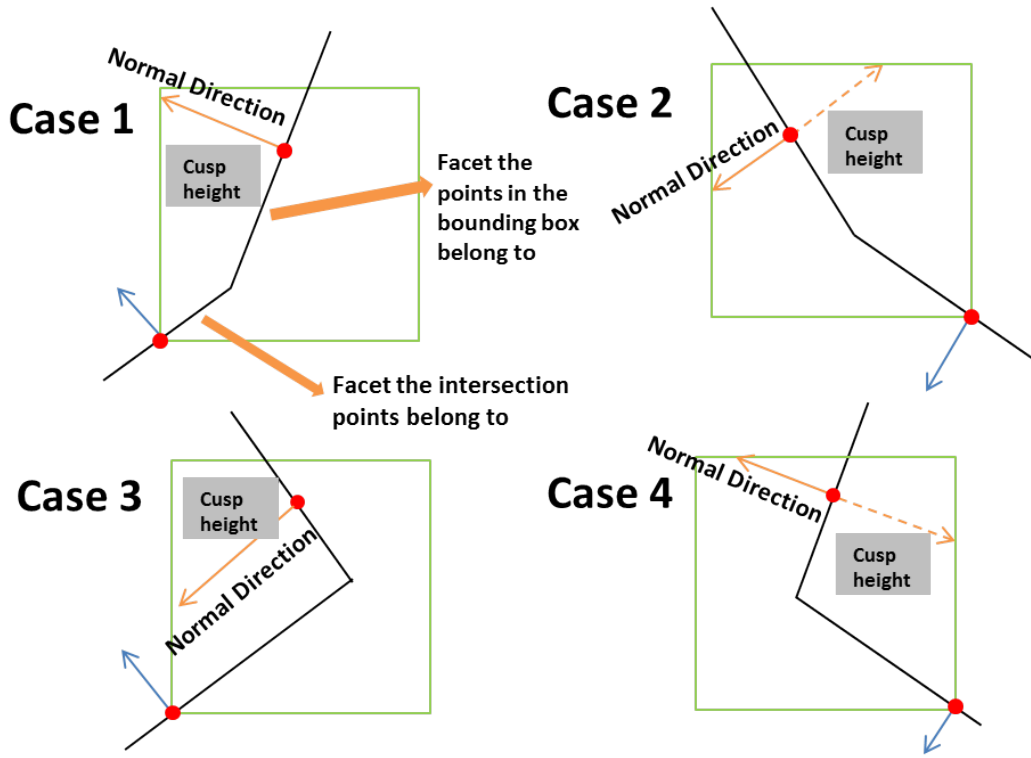
Figure 12: Normal and reverse normal ray tracing.

An example of a ray shooting direction along the facet normal or reversed facet normal is depicted in Fig. 13. In this figure, the slice thickness is intentionally set as a large value to depict the concept, and the point cloud generated in step 1 is shown as red points. The red arrows in both Fig. 13a and b indicate the normal direction. In the Fig. 13b, the ray (blue arrow) is projected in the opposite direction of the normal in order to obtain the correct cusp height.
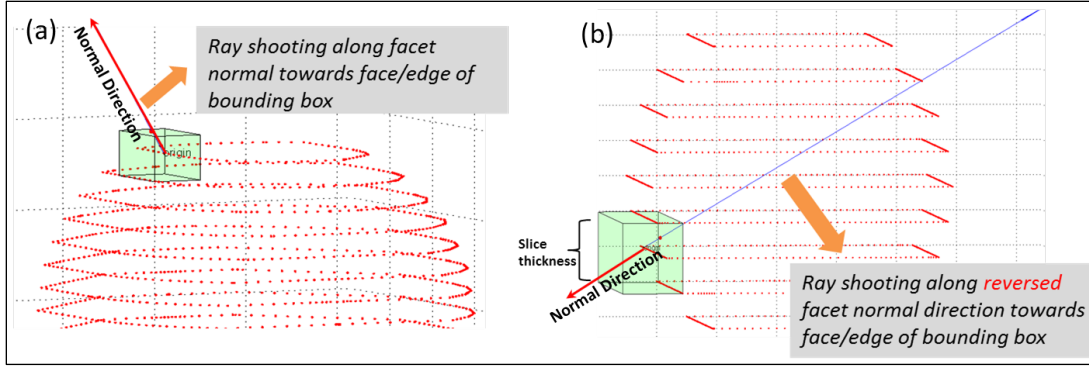
Figure 13: Depiction of ray tracing direction within the bounding box.

The maximum distance among all points in the bounding box will be recorded as the cusp height value of that bounding box. For all the bounding boxes at all the slicing levels, the maximum value of distance will be recorded as the maximum cusp height for the part. The average value among all bounding box cusp height values is considered to be average cusp height of the STL model.

Fig. 14a shows a graph of cusp height value at each slice level of the part (30 slices in total). Each red point in Fig. 14b represents the relative cusp height value from a bounding box at the corresponding Z slicing level.
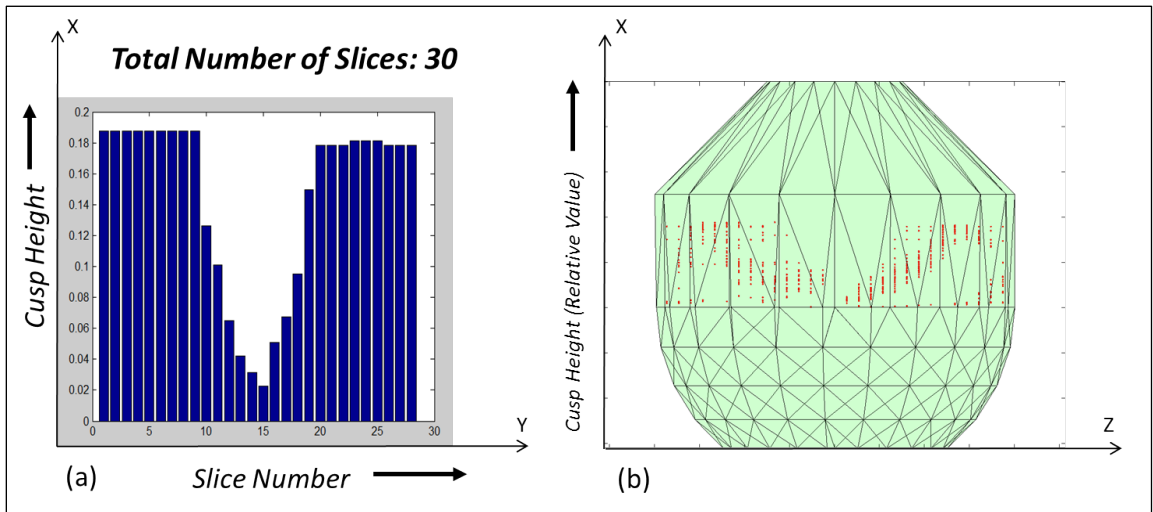
Figure 14: Plot of cusp height calculation at each slice.

3.2   Surface-based Modification Algorithm (SMA)

Surface-based Modification Algorithm (SMA) is a local STL facet densification algorithm that was developed with the main goal of increasing STL model geometric accuracy. The algorithm increases the number of facets in a local area in order to decrease the geometric deviation of the STL model locally compared to the original CAD model. Each of the local original STL facets modified by SMA will be replaced by a number of new facets.

The traditional approach to improve STL model profile quality is to set a smaller uniform export error threshold while converting the entire part CAD model into STL facets, which results in increase in the STL file size. The Surface-based Modification Algorithm (SMA) is surface specific, thus resulting in a localized increase in facet density compared to uniform export option.

3.2.1   Introduction to NURBS surface

Depending on the software vendor, various file formats of a CAD part model are available. Regardless of the exact format, the CAD part model (Siemens NX 8.5 is used in this work and the CAD file format is .prt) can be exported into a neutral format IGS. The IGS part model consists of a number of separated surfaces, each of which is represented by NURBS surface equation [13]:

$$S(u,v) = \frac{\sum_{i=0}^{m}\sum_{j=0}^{n} w_{i,j} P_{i,j} N_{i,p}(u) N_{j,q}(v)}{\sum_{i=0}^{m}\sum_{j=0}^{n} w_{i,j} N_{i,p}(u) N_{j,q}(v)}$$

Fig. 15a shows a basis surface in u, v parametric space and Fig. 15b shows the same surface in 3D Cartesian space. In Fig. 15a, the parameters lie in the range $u \in [0,1]$ and $v \in [0,1]$. NURBS surface is usually the trimmed version of the basis surface [14], thus the minimum and maximum u and v values of a NURBS surface might not necessarily be 0 and 1, but will still be within the [0,1] range.

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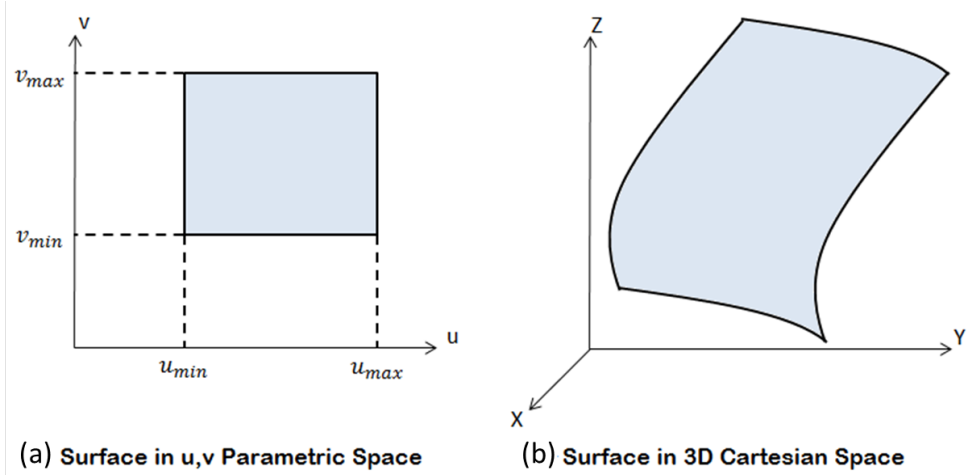
Figure 15: Basis surface in parametric space and Cartesian space.

The transformation from the u, v parametric space to 3D Cartesian space (or the other way around) is critical since the essence of SMA is replacing old STL facets by generating more STL vertices on the CAD surface and forming new STL facets to replace the original one. The new STL vertices are initially obtained in the u, v parametric representation. Once the u, v values of the new vertices are obtained, they are converted to x, y, z coordinates in order to write the vertices information into a new STL file.

The vertices of the STL facet lie on the NURBS surface in the u, v parametric space and should have zero distance with corresponding points represented by x, y, z Cartesian coordinates of the vertices [11]. Thus, the calculation of $S(u_i, v_i)$ or $P_i(x_i, y_i, z_i)$ points of the vertices can be formulated as a nonlinear optimization method below [11]:

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

$$0 \leq u_i \leq 1$$

$$0 \leq v_i \leq 1$$

3.2.2 Calculation of average chordal error

When converting from the CAD model to the STL faceted model, by definition, all the vertices of the STL facets will lie on the original CAD NURBS surface, as shown in Fig. 16. As we move from the

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STL vertices towards the center of the facet, the deviation of the STL facet from the CAD model NURBS surface will be more pronounced.
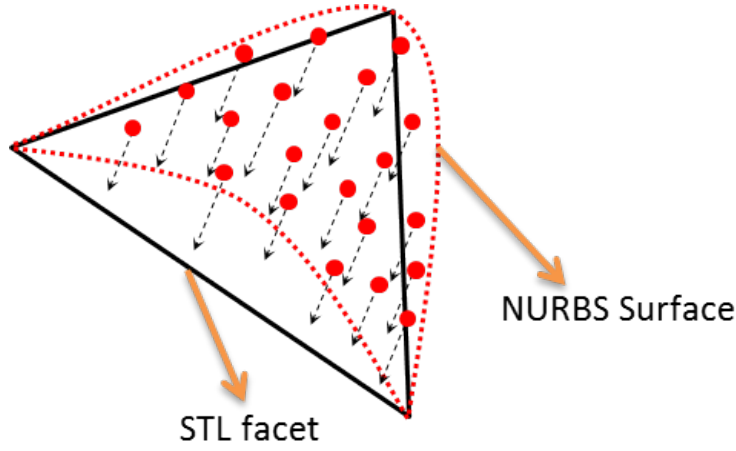
Figure 16: Chordal error calculation (adapted from [11].

Chordal error of a triangular facet is obtained by first discretizing the u, v parameters of the corresponding NURBS patch of each facet into multiple points on the NURBS surface (shown as red points in Fig. 16). Then the distance along the facet normal from each of the discrete u, v points to the STL facet plane is calculated and the maximum of these distances is termed as chordal error.

Since all the points generated within the NURBS patch is based on u, v discretization, there is no guarantee that the exact point with the maximum chordal error can be found. Thus, the value is approximate but is considered close enough to the actual chordal error value of the facet.

3.2.3   Steps of the Surface-based Modification Algorithm (SMA)

1)   Selection of surfaces to be modified (Fig. 17)
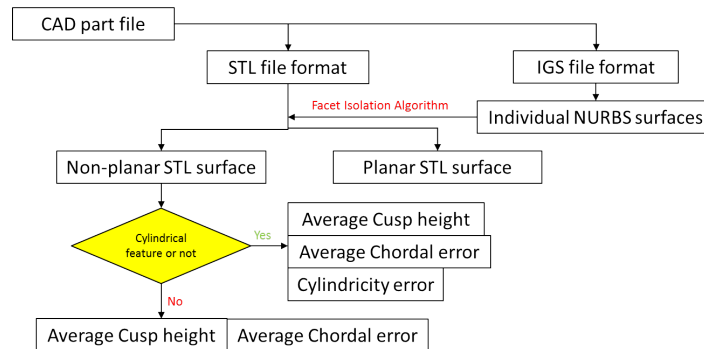
Figure 17: Criteria for selection of STL surfaces to be modified.

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For a specific model, both IGS and STL file format are exported from the original CAD format (for instance, .prt format) with the IGS version containing a certain number of NURBS surfaces. Based on each of the NURBS surfaces, groups of STL facets that correspond to each of the NURBS surface are retrieved using a "Facet Isolation Algorithm" [11]. All the STL facets that correspond to a NURBS surface are considered as a group, which is termed as an "STL surface".

Surface-based Modification Algorithm (SMA) aims at decreasing CAD-STL translation error and since there is no CAD-STL chordal error for planar surfaces, only non-planar surfaces are considered. For each non-planar surface in an STL model, cusp height, chordal error and cylindricity error (if it is a cylindrical feature) will be evaluated to determine if SMA needs to be applied to the STL surface.

2)   Delete the original surfaces selected

The original surfaces that need to be modified will be deleted from the STL model using a "Surface Deletion Algorithm", which will delete the STL surfaces that qualify for the SMA algorithm from the entire list of original STL surfaces.

A secondary intermediate STL model with gaps is created in this process.

3)   Modify the original STL facets with SMA facet formation pattern

As shown in Fig. 18, the STL surface consisting of a group of 13 STL facets that correspond to a NURBS surface is considered for the SMA algorithm. STL facet edges that are on the STL surface contour are considered "outer" edges and are marked red while the STL edges marked green are considered "inner" edges. A contour tracing algorithm is created and adopted to identify all the "outer" and "inner" edges of the STL surface.

The illustration of the rest of the methodology will be based on the NURBS patch (in u, v parametric space) of STL facet #11 in Fig. 18 that has two "inner" edges (highlighted in blue) and one "outer" edge (highlighted in light green).
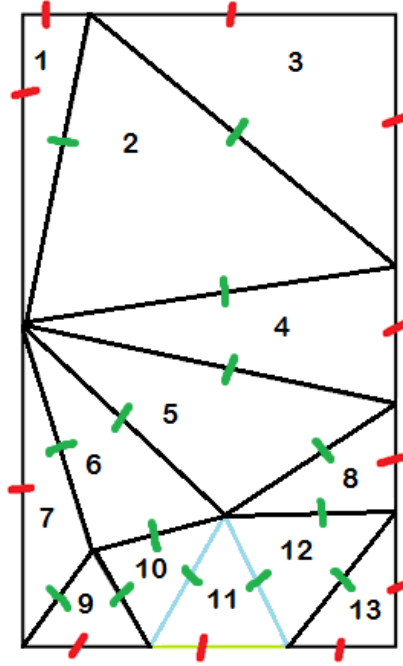
Figure 18: Sample STL surface.

Consider facet #11 in Fig. 18. To start with find the center point P_C of the 2D triangle in Fig. 19 in

u, v parametric space based on the u, v values of the three vertices.

$$U_C = (U_1 + U_2 + U_3)/3$$
$$V_C = (V_1 + V_2 + V_3)/3$$
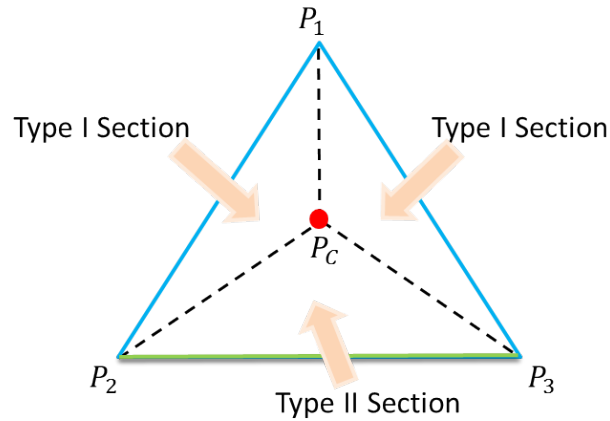
Figure 19: Calculation of parametric center point of STL facet.

The new point P_C and the three vertices P_1, P_2 and P_3 divide the original facet into three sections

as shown in Fig. 19 (for visual illustration purpose only). Two types of sections are defined. Type I

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section is on the "inner" edge side. Type II section is on the "outer" edge side.

Additional new points are created as shown in Fig. 20. The new points in type I section and type II section are located differently. Connect the points to form new facets as shown in Fig. 21, where 9+9+11=29 new facets are formed (In type I section, 9 new facets will be formed and in type II section, 11 facets will be formed), replacing the original facet #11. Note that P_{temp1} and P_{temp2} will not be used for forming new facets.
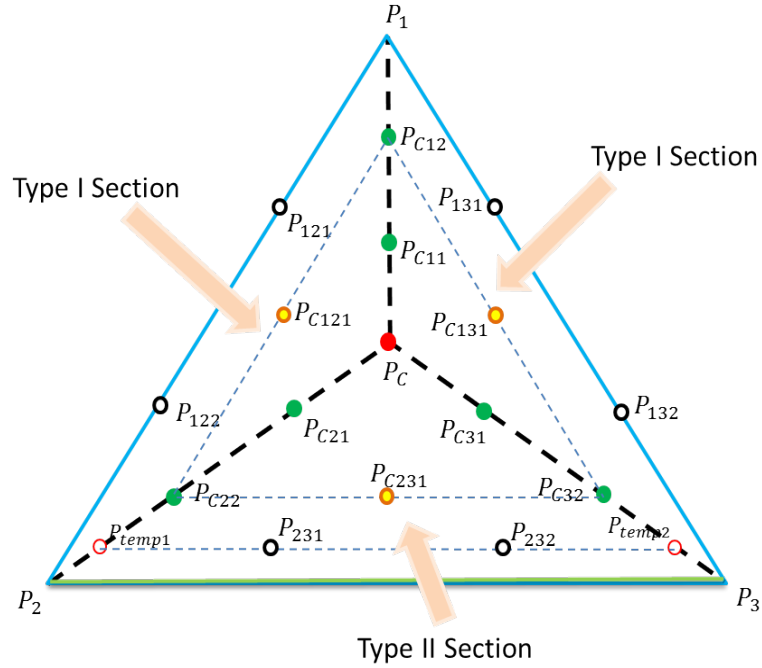
Figure 20: New points introduced in parametric space of the facet.
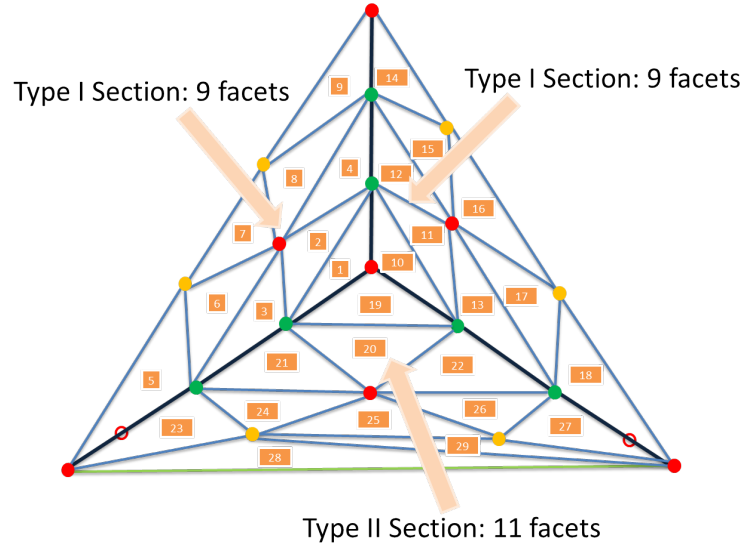
Figure 21: NURBS patch in Cartesian coordinates corresponding to STL facet.

All facets are grouped into three different categories as follows:

Category ONE consisting of three type I sections where 9+9+9=27 new facets are created, when none of the three edges of the original facet is on the contour of the STL surface.

Category TWO consisting of two type I sections and one type II sections where 9+9+11=29 new facets are created, when one of the three edges of the original facet is on the contour of the STL surface.

Category THREE consisting of one type I section and two type II sections where 9+11+11=31 new facets are created, when two of the three edges of the original facet are on the contour of the STL surface.

Based on the above definition, original facet #11 belongs to category TWO.
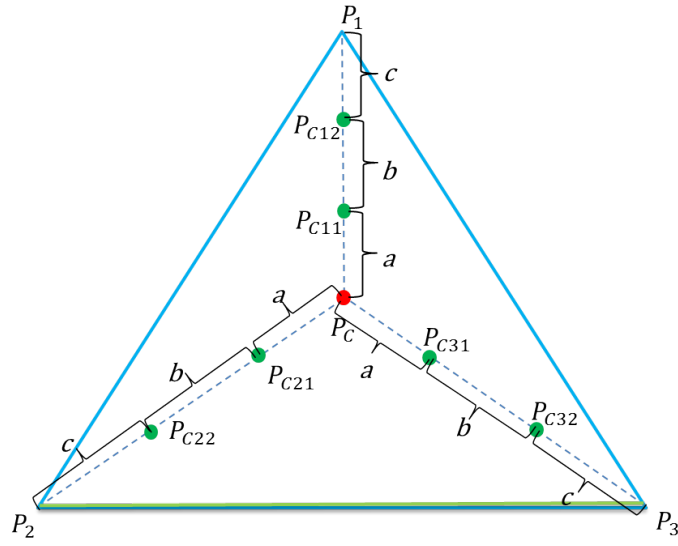
Figure 22: Length ratios for calculation of interior points.
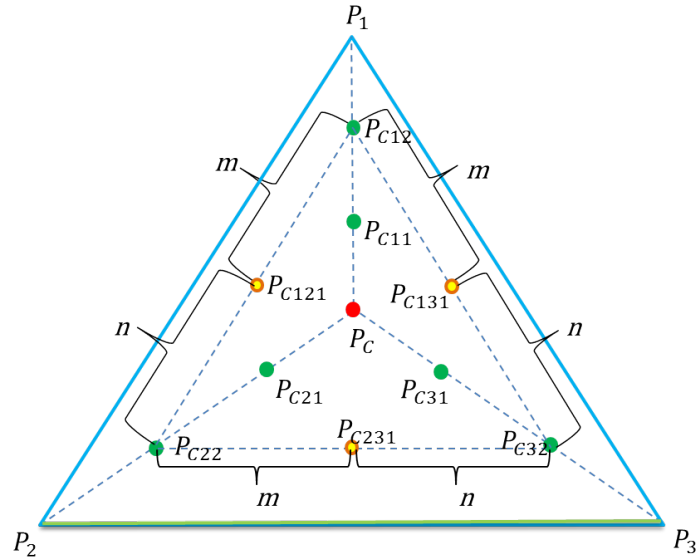
Figure 23: Generation of additional interior points in the parametric space of the facet.
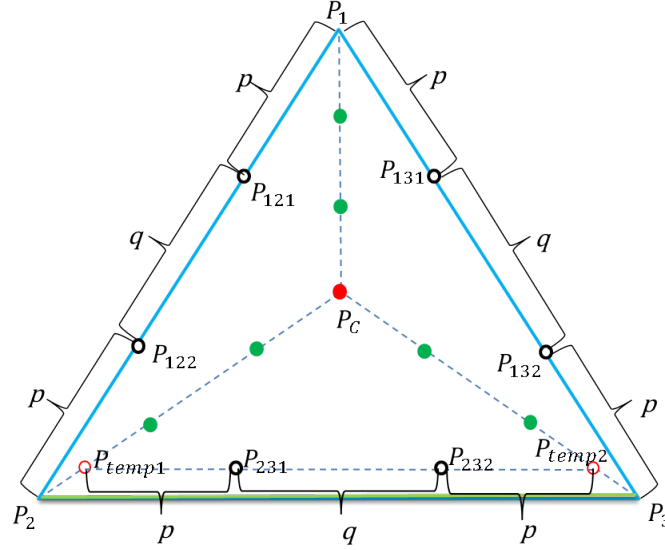
Figure 24: Length ratios for calculation of interior and contour points.

The new points in Fig. 20 are generated based on a fixed ratio of lengths, applied to type I and II sections as shown in Fig. 20. These length ratios are depicted in Figs. 22-24.

The length ratio in Fig. 22 is:

$$P_C P_{C11}: P_{C11} P_{C12}: P_{C12} P_1 = P_C P_{C21}: P_{C21} P_{C22}: P_{C22} P_2 = P_C P_{C31}: P_{C31} P_{C32}: P_{C32} P_3 = a: b: c$$

The length ratio in Fig. 23 is:

$$P_{C12} P_{C121}: P_{C121} P_{C22} = P_{C12} P_{C131}: P_{C131} P_{C31} = P_{C22} P_{C231}: P_{C231} P_{C32} = m: n = 1: 1$$

The length ratio in Fig. 24 is:

$$P_1 P_{121}: P_{121} P_{122}: P_{122} P_2 = P_1 P_{131}: P_{131} P_{132}: P_{132} P_3 = P_{temp1} P_{231}: P_{231} P_{232}: P_{232} P_{temp2} = p: q: p$$

$$P_2 P_{temp1}: P_{temp1} P_C = P_3 P_{temp2}: P_{temp2} P_C = 9: 1$$

Since P_{231} and P_{232} in Fig. 24 are not on the "outer" edge $P_2 P_3$ shown in green, the original facet edge will be unmodified.

The relative value of a, b, c, p and q are user defined. The default ratio is set as, $a: b: c = 3: 4: 3$ and $p: q: p = 3: 4: 3$, which provides relatively good result on some SMA modified STL surfaces.

On the sample surface in Fig. 18, this sequence of SMA operations is performed for all 13 STL facets of the STL surface that corresponds to a particular NURBS surface.

Each of the facets is modified and the new facets formed will connect with each other seamlessly because of the same ratio $p:q:p$ that divides the original facet edge into three new facet edges.

When a specific STL surface needs to be modified, it will be deleted from the STL model first, modified, and then stitched back to the STL model. In order to stitch the modified STL surface back to the STL model correctly, all the STL edges on the modified STL surface contour (such as the edge P_2P_3 highlighted in green in Fig. 24) should always remain intact to maintain connectivity with the neighboring STL facets.
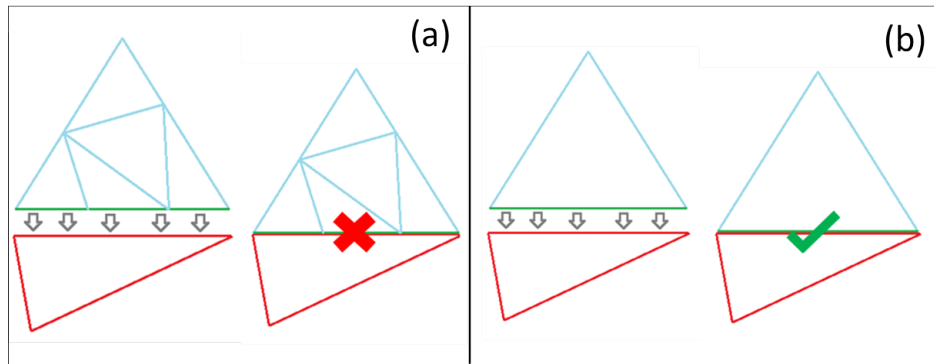
Figure 25: (a) Erroneous stitching of STL facets and d (b) correct stitching of STL facets.

If one of the STL edges on the contour of the STL surface that requires modification is broken into more than one edge, an STL file error results from stitching the modified surface back. For instance, in Fig. 25a, the previous facet (in blue) is modified and replaced by five new facets and the green edge is replaced by three new STL edges. When stitching the facet back to the main STL model (red facet), the basic STL rule that "any single edge can only be shared by maximum two facets" is violated [5].

After calculating the u, v values of all the new points in parametric space, these u, v values are converted into *x, y, z* coordinates in Cartesian space and all the new vertices of the modified STL surface are saved in a new STL file.

4)   Stitch the modified surfaces back to the cavity

The modified surface is then stitched back to the original STL model's cavity, with all the facet edges on the contour of the modified STL surface edge intact.

After the SMA steps have been performed, the new modified model is virtually manufactured to validate the effectiveness of the SMA algorithm on increasing geometric accuracy, as introduced in Chapter 4.

CHAPTER 4   CASE STUDIES & RESULTS

In this section, the application of Surface-based Modification Algorithm (SMA) is demonstrated using one STL surface and two STL parts. The SMA is evaluated by virtually building the original STL model, VTA-modified [11] STL model and SMA-modified STL model and comparing the geometric errors among them. The geometric errors used for comparison are profile error, cusp height, chordal error and cylindricity error.

4.1   Analysis of an individual curved surface
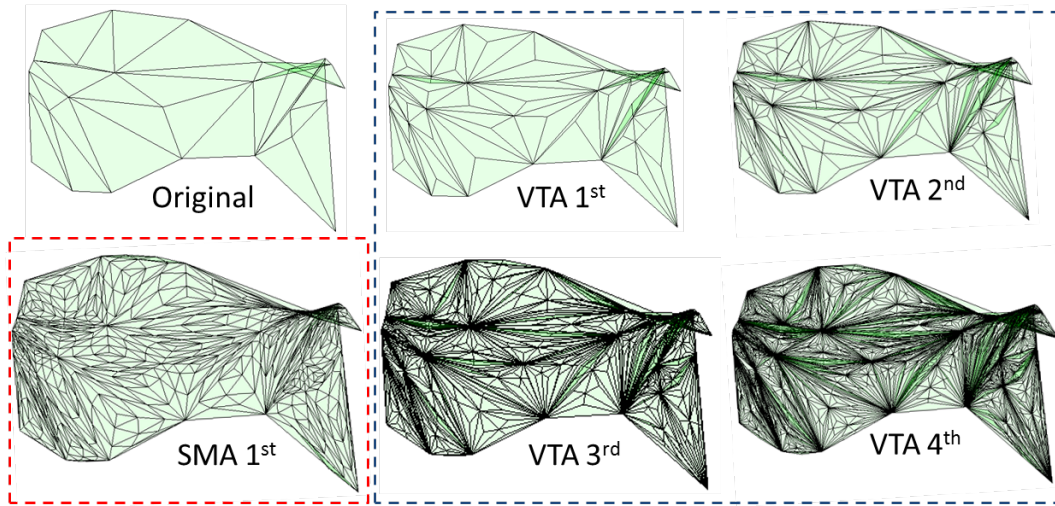
Figure 26: Original and modified versions of a sample surface.

Fig. 26 shows a NURBS surface initially presented in Section 2.3, the original STL surface directly exported from the CAD file, the SMA-modified surface (one iteration), and the VTA-modified surfaces (four versions with different number of iterations).

Table 1: Comparison of metrics of different STL models.

	Number of facets (file size)	Profile error (mm)	Average chordal error (mm)	Processing time (seconds)
Original	35 (2 KB)	0.2431	0.0726	
VTA				
1st iteration	105 (6 KB)	0.2393	0.0472	41.3
2nd iteration	315 (16 KB)	0.233	0.0253	178.1
3rd iteration	945 (47 KB)	0.2167	0.0136	747.1
4th iteration	2811 (138 KB)	0.2123	0.0069	2307
SMA				
1st iteration	979 (48 KB)	0.1263	0.0072	59.1

Table 1 presents a comparison between the original unmodified surface, SMA-modified surface and the VTA-modified surfaces. It can be observed that the number of facets has increased after each iteration with decreasing error values. The size of STL file is proportional to total number of facets. Typically, a small STL file size is preferred since it is difficult for AM machines to read large STL files and the pre-processing time resulting from input of the STL file may increase due to large STL file sizes. Profile error is one of the GD&T parameters specified for free form manufactured surfaces [15]. Average chordal error serves as a measure of the geometric deviation of the STL surface compared to the original CAD surface. The lesser the value of average chordal error, the closer the STL surface is to the original CAD surface that it was converted from.

As can be seen from Table 1, the profile error and chordal error of the STL surface both decrease after each iteration of VTA and SMA application. For approximately the same STL file size (number highlighted in brown), SMA has a smaller profile error and average chordal error value (number highlighted in red) compared to the 3rd iteration of VTA, and with a processing time of only about 8% of the VTA.

4.2   Sample part 1

Fig. 27 shows a simple part model that has five surfaces with corresponding surface numbers specified for identification purpose. The original STL model with a uniform export error threshold of 0.08 has 350 facets and a file size of 17 kB.
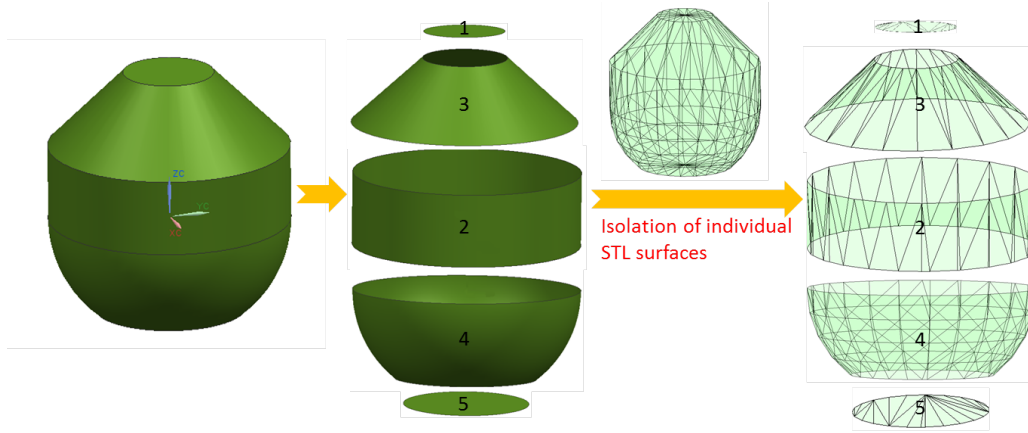
Figure 27: Sample part 1: CAD model and STL model.

Since there are only three non-planar surfaces in the model, SMA is applied only to these non-planar surfaces. Those surfaces are chosen one at a time, or in combination of two at a time, or all three at a time, and the SMA algorithm is applied and subsequently the modified surface stitched back to the main model. This results in a total of $\binom{3}{1} + \binom{3}{2} + \binom{3}{3} = 7$ combinations of SMA-modified STL models. The cusp height value of these seven models are calculated and compared with each other. Based on cusp height value improvement, one modified STL model (Fig. 28) in which surface 2 is modified from the original model resulting in 1872 total facets, is selected to demonstrate improvement after SMA modification.
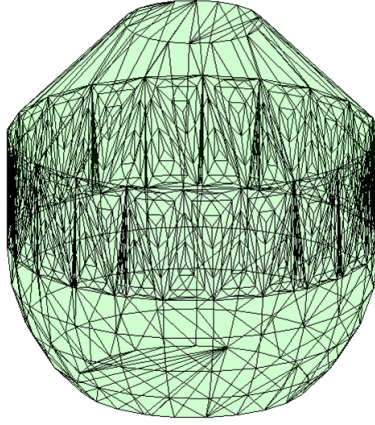
Figure 28: SMA-modified STL model.

The uniformly exported STL models with different export error thresholds that are shown in Fig. 29 are compare with the SMA modified STL model in Table 2. Cusp height values calculated by two different values of slice thickness are used for this comparison. The cusp height calculation is based on the method introduced in Section 3.1.
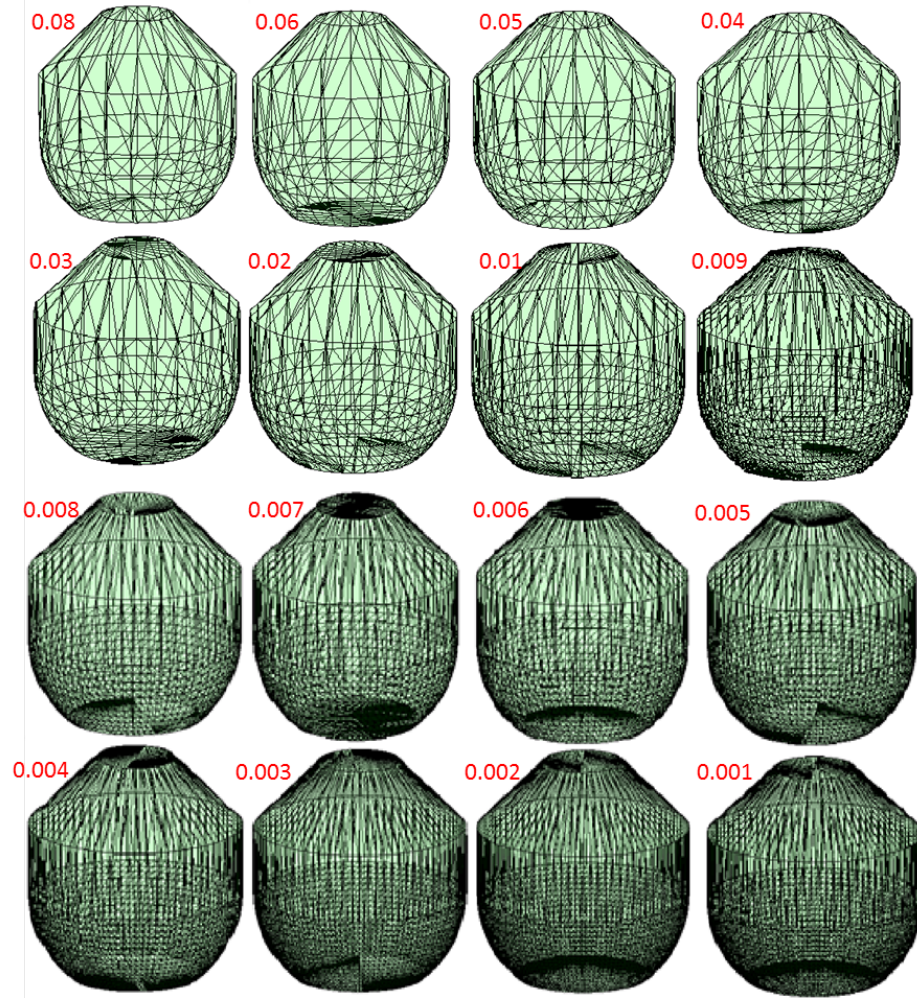
Figure 29: Uniform exported STL models with different error thresholds.

Table 2: Comparison of average cusp height among different STL models.

Sample Part 1	Average Cusp Height		STL size (KB)
	10 slices	50 slices	
Original model used for SMA (0.08 uniform export)	0.1928	0.0443	18
SMA Modified STL model	0.0641	0.0158	92
0.08 uniform export	0.1928	0.0443	17
0.07 uniform export	0.2013	0.0462	18
0.06 uniform export	0.1914	0.0435	19
0.05 uniform export	0.1781	0.0427	23
0.04 uniform export	0.1767	0.0416	26
0.03 uniform export	0.1581	0.0394	33
0.02 uniform export	0.1792	0.0408	45
0.01 uniform export	0.1659	0.0417	75
0.009 uniform export	0.1776	0.0427	86
0.008 uniform export	0.1717	0.0405	98
0.007 uniform export	0.1738	0.0414	105
0.006 uniform export	0.1521	0.0412	122
0.005 uniform export	0.1732	0.041	141
0.004 uniform export	0.1779	0.0419	177
0.003 uniform export	0.1682	0.0422	227
0.002 uniform export	0.1692	0.0403	260
0.001 uniform export	0.1692	0.0403	260

Table 2 shows approximately a 65% decrease in average cusp height (number highlighted in red is compared with the number in yellow) for the SMA modified STL model compared to the original model. The resulting file size increases due to the increase in the total number of facets.

The average cusp height values of the uniformly exported STL models (a common attempt to increase STL model geometric accuracy) are also shown in the table. For uniform export, despite the substantial increase in file size (from 17 to 260 kB), the average cusp height value only has a slight decreasing trend, with only about 10% decrease in cusp height value.

When the 92 kB SMA modified STL model is compared with the 98 kB "0.008 uniform export"

STL model, it is observed that even with a smaller comparable STL file size, the SMA modified STL model has a much smaller average cusp height value than the uniformly exported one.

Besides improvement in cusp height for the entire part, cylindricity error for cylindrical features will also improve due to SMA modification. The minimum zone method [16] is used to obtain cylindricity error. For a cylindrical feature, the point cloud of the cylindrical feature is generated by virtually slicing the cylinder and is used for testing and comparing cylindricity error. From Table 3, a 44.4% decrease in cylindricity error is observed after application of SMA on surface 2.

Table 3: Comparison of cylindricity error of the cylindrical feature surface 2.

	Cylindricity error	% of error decrease
Original Surface 2	0.0407	
Modified Surface 2	0.0226	44.4

4.3   Sample part 2
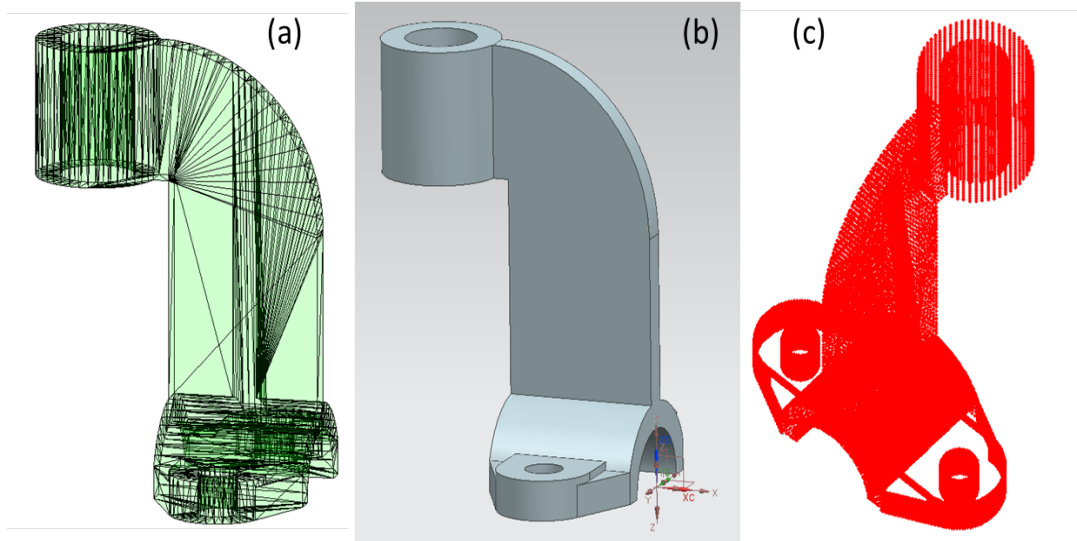
Figure 30: (a) Original STL, (b) CAD model [17] (grabcad.com) and (c) point cloud
generated used for cusp height calculation.

Fig. 30 shows a relatively complex bracket model that has 36 surfaces. The original STL model with a uniform export error threshold of 0.08 has 1020 facets and 50 kB file size. A modified STL model is created in which surfaces 13, 17, 27, 28, 29 and 31 are modified by SMA (Fig. 31) resulting in 9825

facets. The surfaces that are modified were selected based on the rules stated in "Selection of surfaces to be modified" in Section 3.2.4 using cusp height, chordal error and cylindricity error criteria. Tables 4 and 5 present the improvements in all three metrics for individual surfaces after application of SMA.

Table 4: Comparison between original and modified cylindrical surfaces 27, 28, 31 (units in mm).

Surface Number	Average cusp height		Average chordal error		Cylindricity error	
	Original	Modified	Original	Modified	Original	Modified
27	0.0561	0.0026	0.062	0.034	0.0745	0.0369
28	0.0545	0.0026	0.062	0.034	0.0745	0.0369
31	0.0582	0.0027	0.065	0.036	0.0768	0.0581
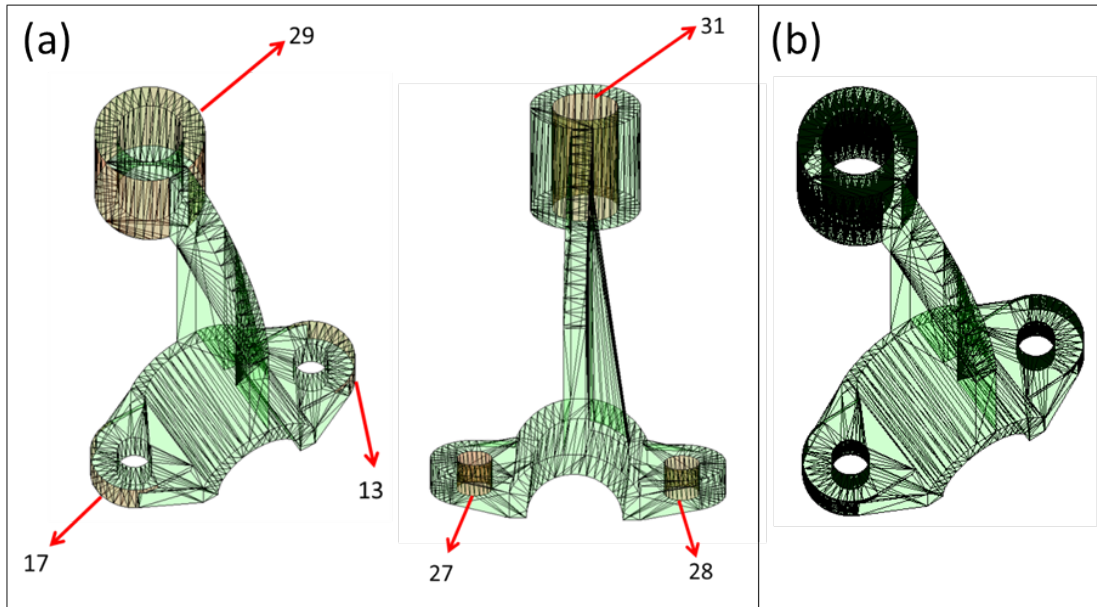
Figure 31: (a) Surfaces to be modified (b) SMA-modified sample part 2.

Table 5: Comparison between original and modified (in mm).

Surface Number	Average cusp height		Average chordal error	
	Original	Modified	Original	Modified
13	0.0546	0.0026	0.0590	0.0056
17	0.0546	0.0026	0.0590	0.0056
29	0.0605	0.0029	0.0701	0.0068

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Table 6 shows a substantial decrease (approximately 93%) in average cusp height of the SMA modified STL model (see the numbers highlighted in red) compared to the original model; a resulting file size increase is also observed. The average cusp height values of two uniformly exported STL models (with error threshold of 0.01 and 0.001, separately) are also shown in Table 6.

Table 6: Comparison of average cusp height.

	Average Cusp Height (mm)		STL size (KB)
	Total Number of slices: 50	Total Number of slices: 100	
Original Model (0.08 uniform export)	0.3711	0.2147	50
Modified STL model	0.0262	0.0156	480
0.01 uniform export	0.3115	0.1799	131
0.001 uniform export	0.2538	0.1488	263

For the uniform export option, the minimum threshold limit of the CAD software, Siemens NX 8.5, is 0.001. Thus, "0.001 uniform export" STL model represents the best geometric accuracy that uniform export can achieve. The cusp height value of "0.001 uniform export" STL model is approximately 10 times the value of the SMA modified STL model.

CHAPTER 5   CONCLUSIONS

5.1   <u>Overview of the Thesis</u>

A novel STL modification algorithm termed as Surface-based Modification Algorithm (SMA) was developed in this work. Based on chordal error, profile error and cylindricity error of individual surfaces of the part, the SMA selectively and adaptively modifies certain STL surfaces in an STL model to decrease cusp height of the model without unnecessary increase of file size.

An algorithm that uses bounding boxes to calculate average cusp height was also developed in order to more accurately calculate the average cusp height of a certain STL part model compared to the generally adopted method which has a more approximate calculation result. This algorithm was developed with the ultimate goal to better assist the execution of Surface-based Modification Algorithm (SMA).

5.2   <u>Possible Limitations of SMA</u>

Surface-based Modification Algorithm (SMA) seeks to decrease the average cusp height, which is one of the major geometric errors of STL models. SMA algorithm is applied to individual surfaces and will most likely increase the STL file size of a surface exponentially. Application of the SMA algorithm is a tradeoff between the smaller file size and higher accuracy.

Consider a simple STL part model that has a few surfaces, SMA application on a particular surface could potentially result in the increase of whole body file size by approximately 10 times. The ratio of SMA modified surfaces to the Total number of part surfaces provides a good indication of the possible increase in final file size. The increase of this ratio beyond certain threshold would make the advantage of the SMA over uniform export option less advantageous from a file size perspective. Beyond a certain value of the ratio, the uniform export option maybe preferable over the application of SMA. This is contingent on the accuracy desired on the various part surfaces per the design specifications.

Due to the substantial decrease in cusp height resulting from SMA application, the SMA modified parts would have a lower average cusp height value that may not be achievable by uniform export option. So, for high accuracy part models with complex features and multiple surfaces, SMA may be a preferred approach over highest accuracy uniform export option.

5.3   **Future Scope**

Future work includes optimization of geometric patterns of new facet formation in SMA and considering other tolerances as a metric for STL file local facets densification. Also, additional research could be performed to develop an intelligent ratio selection algorithm that can automatically determine the optimal length ratios to divide the facets that belong to a particular STL surface based on the feature of that surface.

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