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Adaptive Slicing for SLS Prototyping

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ABSTRACT

Improvement of part surface quality and geometric accuracy by modifying slicing procedure in RP has been a major concern. Reduction in build time and enhancement of part surface quality are two factors which contradict with each other as decreasing build time detracts part quality because of staircase effect. There have been a number of attempts to tackle this problem by using adaptive slicing procedures in which slice thickness is determined by the local part geometry and RP machine specifications. A geometrical parameter known as cusp height is limited to a pre-specified value in various existing adaptive slicing procedures, which is defined for rectangular or sloping edge profiles only. In another approach, relative change in areas of successive slices have been considered as criterion to adaptively slice CAD models but this method has limitation as local geometry of part is not taken into consideration. Therefore, in the present work, a slicing procedure is presented in which statistical surface roughness model developed by Pandey and his group [1] for SLS prototypes has been used as a key to slice the tessellated CAD model adaptively. The adaptive slicing system is implemented as Graphic User Interface in MATLAB-7. The capabilities of developed adaptive slicing system have been demonstrated by case studies.

Keywords: adaptive slicing, rapid prototyping, selective laser sintering, surface roughness.
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1. INTRODUCTION

The focus on productivity has been one of the main concerns of industries worldwide since early 1990's. To increase productivity, industries have attempted to apply more computerized automation in manufacturing. Amongst the latest technologies Rapid Prototyping (RP) is one of the important technologies and is also known as Solid Freeform Fabrication (SFF), Desktop Manufacturing or Layered Manufacturing (LM). It has potential to reduce the manufacturing lead-time of a product up to 50 percent even when the relative part complexity is very high [2]. RP processes are now used in diverse fields like medical sciences, jewelry, coin making, footwear industry, saddlery industry, automobile industry, aircraft industry etc. [18]. The latest trend of research in the area of RP includes development of new materials, advancement in laser technologies, software and computer integrated manufacturing support to RP, development of new methods of layer deposition, methods to reduce build time, improve surface quality and accuracy through adaptive slicing and depositing the part in an orientation to achieve better quality product [9]. Poor surface quality of RP parts is a major limitation and is primarily due to staircase effect. Surface roughness can be controlled below a predefined threshold value by using an adaptive slicing [13].

Slicing of a CAD model is one of the most important and key step of RP process chain [2]. A CAD model can be transferred for deposition to RP system only after slicing it. A CAD model can be sliced with or without tessellation. If a CAD model is sliced directly, without tessellating, it is called direct slicing of CAD models. Many attempts have been made to reduce the build time of RP parts by modifying slicing algorithms. Their approach is mainly based on the variable slice thickness instead of constant thickness and is termed as adaptive slicing. The layer thickness in this method is decided by the local geometry of the CAD model and RP machine specifications. Different reported slicing algorithms can be classified as slicing of tessellated models and direct slicing of CAD models. This classification [12] has been shown in Fig. 1. It can be seen from Fig. 1 that slicing procedures can be broadly classified as slicing with uniform thickness and slicing with variable slice thickness, i.e., adaptive slicing. It is obvious that with the development of RP processes, slicing with uniform thickness was attempted and adopted. Later it was realized that the build time of the prototypes can be reduced if a combination of thicker and thinner layers are deposited based on geometry of the prototype. Pandey et al. [12] thoroughly reviewed the various published adaptive slicing algorithms. The description of few important slicing procedures has been given below.

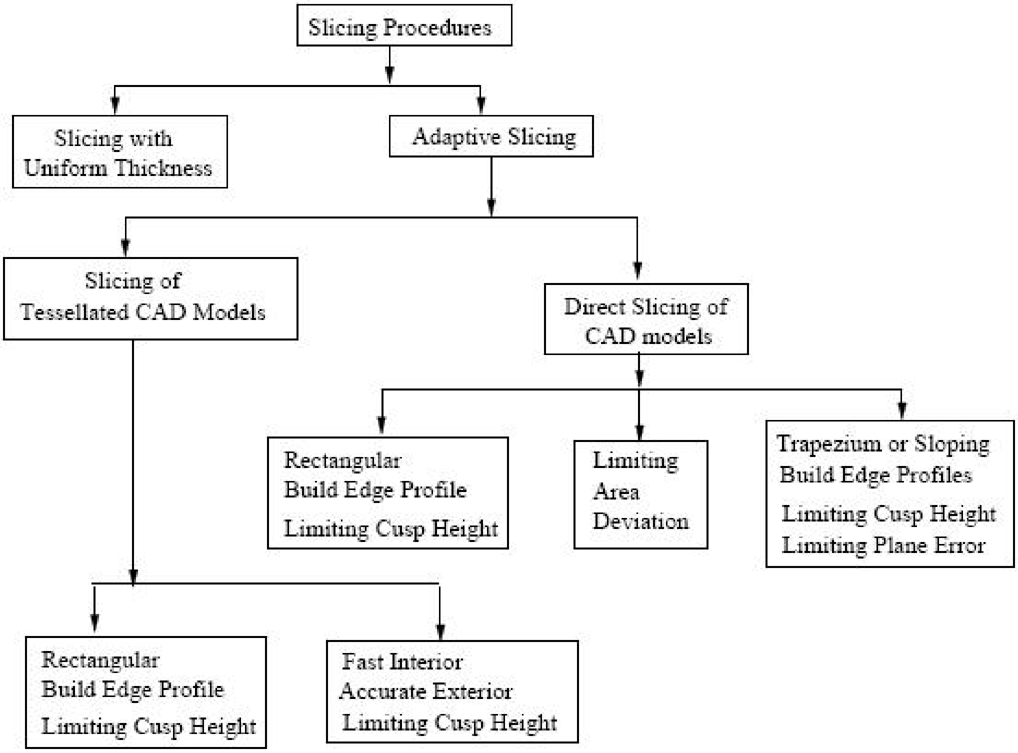


Fig. 1: Classification of slicing algorithms [12].

Dolenc and Makela [4] introduced the concept of cusp height (refer Fig. 2). The layer thickness at a location was computed based on the cusp height, within the user specified maximum allowable cusp height. The thickness of the current layer is estimated using the normals around the boundary of the preceding horizontal plane.

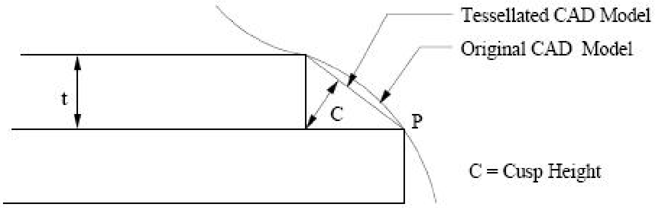


Fig. 2: Definition of cusp height.

Stepwise uniform refinement procedure was proposed by Sabourin et al. [14] which uses the same concept of limiting cusp height introduced by Dolenc and Makela [4]. Here, tessellated CAD model was first divided into uniform, horizontal slabs of thickness equal to the maximum available layer thickness. Those slabs which do not satisfy the cusp height requirement are further subdivided into finer slabs having uniform thickness. Interpolation was used for slice thickness determination. Specifically, a slab was examined both from its bottom slice looking upward and from its top slice looking downward and the succeeding slice is subdivided. This dual direction examination was less likely to miss high-curvature regions as compared to those procedures, which only examine from upward for the determination of current slice thickness.

Local adaptive slicing [16, 17] of parts used the same limiting cusp height concept [4] explained earlier to determine the slice thickness. In this approach, first, individual features in a build were identified and then slicing was carried out independent of one another. It was more often the case for several features to coexist at the same height with different geometries such that each require distinct layer thickness to meet the cusp height conditions. Here, a tessellated CAD model was first sliced into uniformly thick slabs using the maximum thickness available in a RP system. The resulting contours belonging to the slab's top and bottom slices were then matched using topological information to form a set of sub-slabs. Finally, each sub-slab is independently divided into a distinct number of thinner layers based on the vertical slope of its surface or surfaces along the contours. Different tests namely orientation test, multiple part test, proximity test, direct test, indirect test and virtual test are carried out to establish vertical connectivity between two contours. After sub-slabs identification, each one is further subdivided independently into an integer number of uniform layers using the stepwise uniform refinement procedure [14]. They implemented local adaptive slicing on FDM-1600 RP system.

Fast interior and accurate exterior method of slicing was proposed by Sabourin et al. [15]. In this procedure a precise exterior was built with thin layers using slicing concept. At the same time the interior was built with thick and wide material application. Here, the interior layers were not of the same thickness as the exterior layers, but were several times thicker as shown in Fig. 3. The process of fabrication in 3D space using thick and thin layers was coordinated by first slicing the tessellated CAD model into thick horizontal slabs of uniform thickness. These slabs were then processed from the bottom to the top of the part and the contours on the top and bottom of each slab were offset inward into the part in the horizontal plane to form a new set of contours that separate the exterior and interior regions within the slab. These two sets of regions can now be built in sequence. First the exterior region can be built with thin layers and then the interior regions can be back filled with thick layers to complete the fabrication of the part. They reported that accurate exterior and fast interior slicing procedure is important as it could reduce the build time of the prototype from 50-80 percent.

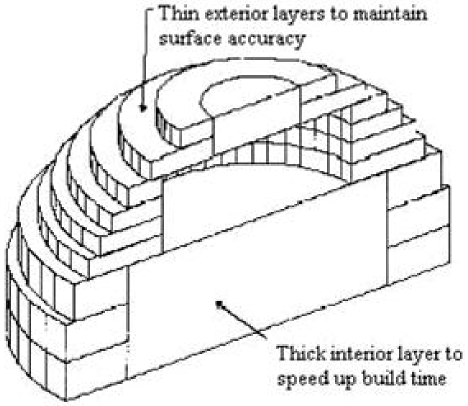


Fig. 3: Fast interior and accurate exterior concept of adaptive slicing [12, 15].

Cormier et al. [3] introduced the concept of non uniform cusp height requirements for the part. Most of the adaptive slicing algorithms assume a maximum allowable cusp height, which applies to the entire part. As far as application of the part is concerned, it may not have uniform cusp height requirement everywhere. Some faces of the part are required to be smooth while other faces are relatively unimportant. In this procedure tessellated CAD model was used as an input. The edges were found by edge finding algorithm and grouping of facets was carried out. The facet model of the part to be sliced was rendered. Designer had an option of specifying maximum allowable cusp heights for different faces as per functional requirement of the part.

Jamieson and Hacker [8] implemented direct slicing of CAD models with uniform slice thickness using Parasolid CAD software and user defined routines in C (a solid modeling kernel of Unigraphics). Parts were modeled using boundary representation (B-rep) method in their work. These models had non-manifold problem which was avoided by giving tolerance to the sectioning plane in positive or negative z-direction. In their work slicing direction was chosen as z-direction. The slicing algorithm started with finding of the highest and lowest points of a part. The slicing of the part was achieved by consecutively calling the function for one slice and then putting the tags of the slice together in an assembly. An option for adaptive slicing was also implemented by Jamieson and Hacker [8] using area deviation. Later, Zhao and Laperriere [19] implemented the similar adaptive slicing procedure using AutoCAD Runtime Extension (ARX).

The effect of containment and staircase on the final product accuracy and surface quality was studied by Kulkarni and Dutta [10]. Vertical normal radius of curvature and normal vector at any point of a CAD model was computed. The normal section at that point was approximated as a circle. This approximation resulted in twelve expressions, when the different possible geometrical conditions and containment requirements were considered. They formulated the adaptive slicing problem as optimization problem and solved using sequential quadratic programming of MATLAB.

In all the earlier approaches of adaptive slicing presented above, the build edges were considered to be rectangular. Hope et al. [6, 7] used sloping build edges instead of rectangular edges for the better approximation of surface of the part. The main advantage achieved was improved surface finish and decreased build time as the thicker layers can be used. In their work, multiple B-spline surfaces (IGES format) were used to define a part. They sliced the model by tracing surface contours and computing the cutting direction at a number of points as specified by the user.

Pandey et al. [13] presented a novel approach where a bound on surface roughness (Ra) was used as key to adaptively slice a tessellated CAD model. The stochastic surface roughness models for FDM parts were developed and the obtained expression was used to calculate the thicknesses of the slices.

It is clear from the above discussion that the limited cusp height and the limited area deviation are the two criteria used for adaptive slicing of the CAD models. While considering limited cusp height as a criterion, consideration of build edges as rectangular is not a realistic assumption. One attempt [7] has also been made to slice CAD models adaptively assuming the build edges as sloping. Cusp height is not a standard design parameter to specify surface roughness in design and manufacturing. Area deviation method has limitation in terms of non-consideration of surface geometry while calculating slice thickness. Pandey et al. [13] have developed an approach to adaptively slice the CAD model and control the surface roughness at critical locations of FDM parts. Development of adaptive slicing algorithm for controlling surface roughness by compromising with the build time for other RP processes may be better as compared to minimization of build time only because surface finish is more important than build time [5] or strength [9] for RP parts.

2. ADAPTIVE SLICING OF SLS PROTOTYPES

Enhancement of part surface quality and geometric accuracy as well as reduction in build time can be achieved by adaptive slicing. Therefore in the present work an attempt has been made to control the surface roughness of SLS prototypes by adaptive slicing the corresponding tessellated CAD model. In this section adaptive slicing algorithm and its implementation has been discussed. The capabilities of the developed algorithm are presented as case studies in next section.

2.1 Adaptive Slicing Algorithm

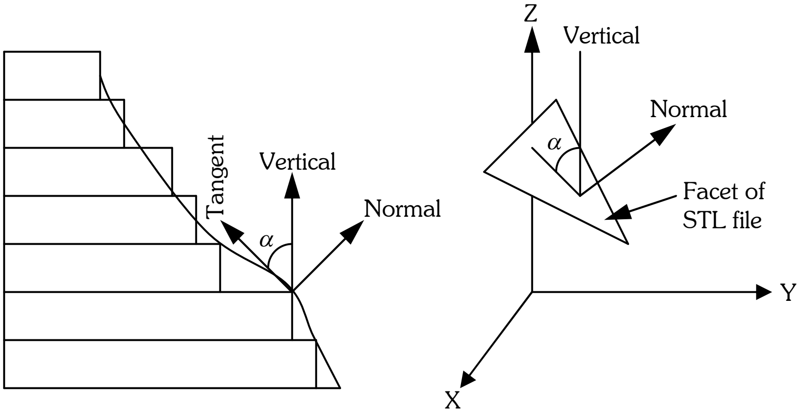
Existing methodologies of adaptive slicing are based on two concepts. First is the limiting cusp height and the second is the limited deviation of cross-sectional area (plane normal to Z axis) of the part. The layer thickness is increased from minimum to maximum slice fabrication thickness which is given as one of the input parameters. In both these procedures the measure of the part surface quality does not come into picture explicitly. An adaptive slicing method based on limiting surface roughness (Ra) value was proposed by Pandey et al. [13] for FDM prototypes. In the present work similar approach has been used to adaptively slice a tessellated CAD model for SLS prototyping in which statistical surface roughness model developed for SLS prototypes by Bacchewar et al. [1] has been used as a key.

Bacchewar et al. [1] developed surface roughness model for SLS prototypes based on statistical design of experiments. Laser power, layer thickness, hatch spacing, scan speed and build orientation were considered as factors and typical SLS prototypes were fabricated as per the standard central composite experimental plan. Total 32 experiments were performed and surface roughness measurement was carried out using Form TalySurf. The obtained values of surface roughness were used as a response and Analysis of Variance (ANOVA) was performed to understand significance of five process factors. In their work, surface roughness of up facing surfaces was effected by build orientation and layer thickness only however the surface roughness of downward facing surfaces was found to be affected by laser power, build orientation and layer thickness. The hatch spacing and scan speed are reported as insignificant factors in their study. They developed two response surfaces to predict the surface roughness values, first for up facing surfaces and second for down facing surfaces. The surface roughness expressions for up facing and down facing surfaces for SLS prototypes made of polyamide material are given by

$$Ra_{up} = -2.04067 - 0.22\alpha + 0.06722 l_t - 0.00136\alpha^2 \tag{1}$$

$$Ra_{down} = 185 - 9.52P - 0.834\alpha - 0.157 l_t + 0.15P^2 - 0.00099\alpha^2 + 0.0058 X\alpha l_t \tag{2}$$

where Ra_{up} and Ra_{down} are local surface roughness in μm, P, is laser power (W), α is build orientation (deg), i.e., angle between and vertical and surface tangent at that point (refer Fig. 4) and l_t is layer thickness (μm).



(a) α = Build orientation

(b) Build orientation of a triangular facet

Fig. 4: Build orientation in SLS prototyping.

Therefore, in the present work the expressions used for determination of slice thickness for up facing surfaces is

$$l_t = \frac{1}{0.06722}\left[Ra_b + 2.04067 - 0.22\alpha + 0.001368\alpha^2\right] \tag{3}$$

and in case of down facing surfaces is

$$l_t = \frac{1}{(0.0058\alpha - 0.157)}\left[Ra_b - 185 - 9.52P + 0.834\alpha - 0.00099\alpha^2\right] \tag{4}$$

here, Ra_b is bound prescribed on surface roughness value.

For a RP process the layer thickness must lie within the minimum and maximum fabrication layer thickness available in that machine, i.e.,

$$l_{t\min} \le l_t \le l_{t\max} \tag{5}$$

Where $l_{t\max}$ and $l_{t\min}$ are the maximum and minimum values of slices thicknesses available with SLS machine.

Eqn. (3) and (4) are used to determine slice thickness in adaptive slicing algorithm. Evaluation of α can be done by using normal vector of any triangular facet of tessellated CAD model by using the following equation

$$\alpha = \sin^{-1}\left(\frac{n_z}{\sqrt{n_x^2 + n_y^2 + n_z^2}}\right) \tag{6}$$

and for a pre-specified value of Ra_b on the surface of the part the slice thickness can be calculated. If the value of slice thickness is less than minimum slice thickness available on SLS machine then slice thickness equal to minimum slice thickness is selected. If the value of slice thickness is more than maximum slice thickness available on SLS machine then slice thickness equal to maximum slice thickness is selected. Otherwise the calculated value of slice thickness from eqn. (3) and (4) is used.

2.2 Implementation Procedure

The slicing algorithm is implemented as graphic user interface (GUI) of MATLAB-7. The input to the developed GUI are STL file, minimum and maximum fabrication thickness available with SLS system and bound to be kept on surface roughness value. The other process parameters like laser power and/or layer thickness is also given as an input. Typical flowchart describing the implementation procedure has been given in Fig. 5. The developed GUI has provisions for slicing with uniform slice thickness, surface roughness simulation and adaptive slicing. The developed GUI is very easy to operate and understand.

3. CASE STUDIES

An axisymmetric part is selected and is modelled in AutoCAD2000. Selected part geometry is symmetrical about vertical axis and faces are inclined to horizontal plane in the increment of 15 degree. The STL file is exported and used as an input to developed GUI for adaptive slicing. A typical output of GUI i.e., display of tessellated model has been shown in Fig. 6. This tessellated CAD model is first sliced with uniform slice thickness of 160 μm and the obtained output has been presented in Fig. 7. Typical surface roughness simulation with uniform slicing of 160 μm for SLS process has been presented in Fig. 8. In SLS process surface finish is better on downward faces as compared to upward faces for same values of build orientation [1] and the same can be observed clearly from Fig. 8. By this surface roughness simulation users can have an idea of maximum surface roughness on the model and can choose suitable surface roughness bound for adaptive slicing.

When this tessellated CAD model is sliced adaptively, the obtained output has been presented in Fig. 9. Minimum and maximum slice thickness considered is 0.05 mm and 0.2 mm respectively and roughness bound is kept 8 μm. It can be seen from Fig. 9 that developed system is able to adaptively slice the tessellated CAD model. It can also be observed from the figure Fig. 9 that the slice thicknesses are somewhat thicker when there are downward facing surfaces. This is probably due to filleting effect reported by Bacchewar et al. [1] for SLS process. The variation of slice thicknesses with the z-height of the part at surface roughness bound 8 μm has been presented in Fig. 10. Another study has been carried out by changing the roughness bound and finding out number of slices and is presented in Fig. 11. It can be seen from this figure that with increase in surface roughness bound the number of slices decreases and then becomes constant as all the slices corresponds to the maximum slice thickness available with SLS machine. In the same study the minimum, maximum and average slice thicknesses for the model with roughness bound has also been plotted in Fig. 12. It can be seen from this figure that the average slice thickness increases continuously with respect to increase in surface roughness bound and same is expected in adaptive slicing. As the build time is directly related to number of slices therefore it can be concluded that build time decreases with the decrease in number of slices.

The objective of the developed system is mainly to control and keep the surface roughness within the given surface roughness bound. In the developed system of adaptive slicing, number of slices may vary with the part complexity even for the same surface roughness bound. If part geometry is simple (e.g. only vertical and horizontal surfaces) part can be made with maximum slice thickness available on the machine and hence the build time with adaptive slicing will be lesser as compared to uniform slicing. Similarly when part geometry is complex (e.g. highly curved surfaces), part should be built with smaller layer thicknesses for better surface finish and hence the build time with adaptive slicing is expected to be higher as compared to uniform slicing.

Another typical part has been selected and modelled in AutoCAD2000 to demonstrate the capabilities of the developed adaptive slicing system. This particular geometry has been selected so that variation in slice thicknesses can easily be observed. After solid modelling the STL file corresponding to CAD model is exported and is used as an input to developed adaptive slicing system. Tessellated CAD model with surface roughness simulation has been presented in Fig. 13. The uniformly sliced CAD model has been presented in Fig. 14. The adaptive slicing has been performed by selecting 30 W laser power, 0.05 mm and 0.2 mm as minimum and maximum slice thicknesses respectively for 9 μm bound on surface roughness. Typical graphical output related to adaptive slicing has been presented in Fig. 15 . It can be seen from Fig. 14 and Fig. 15 that the developed slicing module is able to slice a tessellated CAD model with uniform slice thickness and adaptively.

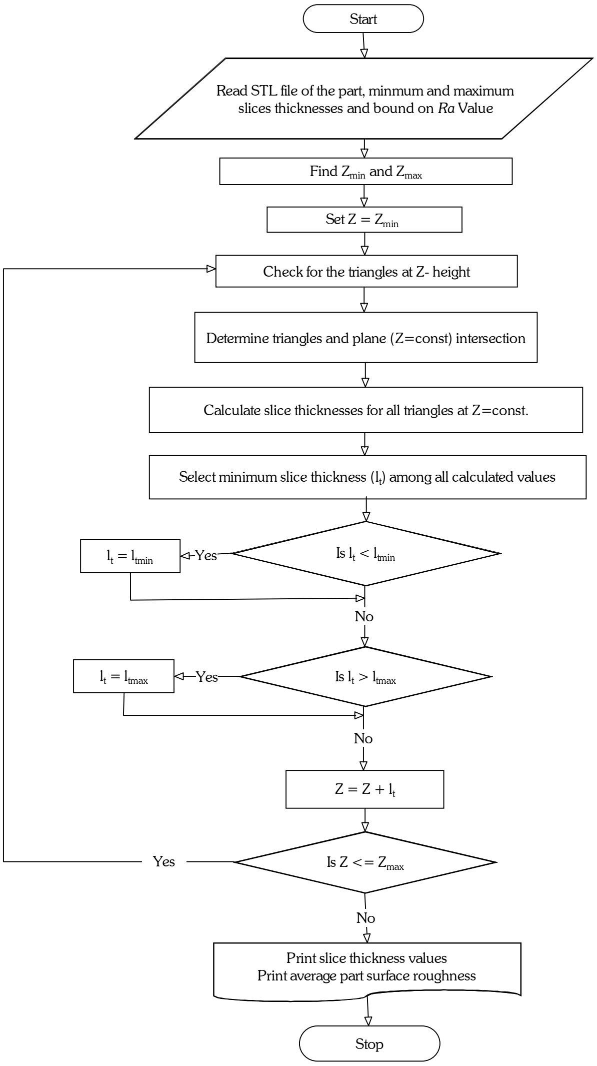


Fig. 5: Implementing of adaptive slicing of tessellated CAD model.

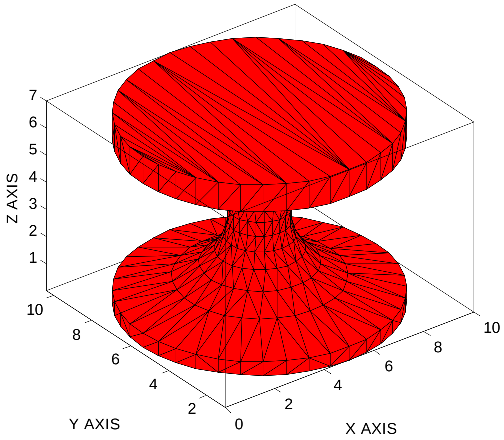


Fig. 6: Tessellated model of axisymmetric part

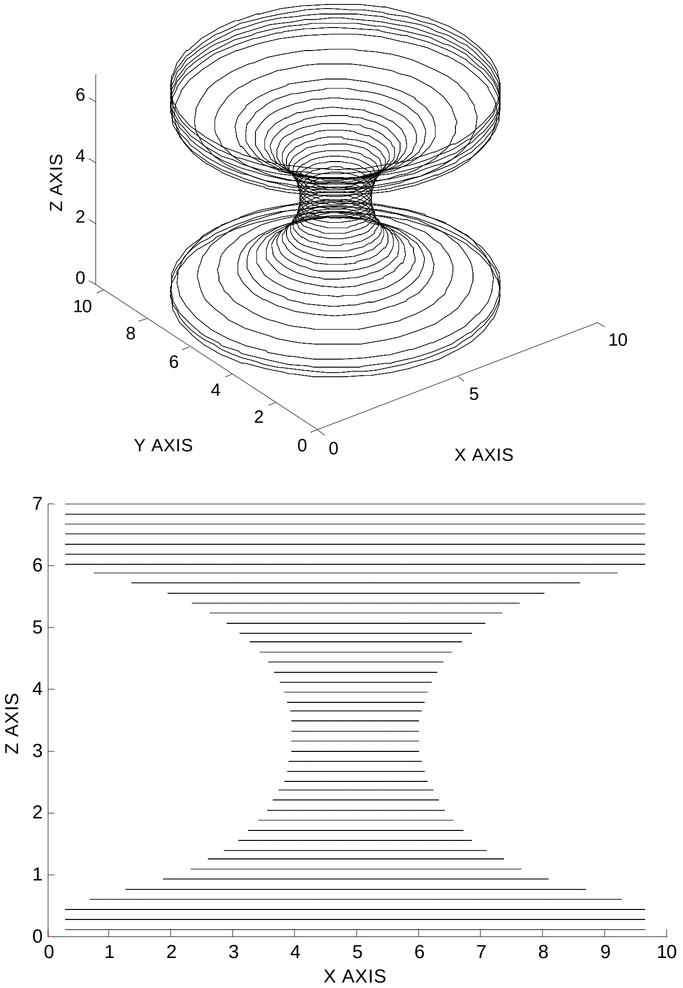


Fig. 7: Axisymmetric CAD model sliced using uniform slice thickness (160 μm).

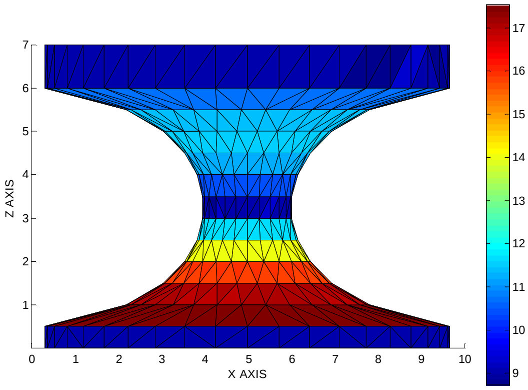


Fig. 8: Surface roughness simulation with uniform slicing.

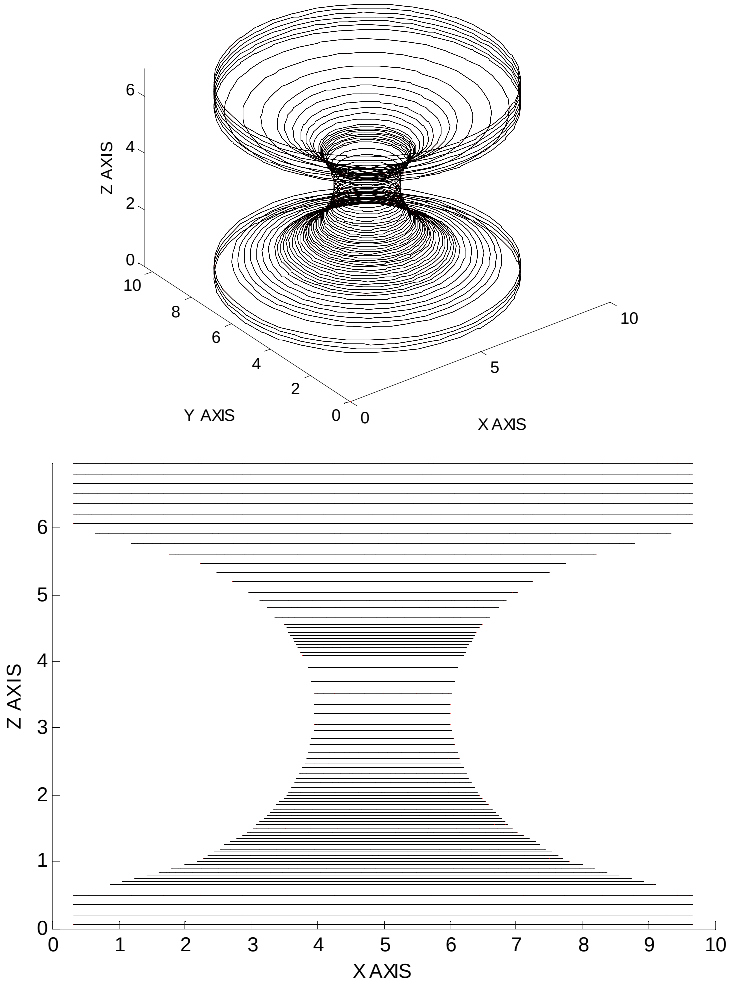


Fig. 9: Typical adaptive slicing output from the developed GUI for axisymmetric part (surface roughness bound 8 µm).

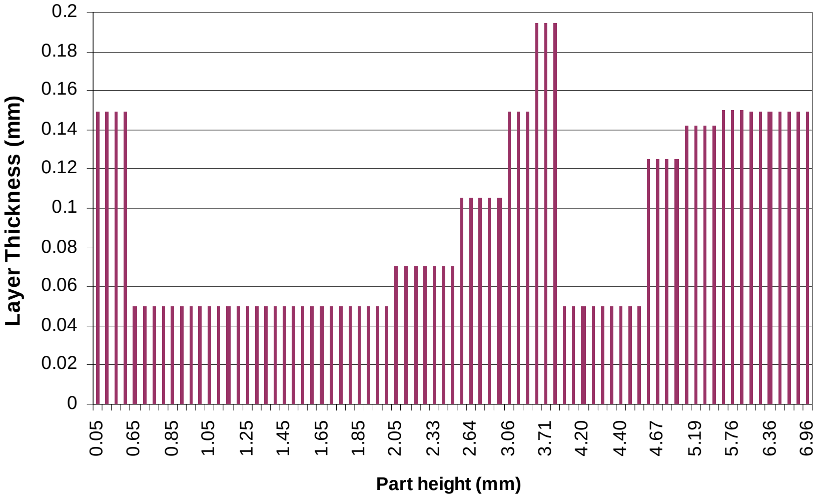


Fig. 10: Variation in layer thickness with z-height (surface roughness bound = 8 μm).

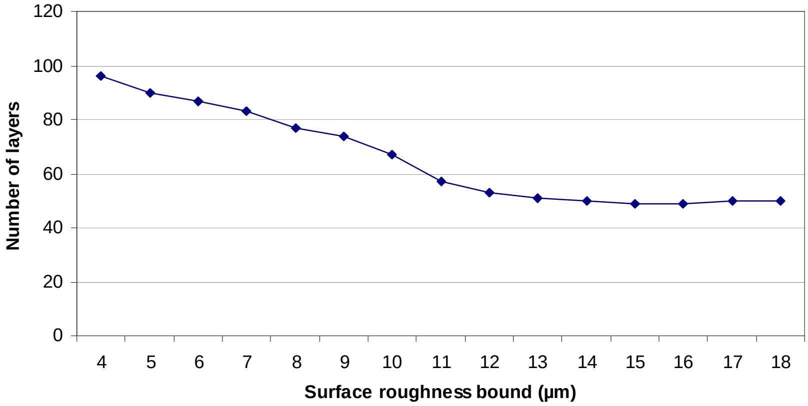


Fig. 11: Variation in number of layers with surface roughness bound.

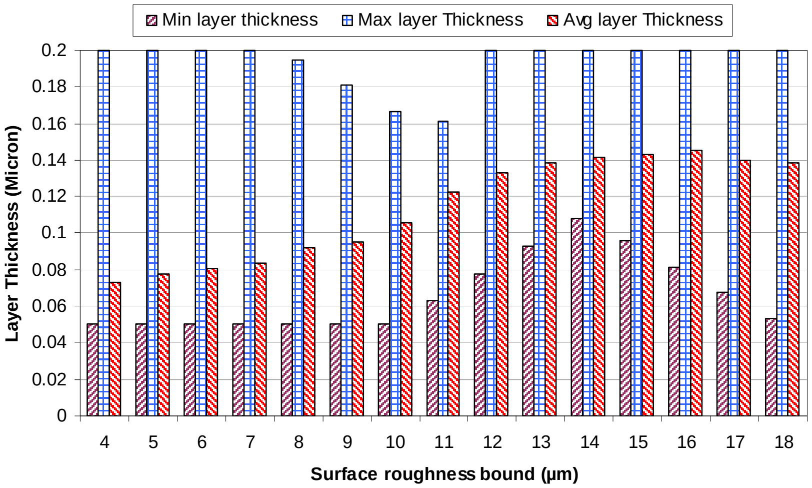


Fig. 12: Surface roughness bound vs. minimum, maximum and average slice thicknesses.

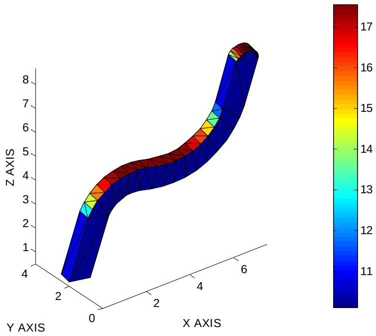


Fig. 13: Surface roughness simulation of typical part modeled in AutoCAD with uniform slicing.

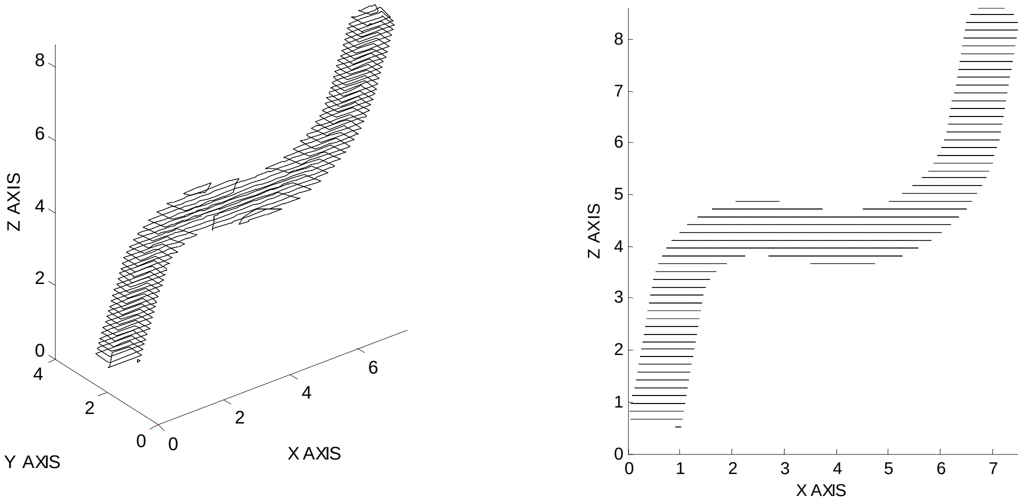


Fig. 14: Tessellated CAD model sliced using uniform slice thickness.

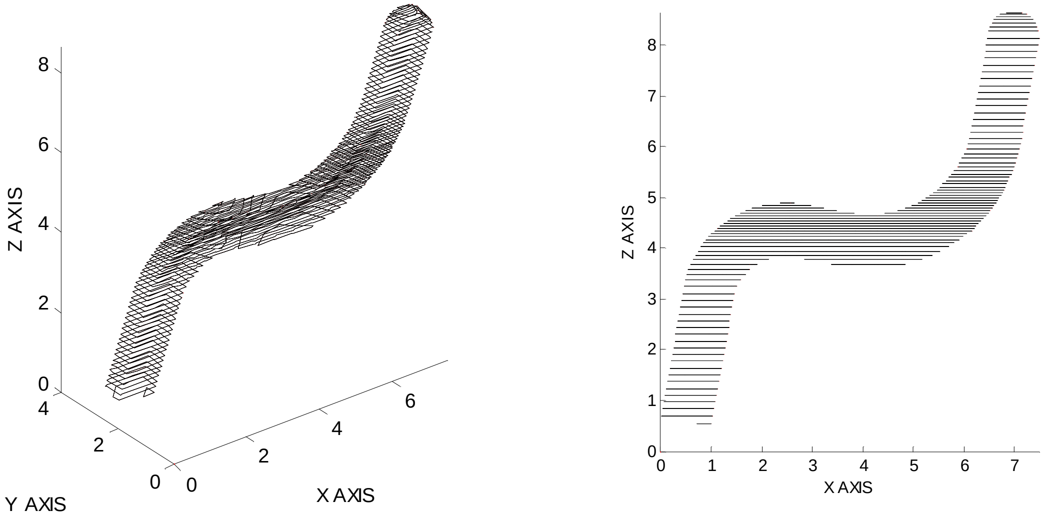


Fig. 15: Typical adaptive slicing output from the developed GUI.

4. CONCLUSIONS

An approach for adaptive slicing of tessellated CAD models based on the statistical surface roughness model for SLS prototyping has been successfully presented and implemented. In comparison to earlier approaches of adaptive slicing based on cusp height and area deviation using the rectangular build edge profiles, it can be easily seen that the present methodology can reduce the build time and control the surface roughness of SLS prototypes below a certain surface roughness bound. The major advantage of the present methodology is that the part quality is expressed in terms of standard *Ra* value which is a standard in design and manufacturing unlike using cusp height. The different variations of the adaptive slicing appeared in literature like stepwise refinement [14], local adaptive slicing [16], specifying non-uniform *Ra* values at different locations [3] of the part can be implemented easily by adding a feature recognition module.

5. ACKNOWLEDGEMENTS

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6. REFERENCES

[1] Bacchewar, P. B.; Singhal, S. K.; Pandey, P. M.: Statistical modelling and optimization of surface roughness in selective laser sintering process, Proc. IMechE Part B: J. of Engineering Manufacture., 221, 2007, 35-52.

[2] Chua, C. K.; Leong, K. F.; Lim, C. S.: Rapid Prototyping: Principles and Applications, 2nd Edition, World Scientific, 2003.

[3] Cormier, D.; Unnanon, K.; Sanni, E.: Specifying non-uniform cusp heights as a potential for adaptive slicing, Rapid Prototyping Journal, 6(3), 2000, 204-11.

[4] Dolenc, A.; Makela, I.: Slicing procedure for layered manufacturing techniques, Computer Aided Design, 1(2), 1994, 4-12.

[5] Frank, D.; Fadel G.: Expert system based selection of the preferred direction of build for rapid prototyping, Journal of Intelligent Manufacturing, 6, 1994, 334-339.

[6] Hope, R. L.; Jacobs, P. A.; Roth, R. N.: Rapid prototyping with sloping surfaces, Rapid Prototyping Journal, 3(1), 1997, 12-19.

[7] Hope, R. L.; Roth, R. N.; Jacobs, P. A.: Adaptive slicing with sloping layer surfaces, Rapid Prototyping Journal, 3(3), 1997, 89-98.

[8] Jamieson, R.; Hacker, H.: Direct slicing of CAD models for rapid prototyping, Rapid Prototyping Journal, 3(1), 1995, 12-19.

[9] Kruth, J. P.; Leu, M. C. T.: Nakagawa, Progress in additive manufacturing and rapid prototyping, Annals of CIRP, 47(2), 1998, 525-540.

[10] Kulkarni, P.; Dutta, D.: An accurate slicing procedure for layered manufacturing, Computer Aided Design, 28(9), 1996, 683-97.

[11] Lee, K. H.; Choi, K.: Generating optimal sliced data for layered manufacturing, International Journal of Advanced Manufacturing Technology, 16, 2000, 277-84.

[12] Pandey, P. M.; Reddy, N. V.; Dhande, S. G.: Slicing procedures in layered manufacturing: a review, Rapid Prototyping Journal, 9 (5), 2003, 274–288.

[13] Pandey, P. M.; Reddy, N. V.; Dhande, S. G.: Real time adaptive slicing for fused deposition modelling, International Journal of Machine tools and Manufacture, 43(1), 2003, 61-71.

[14] Sabourin, E.; Houser, S. A.; Bohn, J. H.: Adaptive slicing using stepwise uniform refinement, Rapid Prototyping Journal, 2(4), 1996, 20-26.

[15] Sabourin, E.; Houser, S. A.; Bohn, J. H.: Accurate exterior, fast interior layered manufacturing, Rapid Prototyping Journal, 3(2), 1997, 44-52.

[16] Tyberg, J.; Bohn, J. H.: Local adaptive slicing, Rapid Prototyping Journal, 4(3), 1998, 118-27.

[17] Tyberg, J.; Bohn, J. H.: FDM systems and local adaptive slicing, Materials and Design, 20, 1999, 77-82.

[18] Wholers, T.: Future potential of rapid prototyping and manufacturing around the world, Rapid Prototyping Journal, 1(1), 1995, 4-10.

[19] Zhao, Z.; Laperriere, L.: Adaptive direct slicing of the solid model for rapid prototyping, International Journal of Production Research, 38(3), 2000, 89-98.