A New Adaptive Slicing Approach for the Fully Dense Freeform Fabrication (FDFF) Process

Mohammad Hayasi, Bahram Asiabanpour[1]

Ingram School of Engineering, 601 University Drive, Texas State University-San Marcos, 78666, Texas, USA

REVIEWED, August 17 2011

Abstract

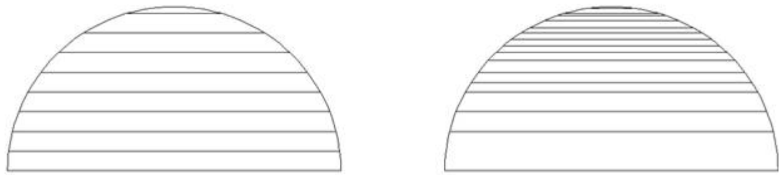
FDFF is a process based on thin line cutting processes, variable thickness layering, slicing in different orientations, and bulk layer attachment. The combination of these capabilities enables the production of good quality complex parts from practically any material at a very fast pace. As for rapid prototypes fabricated by the FDFF process, it is certainly possible to employ adaptive slicing technique due to the possibility of cutting different metal/non-metal sheet at various thicknesses. This paper proposes a new adaptive slicing method whereby the capability of cutting a 3D solid model at the predefined sheets' thicknesses is achieved and the geometry of all internal and external features of a part is also investigated to ensure the reduction of part geometry deviation through the seamless curvature detection. Despite most previous works which start slicing a tessellated or direct CAD model at the maximum available thickness, this system commences the process with available minimum thickness by applying a new adaptive method to all pairs of contours at the top and bottom slices of the layer. Autodesk Inventor solid modeler, as a design-by-feature solid modeler, is used for 3D solid modeling. The proposed system is implemented by Visual Basic codes inside Inventor using API functions to access both geometry and topology information of the design-by-feature solid model . This system has been successfully tested on a variety of complex parts containing sophisticated internal and external features.

Keywords: adaptive slicing, design-by-feature, fully dense freeform fabrication, FDFF

1. Introduction

To satisfy the quality of objects built by rapid prototyping (RP) processes and meet their economic needs at the same time, many attempts to design specific hardware and software tools have been made. In this respect, the use of effective slicing technique (e.g., direct/indirect uniform/adaptive slicing) is intended to enhance part surface quality and shorten build time. All popular RP processes, in fact, make parts of uniform thickness. In the uniform layer thickness method, all layers have equal thickness. Some theoretical and software works have also been proposed in adaptive layer thickness prototyping. In the adaptive slicing technique, the part geometry complexity affects on the determination of the varied slicing thickness. It has been theoretically proven that this method can produce parts with higher accuracy, less part geometry deviation, and shorter build time (Dolenc & Makela, 1994; Kulkarni & Dutta, 1996; Vouzelaud & Bagchi, 1995) (Figure 1).

[1] Corresponding author: ba13@txstate.edu



(a) (b)

Figure 1. The illustration of slicing approach, a) uniform slicing and b) adaptive slicing.

Because of the technical difficulties such as applying material to be cured or sintered at variable thickness in single setup, adaptive slicing has been implemented on very few RP processes (Hayasi & Asiabanpour, 2010; Tyberg & Bohn, 1998). The development of uniform or adaptive slicing approaches can be categorized in terms of direct and indirect slicing. A CAD model through intersecting the model with the XY-plane at each Z increment is a well-known method of path generation. Slicing a CAD model is implemented through different methods such as STL file slicing, neutral format (e.g., IGES, HP/GL, and STEP) (Chua, Gan, & Tong, 1997a, 1997b) or direct model slicing. Among the available RP processes, the STL format is the most widely accepted file format in the RP industry. The reasons for this popularity are its simple format and ease of file generation without the requirement of very sophisticated CAD software (Jurrens, 1999; Koc, Ma, & Lee, 2000). Different methods of slicing an STL file have been proposed (Asiabanpour & Khoshnevis, 2004; Choi & Kwok, 1999; Vuyyuru, Kirschman, Fadel, Bagchi, & Jara, 1994). However the parts fabricated by this system displayed some porosity as a result of missing information in STL file that was created by CAD systems.

Another slicing approach uses exact CAD models. Some direct slicing works by Chang (2004), Jamieson and Hacker (1995), and Chen, Wang, Ye, Xiao, and Huang (2001) have been reported. In these works, researchers have used a CAD software package (e.g., PowerSHARE, Parasolid) to model and then to generate the boundary path. The boundary path (contour) in these three cases is generated by use of macros which are provided by the underlying software. Chang (2004) slices a 3D model designed in PowerSHARE into N sections with the aid of a special macro. The resulting section at each Z level consists of curves such as lines, conic arcs, and Bezier spans. Then, these entities that form a contour are coded and saved into a custom predefined file for generating G-code by using a computer-aided manufacturing software presented by the same company (PowerSHARE). Chen, et al.'s (2001) method creates a PIC file containing boundary loops as a special format that can be used to picture a layer on screen using another software package. Because their approach applies macros to an entire 3D object, the elapsed time for creating contours would be long. In another attempt made by Jamieson and Hacker (1995), B-rep of a solid model designed in Parasolid is used for direct slicing. In this approach, they applied macro(s) to faces of a B-rep model in order to generate a boundary path. As reported in their paper, a simple part comprising cylindrical and rectangular faces takes at least 90 minutes to generate the contours for all layers.

Presented in this paper is a new adaptive slicing approach for CAD models created by Inventor. The kernel of the proposed approach is to project all pairs of corresponding slices at the top and bottom of the considered layer on XY, XZ, and YZ horizontal surface to detect any possible part geometry distortion. A special error for layer thickness determination matched with user-defined sheet thicknesses is then computed. One of the unique features of this new system is its ability to process very large and intricate models with difficult-to-recognize internal and external features. In addition, it is capable of producing machine paths that are compatible with waterjet and laser cutting processes that apply a variety of metal/non-metal sheet thicknesses. Despite previous works that cut the entire part from bottommost to topmost position at maximum available thickness, the proposed system starts cutting at minimum available thickness then allows the current layer becomes thicker or thinner as the comparison of the obtained error with threshold error. This part of the proposed system avoids any large geometry deviation error caused by sharply concave or convex corners. The factors in the form of error computation that help determine the thickness of a layer at Z increment position are discussed in Section 2. Proposed adaptive slicing algorithms which are used to cut sheets of varied thicknesses by waterjet and laser cutting are presented in Sections 3 and 4, respectively. System implementation and results are discussed in Section 5 and 6. The conclusion is presented in Section 7.

2. Types of part geometry distortion errors

Quantifying the geometry distortion error is the main factor in determining the right value for layer thickness in both uniform and adaptive slicing. Dolenc and Makela (1994) introduced one of the widely used errors: cusp height. In fact, the relationship between the maximum allowable cusp height and normal vector at any point on the tessellated model is applied to find the thickness of each layer. Many other researchers (Cormier, Unnanon, & Sanii, 2000; Jung & Ahluwalia, 2005; Pande & Kumar, 2008; Xu, Wong, Loh, Fuh, & Miyazawa, 1997) use this factor as an error measurement in their own algorithms. Investigation of all points on the top or bottom slice of a layer allows for calculation of the values of the maximum allowable cusp height, would lead to the division of the current thickness into small slices or keeping it at maximum thickness. Any sharp concave or convex vertexes might appear whether we apply maximum or minimum thickness (see Figure 2), but it might lead to a significant part geometry deviation if maximum thickness is finally applied by knowing that no geometry distortion at top and bottom slices detected using the desired cusp height. In an attempt to solve this problem, Singhal, Prashant, and Pulak (2008) presented a comprehensive accurate direct slicing procedure in which the sharp concave/convex vertices are first recognized and then named as a block point where no slicing occurs. If such vertexes fall within top and bottom slices of the layer, the slicing position is moved either over or below the identified vertexes. The obtained thickness is then sliced at the smallest available thicknesses.

There are two problems with their work. First, any concave or convex region may be represented by continuous curved surface not only through two or more adjacent slanting surfaces whereby we could easily detect the mentioned vertexes. Second, in the case of subdivision of the obtained layer into smaller ones, it might not be the integer number of available minimum thicknesses that would cause the failure of the slicing process.

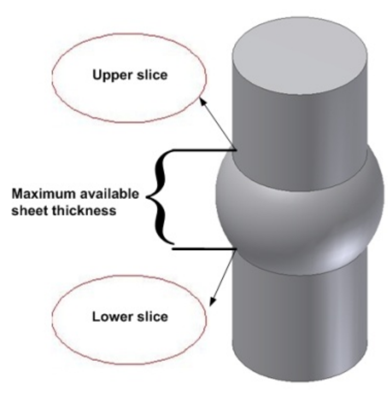


Figure 2. Two identical slices on the bottom and top of the layer cut by maximum thickness approach.

The second error measurement as a surface roughness, Ra, is used to determine the thickness of the layer. The major advantage of applying Ra amount over cusp height is its suitability for integrated design and manufacturing. Pandey, Reddy, and Dhande (2003) utilized Ra value on physical edge profile of fused deposition modeling (FDM) to fit the best thickness for under investigated layer. Singhal, et al. (2008) implemented the design of experiment (DOE) to attain the optimal response value (Ra) for SLS prototypes which is used along with build direction at any point on a pair of slices of the layer in a specific non-linear formula for the purpose of determining an optimal thickness between user-defined minimum and maximum acceptable thicknesses. It seems that the use of this approach in a layer-by-layer fully dense fabrication process may not make sense as there is no realistic correlation between the surface roughness of a single metal/non-metal layer with layer thickness.

Using intermediary STL file format which consists of facets information such as vertexes and normal vectors, previous research attempted to intersect horizontal surfaces at a Z increment with the short list of facets at the Z level in order to obtain connected line segments by which a collection of interior and exterior contours is formed. The vertexes of line segments are used to calculate cusp height as discussed above. This process, however, is very time consuming as it requires investigation of all vertexes for finding optimum cusp height. To solve this problem, Zhao and Laperriere (2000) introduced a new tolerance (area deviation) so as to adaptively slice a CAD model. Despite widely used tessellated CAD models, they worked on direct CAD model inside CAD package software to create contours. Then the interior area of the created top and bottom contours of the layer encompassing entities like lines, circles, and ellipses are computed for the purpose of comparing the measured area deviation with allowable tolerance to see whether the layer becomes thicker or thinner. In Figure 3, a staircase effect appears on the layer while two created contours have an equal area which leads the above mentioned solution to failure.

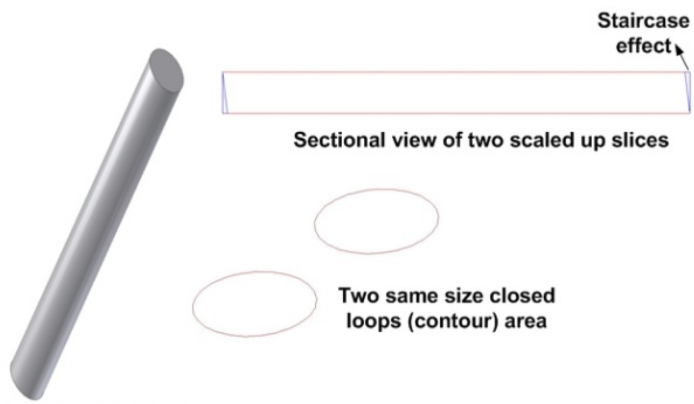


Figure 3. The staircase effect while two created contours are same size in inner area.

All of these tolerances are regarded as 2D measurements in which the degree of layer curvature is measured at different points. This 2D measurement is assumed to become a weaker decision factor in layer thickness selection when the complexity of the geometry of a CAD model is greatly increased. In response to this issue, Kumar and Choudhury (2005) presented a type of 3D tolerance named as volume deviation in direct slicing for achieving higher accuracy in adaptive slicing process. The volume deviation between a CAD model and built-up part in 5-axis laminated object manufacturing is calculated so that the deviation between the actual model and the built-up part is significantly reduced. This technique is, in fact, a promising solution for slicing CAD models with remarkable higher precision, but since it works directly with surfaces of the part to mathematically compute the related volumes the complexity in the geometry of the surfaces would need some complicated mathematical computation that may jeopardize the validity of such system.

Generally speaking, it can be concluded that the higher accuracy of adaptive slicing requires a comprehensive approach by which the geometric complexity of a part is taken into consideration at different dimensions. In the following, the technique in measuring the geometry curvature of the complicated parts towards adaptive slicing is explained.

3. Interior and exterior contour creation

The use of contours (loops) is the initial step in adaptive slicing. The current system slices a CAD model created in Inventor at any X, Y, or Z increment. The intersection between a horizontal surface in a build direction and the selected faces results in a number of interior or exterior contours. These contours are formed by the continuous connection of the line segments obtained from the intersection of a planar surface with the facets generated with higher precision inside Inventor (for more detail on the contour creation algorithm refer to Hayasi and Asiabanpour, 2009). While a contour is created, all faces that used for this particular contour at a Z level are recorded in data array. Any pair of contours at the top and bottom of the layer is identified and grouped by the detection of all their identical faces to which the contour's line segments belong (see Figure 4).

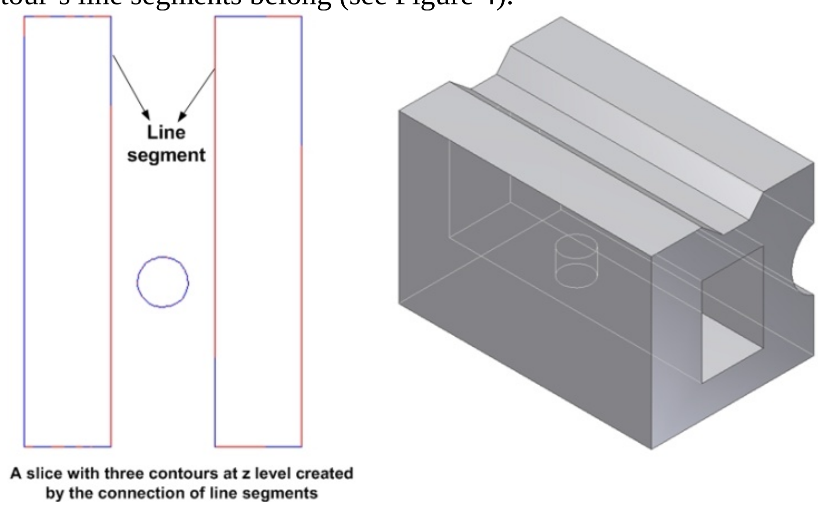


Figure 4. A sample 3D solid CAD model with its slice containing three contours .

4. Adaptive slicing algorithm

The previous works, while very significant in this field, have a few limitations. They commonly slice the direct CAD model or the tessellated version of the CAD model first at maximum available thickness, then apply some specific tolerances to break down the thicker slab into thinner ones or not to do so. The presence of any concave or convex area may yield a significant geometry deviation error when no staircase effect is identified at either slice of the layer. The area deviation could not be solely the accurate estimation for the degree of geometry deviation. Furthermore, the adaptive direct slicing which results in the intricate loops (contours) geometry has not been widely accepted as it needs the parametric equation of the enclosures. In addition, the use of the predefined available thicknesses for slicing purpose both for direct and indirect adaptive slicing has not been reported.

To overcome such limitations, a new direct slicing path algorithm is developed. It starts with the creation of all contours explained in Section 4 at a specific X, Y, or Z level depending on which cutting direction is chosen by the user (for simply explanation Z direction is assumed for slicing). Then, the bottommost slice resulted from the intersection of horizontal surface with the selected faces within Z boundary area (the area between z and $z + LT_{min}$) is created. Note that the bottommost slice at z=0 cannot be obtained as all facets on bottom surfaces are parallel to the XY-plane. Thereafter the position of the second slice at Z direction upward on CAD model is obtained by moving XY-plane parallel to the first slice at the minimum distance (minimum available thickness) in order to avoid significant part geometry deviation when no obvious staircase effect found at either slice. It is interesting to say that even though the presence of concave and convex area between two slices at minimum thickness would be inevitable, the geometry distortion at this point is small enough compared with that of thicker layer. The interior and exterior loops (contours) are then projected onto XZ-plane for the purpose of calculating the maximum and minimum points $(x_{min}, x_{max})$of each pair of projected contours. The triangle areas known as the staircase region at the right and left corners of all projected contours are computed, respectively. If the value of one of the right or left triangle areas of all investigated pair contours is less than the user-defined allowable error, then the second layer is removed from memory (see Figure 5). Unless the imposed condition (allowable error) is not satisfied, the removal of the layers is continued.

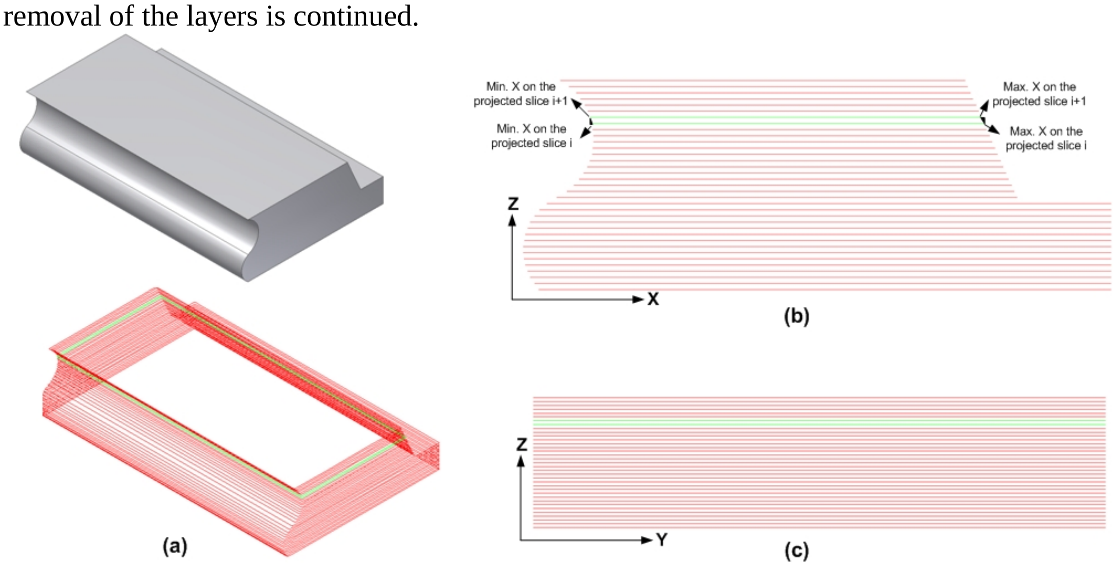


Figure 5. Staircase effect detection a) a 3D solid model with its sliced CAD model b) the identification of staircase effect in either side of the slices projected on ZX-plane c) lack of staircase effect on the right and left side of the slices projected on ZY-plane.

In addition to triangle areas investigation, sudden changes in the curved area on part geometry must be taken into account by comparing the cross product of vectors created by the connection of either maximum or minimum points of upper or lower slices and Z normal vector. It is commenced by figuring out the cross product of the vector $(\overrightarrow{V_{L_i}})$ and Z normal vector $(\vec{A} = \overrightarrow{V_{L_i}} \times \overrightarrow{N_z})$ in the preceding layer (L_i) then comparing it with that of the succeeding layer $(\vec{B} = \overrightarrow{V_{L_{i+1}}} \times \overrightarrow{N_z})$. If the sign of second cross product value is distinct from its corresponding in preceding layer, then eliminating the upper slice is stopped and the appropriate layer thickness is set at the desired amount. Figure 6 shows that how the sudden change might be taken place while it is being tried to execute the slice elimination algorithm. Following the discarding the upper slice, if the current vertical distance between the removed slice and the initial slice is matched with the user defined thicknesses then the adaptive thickness is established, otherwise the current distance is manipulated to fall within available user-defined thicknesses. After reaching a position at Z level where the calculated tolerance exceeds the threshold amount, the new position at $z + LT$ (fitted thickness) is set as the fresh initial Z level. The same approach for slicing the CAD model at the new Z level is iterated.

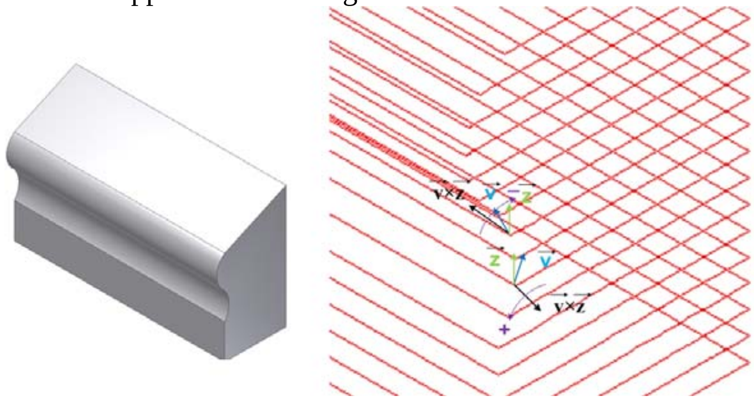


Figure 6. A 3D solid model with its partially enlarged sliced model illustrating the change of curve direction on layers.

Additionally, it is possible that no computed triangle areas as the representative of error threshold would surpass the tolerance when sliced in Z direction. So it is likely that the obtained adaptive slices would disregard the geometry distortion in different views. As a result, in order to identify staircase effects in other directions, a similar approach explained for the slices mapped on XZ-plane is implemented for all pairs of the projected contours on the YZ-plane as well.

Surprisingly, we may not be able to detect all curved area on part while implementing the algorithm on both YZ and XZ planes. Therefore, it might exist any curvature on part geometry which was not revealed by the projection of the contours on either sides. To tackle such problem, it is required to check the area deviation for all pairs of contours generated in lower and upper slices of the layer to see whether or not the area deviation is exceeding the defined tolerance. Because all contours generated in this system were created by the connection of the continuous vectors in clockwise fashion, the inner area of each closed loop boundary (contour) is easily computed by the following equation in contrast with the previous direct slicing approaches that used complex mathematical calculation for each entity (e.g. spline, ellipse, circle, etc) of closed loops.

$$\text{Inner Area}=\frac{(x_1y_2-x_2y_1)+(x_2y_3-x_3y_2)+\cdots(x_ny_1-x_1y_n)}{2}$$

Where x_i, y_i are the coordinates of the initial and ending points of the line segments (vectors). The process of adaptive slicing is continued to reach the topmost of the CAD model (see algorithm flowchart in Figure 7 for more details). To maximize the benefits of adaptive slicing, the proposed system enables users to cut the CAD model in two other orientations (Y, Z) as well. Because there is only two available machines (waterjet and laser cut) by which any metal or non-metal part can be cut into various thickness without need for a proper machine setup, the proposed direct adaptive slicing system was tested on FDFF process which is based on the parts cut by water jet and laser cutter machines.

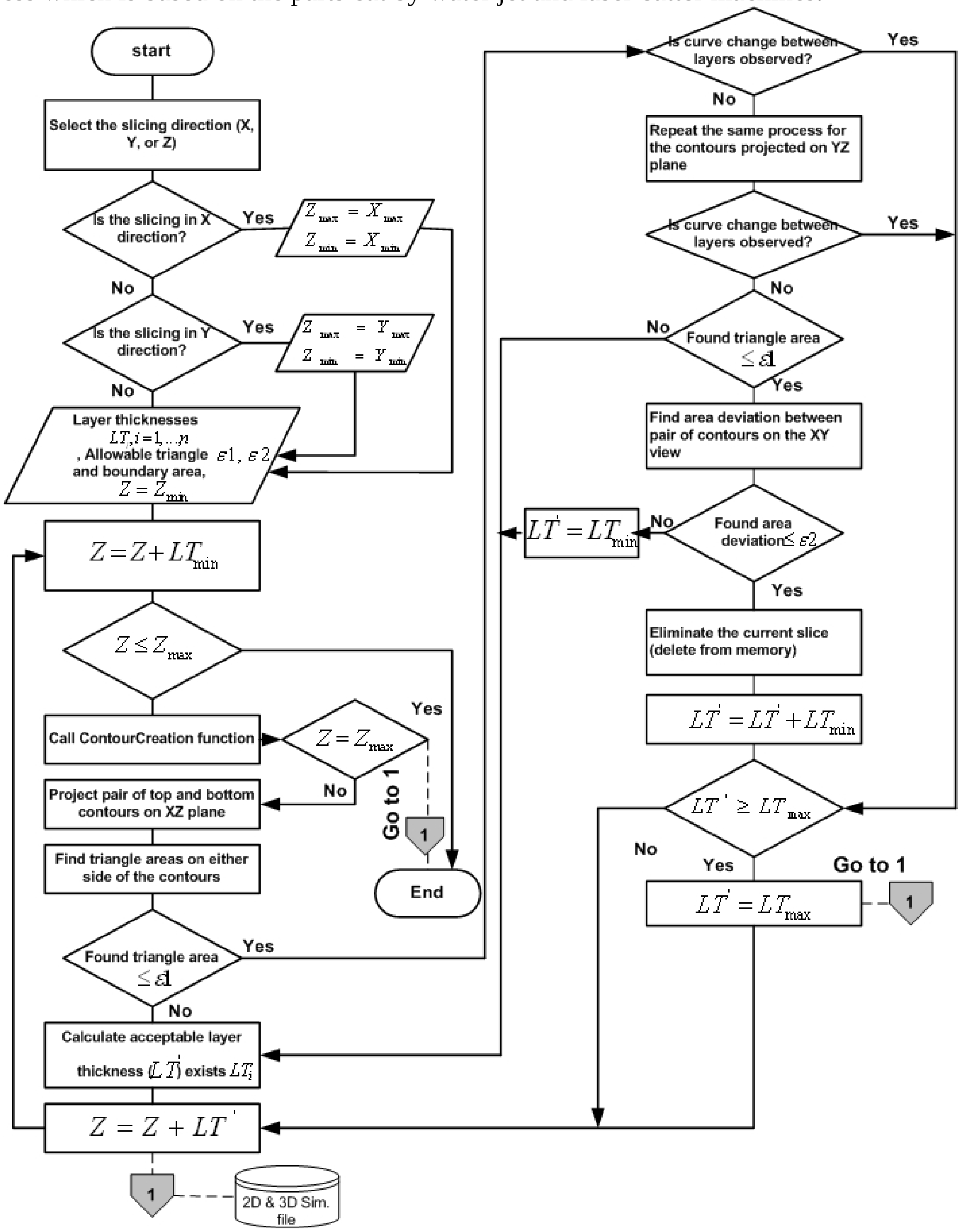


Figure 7. Flow chart for the proposed adaptive slicing algorithm.

5. System implementation

These algorithms were implemented using the Visual Basic for Application (VBA) and Autodesk Inventor mechanical design software. The Autodesk Inventor API functions were used to gain access to specific objects of a part model (e.g., Feature, Type of Feature, Face, Facets, Edge). The Inventor's VBA provided an easy way of accessing the design features and generating the facets for all faces of the features. A user interface form facilitates data entries (i.e., slice direction in either X, Y, or Z directions, various sheet thicknesses, allowable errors for boundary area deviation and triangle area). Figures 8 illustrates user interface form for direct adaptive slicing system. The user can select the file name and directory to save the generated codes. Even though the generated machine codes (i.e., contour data) are saved in one text file, the software output can be demonstrated layer by layer in the 2D and 3D versions. In the 2D version, the generated layers are spread on the XY-plane and grouped in different columns according to their sheet thickness realized by the proposed system. In contrast, in 3D version all layers in their own thickness are stacked together in build direction to form an approximate real 3D solid model for better visualization of the final physical part being fabricated by fully dense freeform fabrication (FDFF) process. This format of demonstration makes it easier to check the accuracy of the generated code.

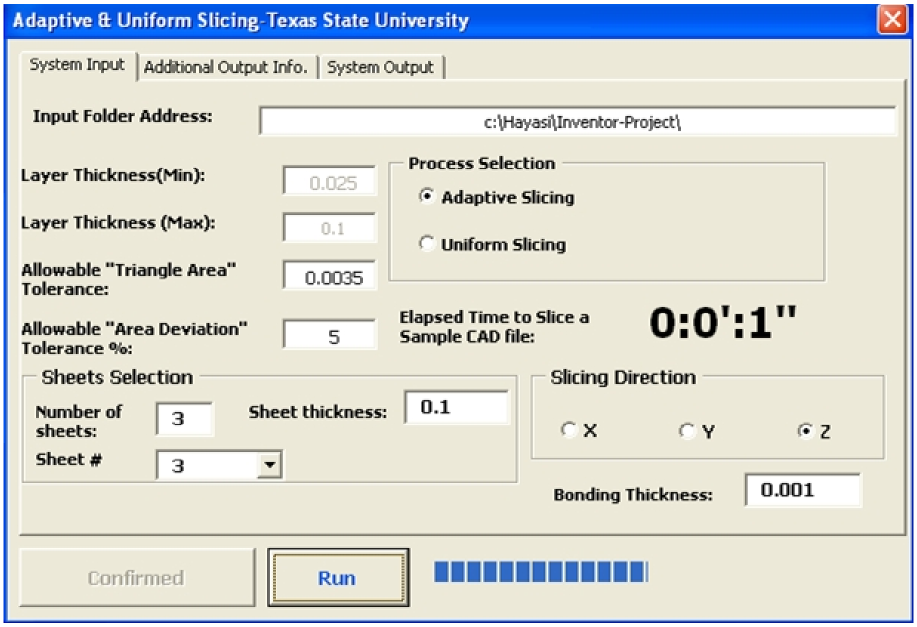


Figure 8. The user interface form.

6. Results

This software was successfully tested for many complex models with a variety of features. For better evaluation of the system, 2D and 3D AutoCAD script files generation were added to the system's output. Such files are easily run in AutoCAD to illustrate the boundary for different layers. The following three examples illustrate system output in AutoCAD environments. In the first two examples, the following required inputs essential to launch the program are entered by the user: three available sheets with thickness of 0.025, 0.1, and 0.2 inch, the slicing orientation of Z, Y, and X for examples 1, 2, and 3 respectively. Allowable triangle area tolerance (0.0045) and allowable boundary area distortion (4%) are provided to control the thickness of the layers based on the part geometry characterization. In the third example, available thicknesses are assumed to be 0.01, 0.03, 0.05, and 0.1 in. and the CAD model is sliced in Z orientation with allowable tolerances as 0.0035 and 3%, respectively.

Example 1 for adaptive slicing with the lack of staircase effect on XZ and YZ views: Figure 9(a) shows the solid CAD model drawn in Inventor. This model is chosen to verify the methodology dedicated to the slicing of a part while the staircase effect is lacking. System starts slicing the CAD model form the bottommost at z=0 featured in region 1(Figure 9b). It continues moving upward at Z-direction by adding minimum thickness of 0.025 in. Because there is no staircase effect in the region 1, the system stop eliminating the thinner layers until it reaches slice #2 where the maximum thickness of 0.2 in. is applied. The same way is followed for the second layer at stop point positioned in slice #3. Then it continues the slicing in region 1 until getting to slice #7. The obtained layer between slices #3 and #7 accounts for the thickness of 1.075 in. which is not in the list of available sheet thickness. To fit the acceptable thickness, the system defines the nearest thickness of 1.0 in. to the current value of 1.075in. Since the thickness (0.075 in.) of the layer from slices #4 to #7 cannot be fitted with any available thicknesses, it is divided into three small slabs each 0.025 in. height. The region 2 is the interesting area where no sign of staircase effects is found while projecting the created contours on either ZX or ZY plane. In this situation, the present system relies on boundary area deviation of the slices projected on XY plane. The computed area deviation for all pair of the slices from #7 to #24 never satisfies the allowable boundary area tolerance meaning that equal thickness of 0.025 in. is applied for all slabs in region 2 (Figure 9c).

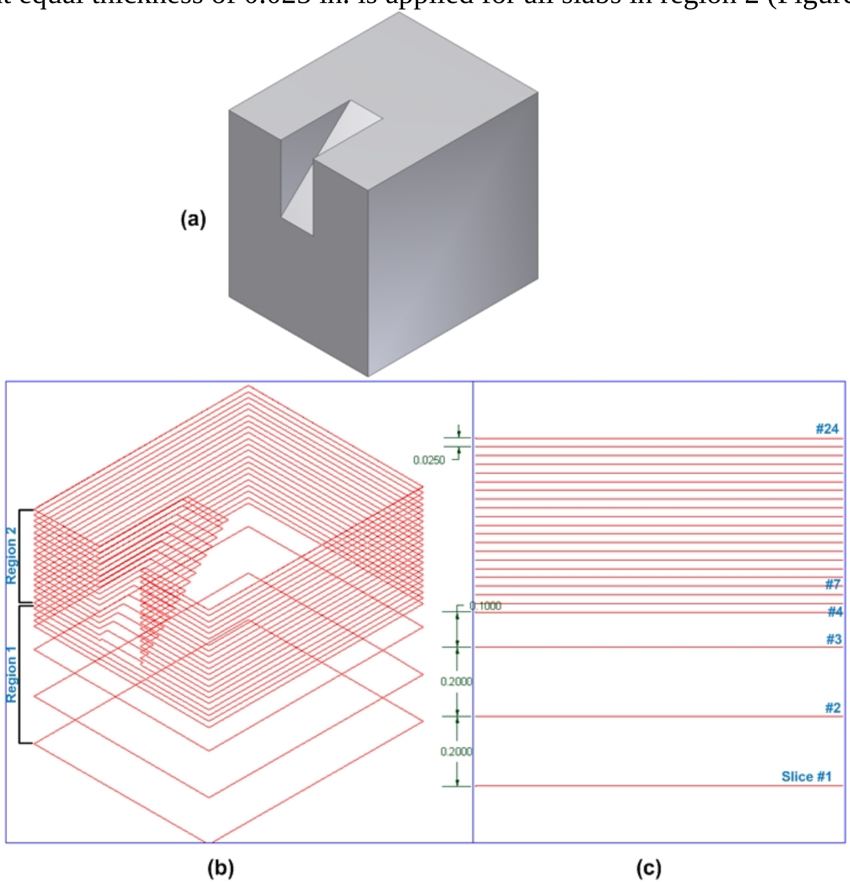


Figure 9. Visualization of the original Inventor CAD model (a) the simulated 3D format in AutoCAD for the adaptively sliced sample part (b) front view of the sliced sample illustrating the variable thicknesses in different regions.

Example 2: Figure 10a depicts a front axle drawn in Inventor. This complex geometry model is chosen to demonstrate the ability of the system in adaptively slicing any sophisticated CAD model with various sheet thicknesses. The system generates 3D simulated file in AutoCAD to display the accuracy of the slicing (Figure 10b). In front view of the sliced CAD model (Figure 10c), the different thicknesses conformed to the available sheet thicknesses are applied throughout the part according to its geometry. In addition to 3D sliced file, a 2D file encompassing all layers spread on XY plane is generated. The generated layers are grouped based on their equal value of thickness in different columns parallel to each other to distinguish the layers required to be cut at single setup on Waterjet cutting machine (see Figure 10d). It has to be noted that very few slices (at most one or two) shown in Figure 10d as red color might be left at the topmost of the part with the unmatched thickness while slicing the CAD model due to having thickness less than the available minimum one.

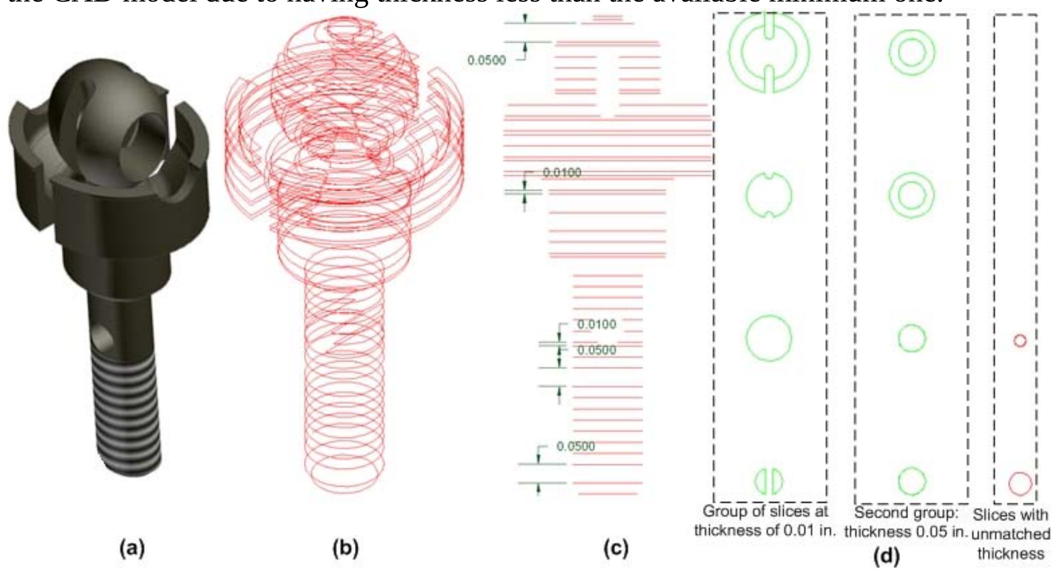


Figure 10. Visualization of the original Inventor CAD model (a), adaptive 3D slices (b), front view of the sliced CAD model (c), the illustration of few layers grouped based on their similar thickness and spread on 2D plane (d).

Functionality test for metallic parts. To test the accuracy of the proposed system, different models were sliced and built by the FDFF process. Figure 11 illustrates some of the manufactured functional prototypes by variable sheet metal thicknesses.

Figure 11. Functional parts, including a demolition hammer head, bike crank, and a composite bridge test car manufactured by FDFF.

7. Conclusion

This paper describes a new adaptive slicing approach for prototypes fabricated by FDFF process with sheets of variable thicknesses. In the proposed system, the combination of the area deviation and triangle area tolerances of the projected contours on top and side views were utilized for complex geometry detection. Since this system started cutting the CAD model from the bottom upward at the minimum thickness, any sudden changes to a part's geometry by appearing convex or concave regions were well detected in order to avoid any big geometry distortion error. The proposed system was implemented by Visual Basic code inside Autodesk Inventor. The developed system was tested for several models with complex features.

Future research of the adaptive slicing for FDFF process should focus on the generation of adaptive paths with variable cutting angles for the five-axis abrasive waterjet cutter machine to cut with both positive and negative angles. It is expected that the combination of adaptive slicing with angular cutting will remarkably improve the dimensional accuracy and the surface quality of the parts through significant reduction of the part geometry distortion.

References

Asiabanpour, B., & Khoshnevis, B. (2004). Machine path generation for the SIS process. *Robotics and Computer-Integrated Manufacturing, 20*, 167-175.

Chang, C. C. (2004). Direct slicing and G-code contour for rapid prototyping machine of UV resin spray using PowerSOLUTION macro commands. *International Journal of Advanced Manufacturing Technology, 23*(5-6), 358-365.

Chen, X., Wang, C., Ye, X., Xiao, Y., & Huang, S. (2001). Direct slicing from PowerSHAPE models for rapid prototyping. *International Journal of Advanced Manufacturing Technology, 17*(7), 543-547.

Choi, S. H., & Kwok, K. T. (1999). *A memory efficient slicing algorithm for large STL file.* Paper presented at the Solid Freeform Fabrication Symposium, Austin, Texas.

Chua, C. K., Gan, J. G. K., & Tong, M. (1997a). Interface between CAD and Rapid Prototyping systems .1. A study of existing interfaces. *International Journal of Advanced Manufacturing Technology, 13*(8), 566-570.

Chua, C. K., Gan, J. G. K., & Tong, M. (1997b). Interface between CAD and Rapid Prototyping systems .2. LMI - An improved interface. *International Journal of Advanced Manufacturing Technology, 13*(8), 571-576.

Cormier, D., Unnanon, K., & Sanii, E. (2000). Specifying non-uniform cusp heights as a potential aid for adaptive slicing. *Rapid Prototyping Journal, 6*(3), 204-211.

Dolenc, A., & Makela, I. (1994). Slicing Procedures for Layered Manufacturing Techniques. *Computer-Aided Design, 26*(2), 119-126.

Hayasi, M. T., & Asiabanpour, B. (2009). Machine path generation using direct slicing from design-by-feature solid model for rapid prototyping. *International Journal of Advanced Manufacturing Technology, 45*(1-2), 170-180.

Hayasi, M. T., & Asiabanpour, B. (2010). *Adaptive Layering Technique for the Fully Dense Freeform Fabrication (FDFF) Process*. Paper presented at the Second International Research Conference for Graduate Students, Texas State University-San Marcos.

Jamieson, R., & Hacker, H. (1995). Direct slicing of CAD models for rapid prototyping. *Rapid Prototyping Journal, 1*(2), 4-12.

Jung, J. Y., & Ahluwalia, R. S. (2005). NC tool path generation for 5-axis machining of free formed surfaces. *Journal of Intelligent Manufacturing, 16*(1), 115-127.

Jurrens, K. K. (1999). Standards for the rapid prototyping in industry. *Rapid Prototyping Journal, 5*(4), 169-178.

Koc, B., Ma, Y. W., & Lee, Y. S. (2000). Smoothing STL files by Max-Fit biarc curves for rapid prototyping. *Rapid Prototyping Journal, 6*(3), 186-203.

Kulkarni, P., & Dutta, D. (1996). An accurate slicing procedure for layered manufacturing. *Computer-Aided Design, 28*(9), 683-697.

Kumar, C., & Choudhury, A. R. (2005). Volume deviation in direct slicing. *Rapid Prototyping Journal, 11*(3), 174-184.

Pande, S. S., & Kumar, S. (2008). A generative process planning system for parts produced by rapid prototyping. *International Journal of Production Research, 46*(22), 6431-6460.

Pandey, P. M., Reddy, N. V., & Dhande, S. G. (2003). Real time adaptive slicing for fused deposition modelling. *International Journal of Machine Tools & Manufacture, 43*(1), 61-71.

Singhal, S. K., Prashant, K. J., & Pulak, M. P. (2008). Adaptive Slicing for SLS Prototyping. *Computer-Aided Design and Applications, 5*(1-4), 421-423.

Tyberg, J., & Bohn, J. H. (1998). Local adaptive slicing. *Rapid Prototyping Journal, 4*(3), 118-127.

Vouzelaud, T., & Bagchi, A. (1995). 5, 432, 704.

Vuyyuru, P., Kirschman, C. F., Fadel, G., Bagchi, A., & Jara, C. C. (1994). *A NURBS-based approach for rapid product realization.* Paper presented at the Proceedings of the 5th International Conference on Rapid Prototyping, The University of Dayton.

Xu, F., Wong, Y. S., Loh, H. T., Fuh, J. Y. H., & Miyazawa, T. (1997). Optimal orientation with variable slicing in stereolithography. *Rapid Prototyping Journal, 3*(3), 76-88.

Zhao, Z. W., & Laperriere, L. (2000). Adaptive direct slicing of the solid model for rapid prototyping. *International Journal of Production Research, 38*(1), 69-83.