International Journal of
Science and Engineering Investigations vol. 8, issue 86, March 2019
Received on March 6, 2019 ISSN: 2251-8843

Optimal Building Orientation Based on Minimum Volumetric Error Using a New Direct Slicing Algorithm

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Abstract- Model orientation is one of the most critical process parameters in Additive Manufacturing (AM) processes since it affects part quality. There are many different numbers of criteria may be used for assessing the prototype's error. The volumetric error of model approximation is considered in this study. This paper was aimed to determine the optimal build-up direction of a model based on a volumetric error approach by using a uniform direct slicing algorithm. In the current work, firstly slices the CAD model uniformly with horizontal planes and control the geometrical accuracy of the generated layers by using a new refinement approach. Then computes the volumetric error at different orientations by an automated rotation system with step angle about the user-specified axes. The validity and efficiency of the algorithm are evaluated by an example with a complex shape. This algorithm will be useful for AM users in creating AM physical models with a higher level of dimensional accuracy and surface finish. The algorithm is developed and implemented by PTC Creo Parametric 3.0 which also used as a design-by-feature solid modeler.

Keywords- *Additive Manufacturing, Direct Slicing, Model Orientation, Volumetric Error*

I. INTRODUCTION

The growth of Additive Manufacturing (AM) in various applications has created the need for better technology in terms of model accuracy [1]. In commercial AM systems, the process begins by slicing the CAD model to obtain a 2D contour at each level of the build axis (Z-axis). Starting from the base 2D contour, slice thickness is defined by the user which added cumulatively at successive slicing planes [2]. This layer by layer stacking gives rise to an error in the part because of the amount of material used compared to the volume specified by the computer-aided design (CAD) software, the magnitude of this error, called a staircase error. The effect of the staircase feature is illustrated in Fig. 1. This effect varies with the type of surface of the part. Inclined and curved surfaces show staircase effects significantly more than other surfaces which leads to poor surface quality of the part [3]. Also, the orientation at which the part is built can have a significant effect on the part quality of its various surfaces types because of this staircase effect. This hateful feature is impossible to eliminate it completely but can be reduced by decreasing the layer thickness and by orienting the part so that the effect of the overall staircase error is significantly reduced. Thus, the determination of an appropriate orientation of the part during the building process has therefore been an important issue in AM for improving the geometrical accuracy and parts quality [4, 5]. Traditionally, the AM process involves the conversion of the 3D models into the STereoLithography (STL) format. The STL format is a polyhedral representation of the CAD model with triangular facets. It is generated by any CAD software through a process known as tessellation, which generates facets to approximate the CAD model [6]. The tessellation procedure means the model is approximated by triangles, sliced and then fabricated by the device. This process is inadequate for designing complex parts. This is due to a large number of triangles required to represent small features in these complex parts which result in failure during the conversion process [7]. The original CAD model already accurately represents the determined design, but STL files decrease the accuracy of the model. Also, the STL files generally carry defects like gaps, overlaps, degenerate facets etc. and it has a high degree of redundancy since each triangle is individually recorded and shared ordinates are duplicated. Hence, repair software is needed. The production of the high surface of the physical model using the STL format will cause the file to a huge, slice time-consuming. There is an urgent need to obtain more precise data from the CAD model section that describes the information of CAD directly [8].

Figure 1. "Staircase" effect showed in spherical shape during Additive Manufacturing

Direct slicing of CAD models without the intermediate files is preferred because it helps keep the geometric that the original data have and no intermediate conversion process is required. The concept of direct slicing is utilized the exact boundary of the original CAD model instead of the approximated boundary of its tessellated model [9]. To reduce errors in the X-Y plane, direct slicing uses the exact contour of the CAD model instead of using STL files. The direct slicing has advantages over the traditional slicing method which include greater model accuracy, pre-processing time reduction, checking and elimination of repair routines and file size reduction [10]. Slice thickness, building orientation, thermal errors, support structures are a few major parameters which affect part accuracy [11].

This study introduces a new part orientation system, which used a new method to uniformly slice of a solid model of any complexity in a CAD system with horizontal planes at a referenced layer thickness. This system was designed to represent the boundary (contour) of each sliced layer in a new refinement approach. The system then determines the volumetric error in the part at different orientations by rotation about user-specified axes. The system takes into account the volumetric error in parts during the building process to determine the optimal orientation.

II. Literature Review

The influence of build orientation on dimensional accuracy based on volumetric errors has not been studied in detail and a limited number of papers have been published. The following section presents some of the prior research that has been published in each of these areas;

[12, 13], analyzed the effect of build orientation on circularity error and developed a correlation between circularity errors, slice thickness and build orientation. The authors also introduced a graphical approach to finding the optimal build orientation. [14], calculated the volumetric errors of the CAD part at different orientations by assuming that a complex part is constructed by combining basic primitive volumes. The paper recommended the best build orientation to be the one with the least volumetric error. [15] presented an algorithm for building a software program to read STL file, reorient the model with the definite step of angle for actual different values of layer thicknesses and estimate the total building error in each step and give the optimum building orientation with an appropriate layer thickness in order to improve the RP part accuracy. [16], defined the adaptive slicing structure with a focus to reduce part geometric errors. [17], used the ANOVA technique to evaluate circularity error for parts built by the AM process using the experimental procedure. [18], experimentally investigated the influence of process parameters including layer thickness, part orientation, raster angle, air gap and raster width on dimensional accuracy in FDM processes. Also, the author used Taguchi method to attain an optimal level of process parameters to minimize shrinkage and maintain part accuracy. [11], developed an algorithm to obtain an optimal build orientation while minimizing part errors and support structures. [19], analyzed the effect of the staircase error on the overall part accuracy and quality by formulating adaptive slicing algorithm as an optimization problem. [20], conducted an experimental study on GD&T (Geometric Dimensioning and Tolerancing) form errors including straightness, flatness and circularity errors. An experimental validation includes the analysis of above errors on a set of eight parts manufactured using an adaptive sampling procedure. [21], applied Response Surface Methodology while studying the effect of process parameters on six tolerances: positional, flatness, parallelism, perpendicularity, concentricity and circularity. For their design of experiment study, they used wait time, slice thickness, over cure and sweep period as their input variables and used a second-order response surface to correlate the part errors with the inputs.

This previous effort provided good contribution but does not present an algorithm to choose the best building orientation with direct slicing to minimum building volumetric error. In addition, it does not present good explanation and detailed algorithms to help the researchers make software to study the different parameters in AM without the experimental work. This paper presents an algorithm to determining the optimal build-up direction of a model based on a volumetric error approach by developing a new uniform direct slicing algorithm. In addition, a new refinement approach was proposed to control the geometrical accuracy of the generated layers. This algorithm will be useful for AM users in creating AM physical models with a higher level of dimensional accuracy.

III. The Presented Algorithm

The present algorithm consists of two stages is shown in Fig. 2, the first one will establish the new orientation system in an automated manner, while the second stage will involve refinement of each layer boundary contour accuracy that used instead of any other adopted parametric representation methods. The presented algorithm consists of the following three modules;

A. *Module 1:*

Automated numerical method to find out a several of orientation data files for the 3D CAD model, that occurs during rotation of the CAD model with pre-specified step angles around X, Y axes (θx and θy respectively) the combination of them.

B. *Module 2:*

A direct slicing algorithm to slice a 3D CAD solid model directly by a constant layer thickness instead of using the STL file. During this module, a new approach is proposed to represent the boundary contour of each sliced layer to geometric refinement to maintaining the representation accuracy of an original CAD model.

C. *Module 3:*

Geometrical accuracy analysis is used for volumetric error computation and evaluation.

In the steps that follow, explaining the details regarding CAD Model auto-orientation, Auto-Section, refinement approach and selection of optimal orientation based on a volumetric error approach.

1) Step 1: CAD Part Creation

PTC Creo Parametric 3.0 software used in this study as a design-by-feature solid modeler and also used for implement the proposed algorithm. At first; modeled a column that uses a tool for implementing the uniform direct slicing process CAD model by programmed all procedure of slicing process through it. This slicing is done for CAD model by call slicing sub-routine after merging it with the column. This column created with a specific diameter and height. PTC CAD software also used here for modeled the presented case study to validate this research. To test the concepts to determine the optimum part orientation, consider the Hammer Head as an example as shown in Fig. 3.

The length, width (diameter), height and volume of the model are 25.456 mm, 45.000 mm, 87.930 mm and 26831.6 mm3 respectively.

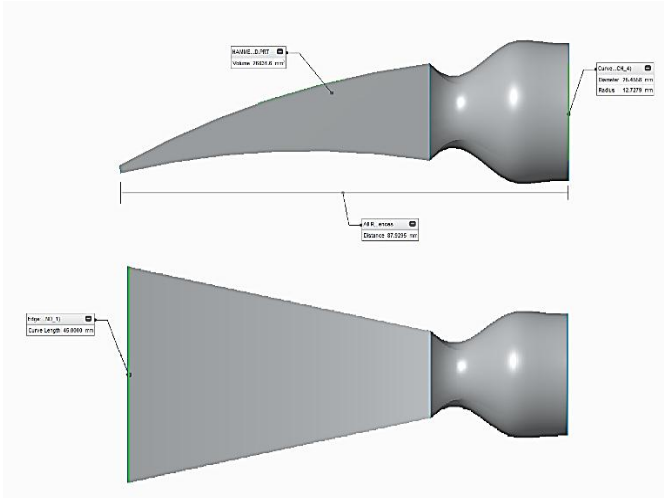

Figure 3. The 3D CAD model in its designed orientation

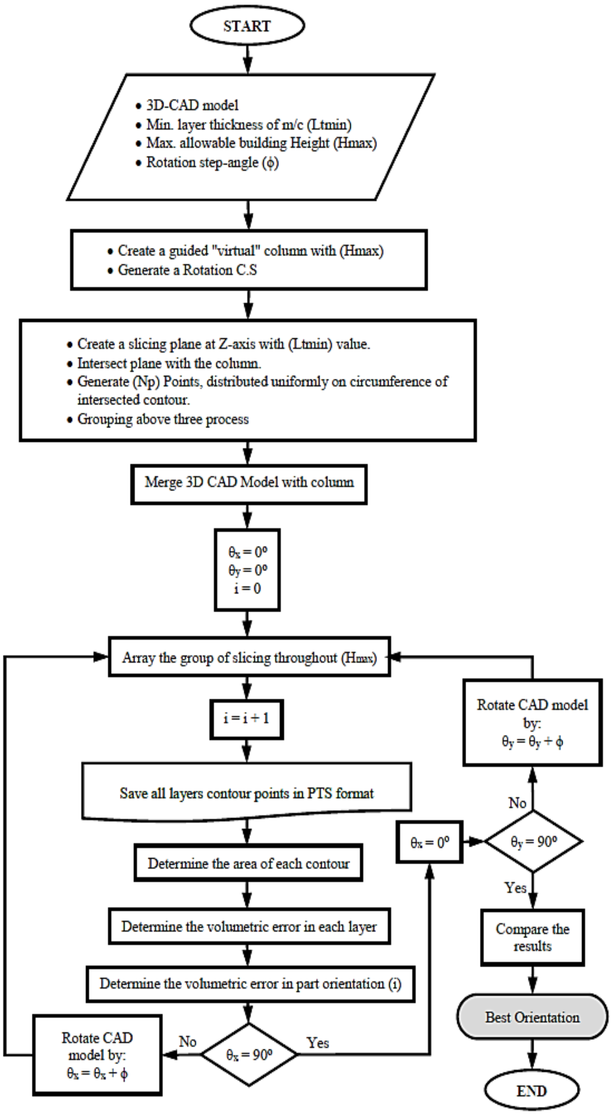

Figure 2. Flowchart for determining the optimum orientation about two axes based on a volumetric error.

2) Step 2: Automated CAD model orientation

The model orientation within the fabrication platform of the AM system affects the surface finish, part strength and building time. Thus, before the building of the physical part, a minimization of certain objective criteria specified by the designer will be done to find the optimal building orientation. There is various number of orientation schemes have been devised. In the presented study, the authors have used a new scheme in which the model is incrementally oriented about user-specified axes (x, and y) automatically to obtain a certain orientation of the 3D model, to be ready for next step.

3) Step 3: CAD Model Auto-Section

In this step; each oriented CAD model is sliced uniformly from bottom to top by horizontal planes separated by a distance equal to the selected layer thickness (shown in Fig. 4). This slicing procedure developed using the PTC Creo Parametric 3.0 CAD software features by the authors and saved as a subroutine which can be called after merged the CAD model with the guided column. This Auto-Section procedure creates a large number of intersection contours for each CAD model and saves them as IGES (Initial Graphics Exchange Specification) files.

4) Step 4: Layers Contour Refinement

Refinement of the generated contours is the process in which an addition of more points is added to the boundary without changing its original shape. The process is implemented using the PTC Creo Parametric 3.0 CAD software. The main idea of refinement is creating many points that coincident and distributed uniformly on layer contour. Increasing the layer contour points will reduce the line segment's distance (polyline) that represent the 2D contours and will increase the accuracy in the X-Y plane. The generated points are saved as PTS (Points) files which sorted automatically. The refinement procedure is illustrated in Fig. 5. This approach is more efficient and accurate compared with NURBS curve based representation or any other adopted parametric representation.

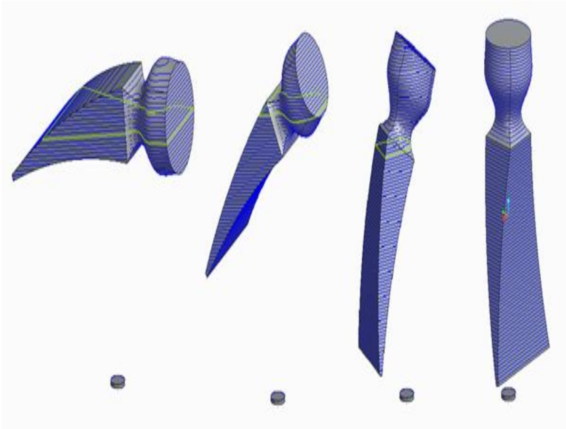

Figure 4. Auto-Section (slicing) procedure at a different orientation

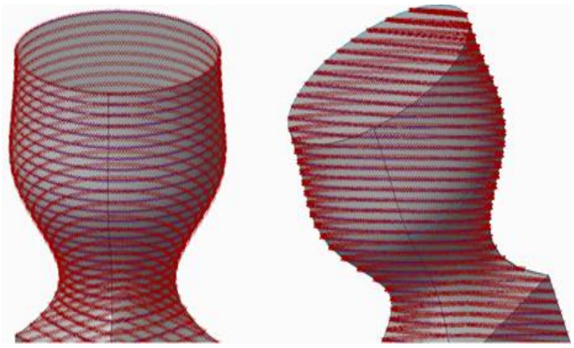

Figure 5. Case study after refining the intersection contour of each layer

IV. Decision Criteria for Determining the Part Orientation

The main objective of this research is to find the optimum orientation of the 3D CAD model that lead to improving the part quality. Volumetric error, which mainly caused by the difference between the CAD and physical mode is used to assess the part quality.

A. *Geometrical Accuracy Analysis Model*

In this research, the volumetric error evaluation is used for geometrical accuracy analysis of AM models. The geometrical error of an AM model can be calculated below;

$$E = \frac{G_{error}}{V_{CAD}} \times 100 \quad \%$$

Where E represents the percent of geometrical error; VCAD is the actual volume of the CAD model; Gerror is the predicted volume error of the AM model (shown in Fig. 6).

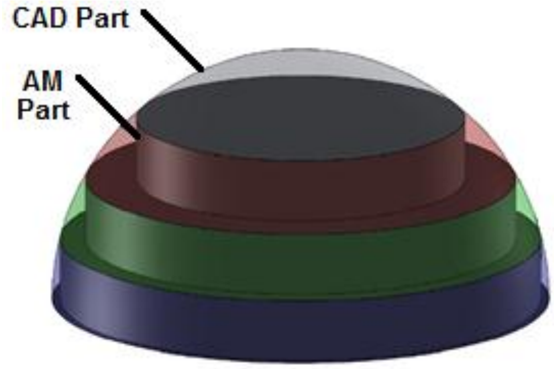

Figure 6. Illustration of Geometrical error for a hemispherical part.

G_{error} can be computed below:

$$G_{error} = V_{CAD} - V_{AM}$$

$$G_{error} = \sum_{i=1}^{n} G_{error}^{i}$$

Where V_{AM} represents the actual volume of the physical AM part; i is the index of a sliced layer; n is the total number of the layers; G_{error}^{i} is the geometrical error on the ith layer of the model (shown in Fig. 7).

G_{error}^{i} is from a Type I error $G_{error-\text{type I}}^{i}$ and a Type II error $G_{error-\text{ type II}}^{i}$ (shown in Fig. 8). The two errors are defined as follows:

A Type I error $G_{error-\text{type I}}^{i}$ is accumulated between consecutive layers, and it is the principle error of AM. It is affected by the thickness of the layer: the thicker of the layer, the greater of the Type I error.

A Type II error $G_{error-\text{ type II}}^{i}$ is accumulated along the boundary of every layer. It is in the boundary area which is not filled during the AM process.

G_{error}^{i} is computed below:

$$G_{error}^{i} = f\left(G_{error-\text{type I}}^{i}, G_{error-\text{ type II}}^{i}\right)$$

$$G_{error} = V_{CAD} - \sum_{i=1}^{n} V_{AM}^{i}$$

Where V_{AM}^{i} is the AM model volume of the ith layer, computed below;

$$V_{AM}^{i} = a^{i} \times H^{i}$$

Where a^{i} is the AM local area of the ith layer, and H^{i} is the thickness of the ith layer.

$$\therefore G_{error} = V_{CAD} - \sum_{i=1}^{n} a^{i} \times H^{i}$$

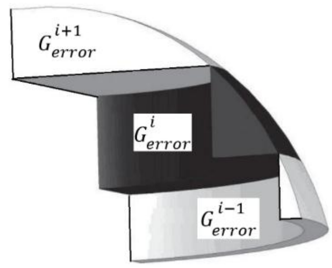

Figure 7. Local volumetric error in some successive layers

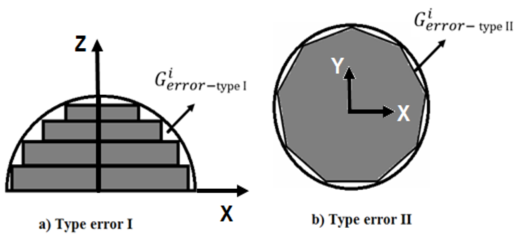

Figure 8. Geometrical errors calculation of AM model.

The percentage of relative volumetric errors are shown in table I. These data for the Hummer Head as a case study. It was displayed and computed using the new algorithm at each orientation which model rotated about the x- and y-axis by steps equal 30°, in ranging from 0° to 90°. This orientation process implemented after the direct slicing process that occurs uniformly with 1 mm as a constant value of layer thickness and also after contour refinement process for each layer.

TABLE I. PERCENTAGE VOLUMETRIC ERROR FOR A HUMMER HEAD PART ROTATED ABOUT THE X AND Y-AXIS.

Orientation	θx	θy	No. of layers	VAM (mm3)	Gerror (mm3)	% E
1	0	0	26	26476.4438	355.1562	1.32364897
2	0	30	93	26555.8912	275.70883	1.02755268
3	0	60	74	26487.6223	343.97774	1.28198745
4	0	90	26	26322.6223	508.97774	1.896934
5	30	0	64	27050.6248	-219.0248	-0.81629422
6	30	30	90	26631.8941	199.70593	0.74429379
7	30	60	72	26929.7851	-98.185083	-0.36593078
8	30	90	40	26980.9245	-149.32446	-0.55652461
9	60	0	87	26941.6943	-110.09433	-0.41031594
10	60	30	69	27157.1079	-325.50793	-1.2131514
11	60	60	63	26971.5364	-139.9364	-0.52153581
12	60	90	36	27157.6673	-326.06731	-1.21523619
13	90	0	88	26823.2901	8.3098515	0.03097039
14	90	30	33	26538.9424	292.65759	1.09071987
15	90	60	38	26629.2843	202.31565	0.75402008
16	90	90	45	26451.5559	380.04406	1.41640477

Fig. 9 , that shows the variation of relative volumetric error versus different orientations of CAD model in the x- and y-axis, It is found that the best orientation angle recommended by this system is (orientation # 13) 90° and 0° in x and y-axis.

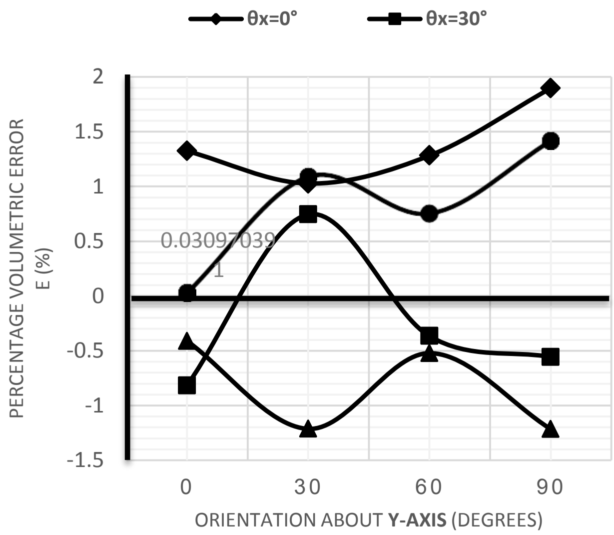

Figure 9. Variation of relative volumetric error

V. CONCLUSION

This work proposed a new algorithm able to determine the optimum orientation in the additive manufacturing processes for any complex solid part on the basis of minimum volumetric error. From the work presented, the following conclusions are drawn:

- The part orientation problem can be tackled in additive manufacturing by determination of the volumetric error encountered during the part building process for any part.
- The proposed system has also been verified analytically for parts with a combination of primitives and for several test parts of different complexity.
- Hummer head part example is presented using the proposed system.
- The methodology presented in this work has several advantages in helping to build good-quality prototypes in a reasonable time, Also will enable the AM user to make better decisions in fabricating AM parts with a higher degree of accuracy and surface finish.

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How to Cite this Article:

Sobhi, A., Hamoud, M. & Barakat A. (2019) Optimal Building Orientation Based on Minimum Volumetric Error Using a New Direct Slicing Algorithm. International Journal of Science and Engineering Investigations (IJSEI), 8(86), 43-48. http://www.ijsei.com/papers/ijsei-88619-06.pdf