Geometry Attributes Computation of 3D Model for Additive Manufacturing

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Abstract. Additive manufacturing (AM) is a process to create objects layer-by-layer directly from a CAD model. In principle, any product even with complex structures can be created by AM technology successfully. However, restricted by equipment, material, prototyping process etc., some features with special geometry attributes may fail to be created. Therefore, it's necessary to analyze and compute the geometry attributes of a model and further simulating the printing process before manufacturing. A peeling method based on voxel model and constraint size is presented to calculate the geometries. First, the geometry features of 3D model are classified into positive and negative features for AM. Next, the negative model is defined and identified based on voxel-based model. Then, the peeling methods for the computation of positive feature and negative feature based on constraint size are developed. Finally, the error of this method is analyzed and the main advantages of the proposed method is discussed.

Keywords: Additive manufacturing, Geometry attributes computation, Process analysis, Thickness, Negative model.
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1 INTRODUCTION

Since the development of 3D printing, researchers focus on how to manufacture the part. However, few attentions are paid to the relation about design, manufacturing and function realization. From the view of manufacturing, process inspection of part is one of the most important evaluation whether a design part can be successfully manufactured in order to achieve its function. Computation of geometry attributes of 3D model based on manufacturing ability is a necessary and feasible method to inspect process for additive manufacturing (AM). As so far, most of the research on manufacturability focus on design rules for AM (DfAM). Additionally, such rules are expected to provide direct guidelines for designing AM-destined parts in order to avoid or reduce the constraints of manufacturability lead by geometry attributes of 3D model. However, few reference is about geometrical attributes processing inspection of 3D model based on manufacturing feasibility. And currently, there is no provision in CAD software programs to automatically identify manufacturing constraints [15].

Doctor Thomas [16] in the University of Wales studied on the design rules of typical geometrical features in selective laser melting (SLM) by a range of experimental methods, including flat surface, cylinder, holes, overhanging faces and surfaces. In the white paper for DfAM of HCL Technologies Ltd. [4], the geometrical attributes constraints in the DfAM are discussed, including the maximum part size, faces requiring support, minimum wall thickness and rigidity, minimum feature size, and so on. To promote the application of additive manufacturing technology in different fields, a project named "Direct Manufacturing Design Rules" was proposed in Germany [1]. Adam and Zimmer [1] defined standard elements and divided them into three groups: basic elements or elementary geometrical shapes (e.g. Cylinders), element transitions (e.g. Joints) and aggregated structures (e.g. Overhangs) by a process independent method. In their research, design rules about sharp edges, gaps, overhangs in SLM and Fused Deposition Modeling (FDM) are investigated. With a view to the variations of design rules among different part structures, materials and processes, design rules as sets of modular components and associated formalisms are presented by Jee [6], so that the people can modify, extend, reconfigure, or customize generalized rules as needed instinctively and deliberately. Meisel and Williams [9] presented a series of designed experiments to determine key parameters that influence four specific manufacturing constraints, including minimum feature size, support material removal, feature survivability and self-supporting angles in the PolyJet process.

As so far, the research on the design rules for AM is mainly based on the physical test method with the benchmark model [2],[7],[17].However, the design rules based on this method are obviously directly related to the inherent constraints such as experimental equipment, so the conclusion may be biased [18].It can be seen that the design rules derived from the physical test method based on the benchmark model have obvious limitations, and are only applicable to the printing situation equivalent to the physical test, and have no general guidance and generalization.

Commercial software for design models analysis and slice data generation, such as Blender, Magics, and Maya, can estimate the print time and print consumables [3], optimize the print orientation, add support automatically, and generate print path [10],[14].Although these softwares can also identify some geometric errors, such as repeated vertices and self-intersections [12], the potential print constraint problems of 3Dmodels are not yet recognized due to the lack of suitable methods [9],[14]. As the printable thin walls may be limited by the type of AM process and resolution of the machine [8], or be so fragile as not to be able to survive post-processing [9], the minimum feature size is one of the most important AM constraints. As so far, MAT-based method (Medial Axis Transformation) [5],[10], distance transform method [14], peeling approach [11],[13] and offsetting method [2] are the main methods for the computation of the minimum wall thickness (minimum feature size) of an object. The advantages and limitations of MAT and point-based offsetting operation can be found in reference [15]. In Tedia and Williams' research [15], the input triangular mesh model is first converted into a voxel representation using Ray Casting. When they computed the minimum feature size, they transformed the thickness problem into a 2D problem. The feature size/thickness of any section of the object in Z direction is calculated by the equation: $t = \text{dist.}(R_i\ , R_{i+1}) = n \times d_j$, where d_j is the voxel dimension in the direction of voxelization. Then, the same procedure is repeated from other two coordinate axes directions and the results are combined together. However, the result relied on the selected coordinate axes or the aligned voxels. Additionally, as they defined the thickness of a sample section of the object along the ray direction as the distance from P to the intersection point of the ray with the opposite surface Q, the computation result may not be necessarily the real minimum thickness which constraint the manufacturability. In Subburaj's research [13], they presented three generic definitions of thickness: interior thickness of points inside an object, exterior thickness for points on the object surface, and radiographic thickness along a view direction. They also presented successive skin removal method and radiographic scanning normal to a viewing direction to calculate the three thickness.

Not only the thickness of an object is the important geometry attribute for manufacturability analysis, but also other minimum features as small hole, gap, slot, slender column, sharp corner are critical manufacturing constraints for AM. However, methods for thickness computation have received relatively more attention, but the calculation of other minimum features such as gap and slot are still not mentioned in these papers. Based on the DfAM and the requirement of process inspection, in this paper, a negative model for negative feature and a peeling method based on constraint size are proposed to analyze and compute the geometry attributes of CAD models for AM. First, the features are classified as positive features and negative features. And the negative model for the negative features is presented and defined. Next, a peeling method based on constraint size for voxelized model is proposed to compute the constrained features for AM. Then, the error lead by the voxelization is analyzed. Finally, the main advantages are discussed in the end.

2 FEATURE CLASSIFICATION AND NEGATIVE MODEL

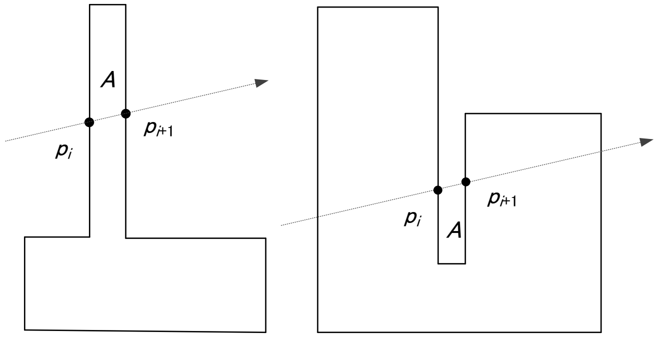
Holes are defined as one kind of negative features and are identified using ray method based on voxel model in Tedia and Williams' research [15]. However, they didn't give the unique definition of negative features and the computation result is slightly different (could be either more or less) from that along the coordinate axes along which the voxels are aligned. Here, the negative feature and the corresponding negative model are defined.

2.1 Negative Feature Definition

Given a ray l intersect a feature A of an model M with at least two points p_i and p_{i+1}, where p_i and p_{i+1} are both on the boundary of A, if

(1) points on the ray l between p_i and p_{i+1} are all inside of the model M, then feature A is a positive feature of M (Figure 1(a)).

(2) points on the ray l between p_i and p_{i+1} are all outside of the model M, then feature A is a negative feature of M (Figure 1(b)).



(a) (b)

Figure 1: Positive feature and negative feature: (a) positive feature A, (b) negative feature A.

According to the definition, thin walls, sharp corners, cylinders, bosses of a model are positive features while holes, gaps and slots are negative features.

2.2 Negative Model

Given B_M is the oriented bounding box (OBB) of model M, then model N where $N = B_M - M = \sum N_i$ (i = 1,2, ⋯, n) is the negative model of M (Figure 2). As shown in Figure 2, the negative model is separated into two independent parts N_1 AND N_2.

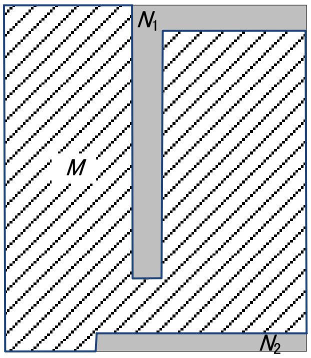


Figure 2: Negative model N (N = {N_1, N_2) of model M.

To obtain the negative model, the whole space inside of OBB, including the model M, is voxelized first. Given i, j, k are the values of the center point of a voxel, and the center point represents the related voxel in this paper. The voxels in the OBB space are classified into three types and the corresponding flag function satisfies the Equation (2.1):

$$f(i,j,k) = \begin{cases} -1, & \textit{if the voxel is outside of the model } M \\ 0, & \textit{if the voxel is on the surface of the model } M \\ 1, & \textit{if the vexel is inside of the model } M \end{cases} \tag{2.1}$$

Then all the voxels in the OBB are marked as Figure 3 and the voxels valued -1 and 0 construct the negative model.

-1	-1	-1	-1	0	0	0	-1	-1	-1
-1	-1	-1	-1	0	1	0	-1	-1	-1
-1	-1	-1	-1	0	1	0	-1	-1	-1
-1	-1	-1	-1	0	1	0	-1	-1	-1
-1	-1	-1	-1	0	1	0	-1	-1	-1
0	0	0	0	0	1	0	0	0	0
0	1	1	1	1	1	1	1	1	0
0	1	1	1	1	1	1	1	1	0
0	1	1	1	1	1	1	1	1	0
0	1	1	1	1	1	1	1	1	0
0	0	0	0	0	0	0	0	0	0

Figure 3: Voxels in OBB space are marked by the positions.

3 COMPUTATION OF GEOMETRY ATTRIBUTES BASED ON CONSTRAINT SIZE

The proposed method is based on voxel model and successive skin removal. The higher the resolution of voxelization is, the higher the computation accuracy is.

3.1 Computation of Positive Features with Constraint Size

As we know, the minimum printable thickness is one of the most critical parameter of each 3D printing machine. When the wall thickness of a model is less than the minimum printable thickness, the corresponding features would not be manufactured correctly. Thus, thickness computation with constraint size is proposed in this paper and peeling method or skin removal method is applied.

For a voxel-based model, a surface voxel of a positive model is one that has at least one exposed face (missing neighbor voxel) among the six faces. The surface voxels with value 0 represent the object skin. During an iteration, to remove the skin, a surface voxel is reset as -1 while its face-neighbored voxel marked 1 is reset as 0. Given the constraint size which is the smallest printable size is T, and t_0 is the voxel cell size, this peeling process can be repeated S times according to T,

$$S = \begin{cases} 0, & T \le t_0 \\ \left[\dfrac{T}{2t_0} \right], & T > t_0, 0 \le T\%(2t_0) \le t_0 \\ \left[\dfrac{T}{2t_0} \right] + 1, & T\%(2t_0) > t_0 \end{cases} \tag{3.1}$$

In Equation (3.1), $[T/(2t_0)]$ represents the round to nearest of T divided by $2t_0$, and $T\%(2t_0)$ is the reminder of $T\%(2t_0)$. Among the process, voxels satisfied one of the following cases (iteration end conditions) are highlighted as they are considered to represent the features under the limited size:

(1) $n \le S$ and the voxels of some part of the model cannot be removed anymore (Figure 4(a));

(2) $n \le S$ and only the innermost voxels are left (Figure 4(b)).

0	0
0	0
0	0
0	0
0	0
0	0

(a)

0	0	0
0	1	0
0	1	0
0	1	0
0	1	0
0	0	0

(b)

Figure 4: Iteration end conditions (a) and (b) from left to right.

Wherein, n is the layers of the feature can be peeled. Additionally, when the voxels are peeled more than S times without satisfying any of the conditions shown in Figure 4(a) or Figure 4(b), the peeling process can also stop and there's no feature is under the limited size.

3.2 Negative Features Computation with Size Constraint

As the negative model may include several parts, some of them may have small sizes under the limited geometry size. However, some of these undersize negative model parts don't represent holes or gaps or slots of the original object (like N_2 in Figure 2). Thus, special measures are needed to apply when skin removal method is used to identify the effective undersize negative features.

The voxels of negative model are classified three types and the corresponding flag function g(i, j, k) satisfies the following Equation (3.2):

$$g(i,j,k)=\begin{cases}-1, & \textit{if the voxel is on the surface of bounding box} \\ 0, & \textit{if the voxel is on the surface of the model } M \\ 1, & \textit{if the vexel is inside of the negative model}\end{cases} \tag{3.2}$$

Then, the negative model part N_1 in Figure 2 can be voxelized and marked as depicted in Figure 5. Where, if a voxel intersects with both the OBB and the model M surfaces, this voxel is marked 0(seen voxels v_1 and v_2 in Figure 5). Then, only voxel signed with value 0 and 1 will be peeled in the skin removal method.

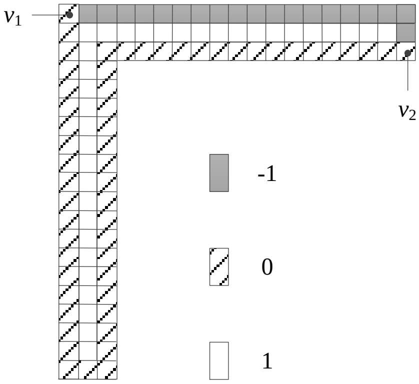


Figure 5: Voxels of N_1 are classified.

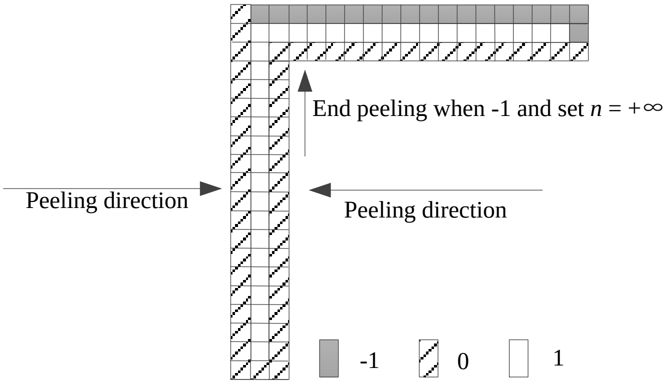


Figure 6: Voxels with mark -1 would not be peeled.

As same to the computation of positive feature, the peeling method is also used in the negative feature computation. Besides the iteration end conditions shown in section 3.1, OBB voxels are considered in the removing process. During an iteration, to remove the skin, a surface voxel with marked value 0 is reset as 2. Meanwhile, if its face-neighbored voxel's mark is -1, then end the searching of the voxel's neighboring voxels and set the voxel as 2. Its corresponding peeling layer number n is set as $+\infty$ (Figure 6). Equation (3.1) in section 3.1 is also applicable to the negative feature computation.

3.3 Implementation

Figure 7 shows the negative and positive voxel models construction algorithm flowchart. And Figure 8 is the algorithm flowchart of positive feature under the limited size identification. For negative features, the computation method is similar to method for positive features with little modification about the iteration end conditions.

3.4 Error Analysis

Because of the approximate representation of the voxelization model, the proposed method may lead error. And the size of the error depends on the size of voxel cell size. Specially, if the resolution is not high enough, small negative features may be lost. In addition, according to the peeling computation method, if a feature with wall thickness x satisfies $T < x \leqslant (2S+1)\ t_0$, where T is the constraint size, then this feature may be identified as the target feature by error. An example of this error is illustrated in Figure 9. When the constraint size T is set as 10 and the applied voxel cell size t_0 = 3, the features with number of removable layers smaller than or equal to S = 2 are identified as the undersize features.

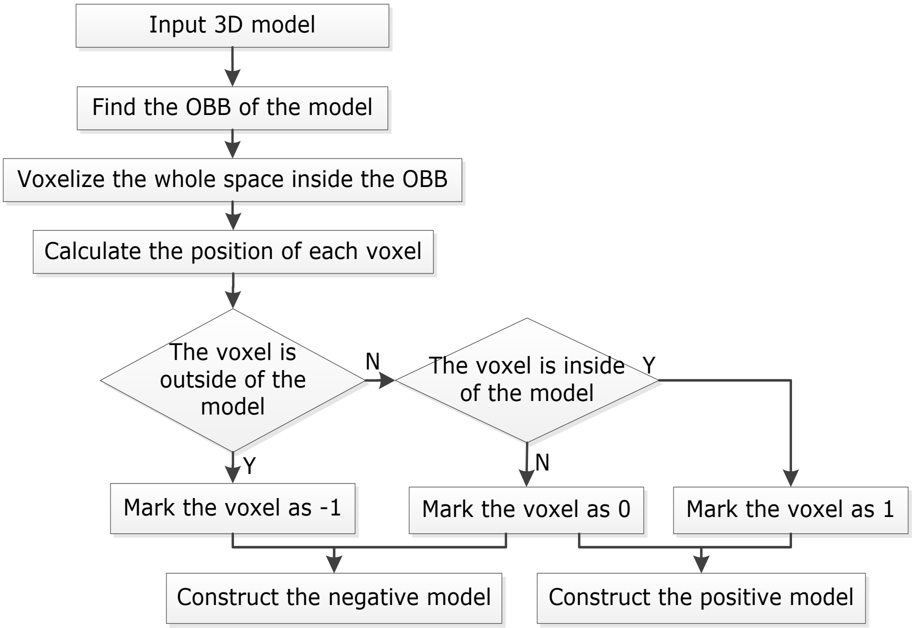


Figure 7: Flowchart of negative and positive voxel models construction.

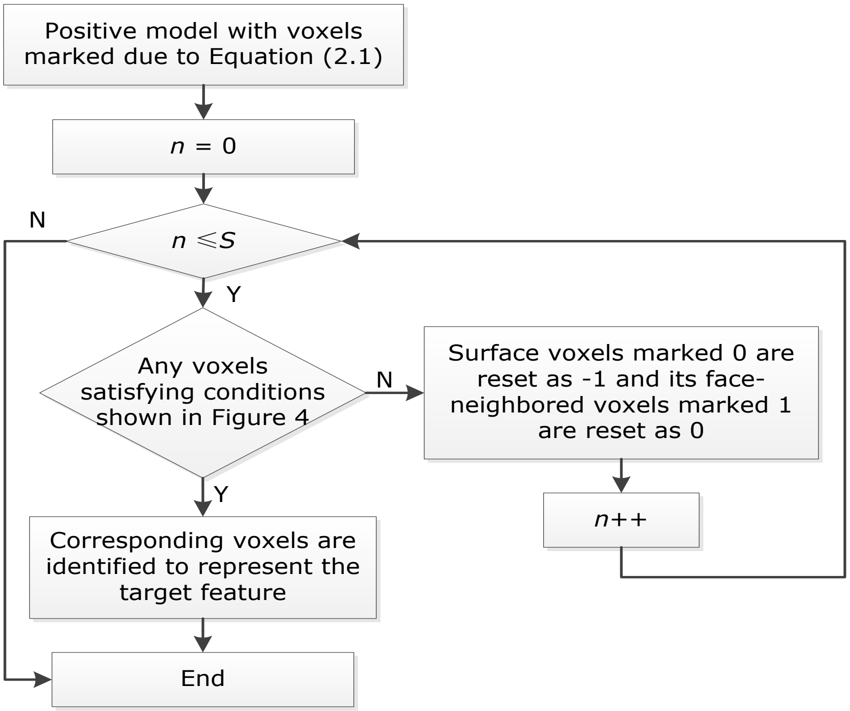


Figure 8: Flowchart of the limitation feature identification for the positive model.

However, as seen in Figure 9, when the thickness x = 15, its number of removable layers is also 2. To minimize this error, the voxel cell size should be minimized as 1. To avoid the error lead by voxel cell size set, after the candidate target voxels are identified, the corresponding distance between opposite surfaces/boundaries should be further calculated.

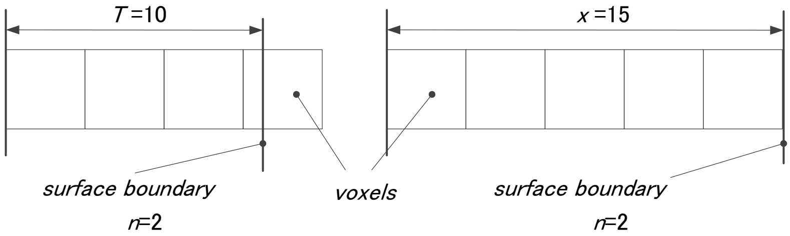


Figure 9: Schematic diagram of computation error.

4 DISCUSSION AND CONCLUSION

Voxelization is very important to model computation for AM. Besides the geometry computation of minimum feature, they are better capable of representing objects with multiple materials, functional gradients, and etc. In this paper, the features are first classified positive features and negative features whose related negative model is also defined. Then, peeling method is applied for the voxel-based model to calculate the minimum features based on the given constraint size. As a result, the voxels representing the minimum features, including positive features such as cylinder, sharp corner and thin wall, and negative features such as gap, slot and kinds of holes can be identified. Finally, the possible errors lead by the proposed method, the causes of the errors and the solutions are discussed. Overall, the main advantages of this proposal compared to the previous research by others are summarized as following:

(1) This method and the computation results does not depend on the coordinate system.

(2) The negative model is proposed and the negative features such as slot, gap and kinds of holes can be identified.

(3) The method is based on constraint size, which would decrease the computation.

Additionally, examples will be implemented to further improve the proposed method in the next step. And the relationship model between the geometrical attributes and the manufacturing feasibility of AM feature will be researched and established in the future work.

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