Title:
Geometry Attributes Computation of Components' 3D Model for Additive Manufacturing

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Introduction:
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. Geometry attributes computation of components' 3D model based on manufacturing ability is a necessary and feasible method to inspect process for additive manufacturing (AM). As the printable thin walls may be limited by the type of AM process and resolution of the machine [3], or be so fragile as not to be able to survive post-processing [4], the minimum feature size is one of the most important AM constraints. As so far, MAT-based method (Medial Axis Transformation) [5, 2], distance transform method [8], peeling approach [6, 7] and offsetting method [1] 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 [9]. In Tedia and Williams' research [9], 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 = 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 [7], 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. 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.

Feature classification and negative model

Negative feature definition

Given a ray l intersect a feature A of a 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 (Fig.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 (Fig.1(b).).

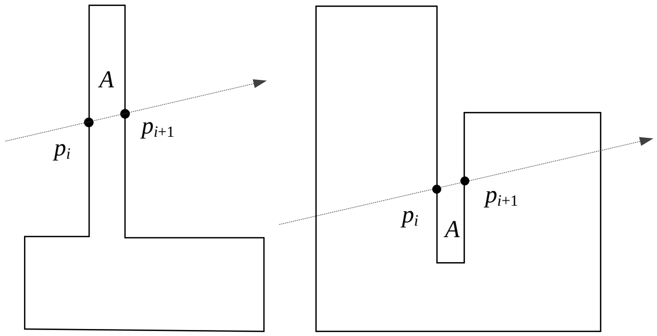

Fig. 1: Positive feature and negative feature: (a) positive feature A, (b) negative feature A.

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

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 (Fig.2). As shown in Fig.2, the negative model is separated into two independent parts N_1 AND N_2.

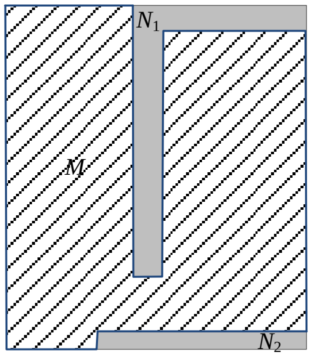

Fig. 2: Negative model N (N = N_1+N_2) of model M

-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

Fig.3 Voxels in OBB space are marked by the positions.

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 point represents the related voxel in this paper. The voxels in the OBB space are classified into three types and the corresponding flag function $f(i, j, k)$ satisfies the Eqn.(1.1).:

$$f(i,j,k)=\begin{cases}-1, & \textit{if the voxel is outside of the model } M\\ 0, & \textit{if the voxel is on the surface of the model } M\\ 1, & \textit{if the vexel is inside of the model } M\end{cases} \tag{1.1}$$

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

<u>Geometry computation attributes based on constraint size</u>
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.

Positive features computation 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 is T while t_0 is the voxel cell size, this peeling process can be repeated S times according to T,

$$S=\begin{cases}0, & T\le t_0\\ \left[\dfrac{T}{2t_0}\right], & T>t_0, 0\le T\%(2t_0)\le t_0\\ \left[\dfrac{T}{2t_0}\right]+1, & T\%(2t_0)>t_0\end{cases} \tag{2.1}$$

Where, $[T/(2t_0)]$ 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) The voxels of some part of the model cannot be removed anymore (Fig.4(a).);

(2) Only the innermost voxels are left (Fig.4(b).);

(3) $n > S$

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

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

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

In another word, if a feature can only be peeled as n layers and $n < S$, then the wall thickness of this feature is undersize.

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 Fig.2.). Thus, special measures are needed to applied 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 equations:

$$g(i,j,k)=\begin{cases}-1, & \text{if the voxel is on the surface of bounding box}\\ 0, & \text{if the voxel is on the surface of the model } M\\ 1, & \text{if the vexel is inside of the negative model}\end{cases} \tag{2.2}$$

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

As same to the computation of positive feature, the peeling method is also used in the negative feature computation. Besides the iteration end considerations, 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 $+\infty$ (Fig. 6.). Eqn. (2.1) is also applicable to the negative feature computation.

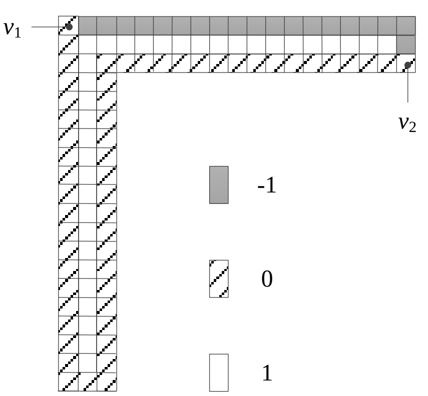

Fig. 5: Voxels of N_1 are classified.

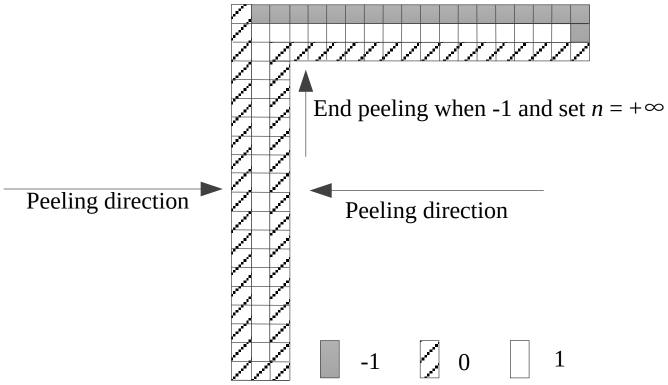

Fig. 6: Voxels with mark -1 would not be peeled.

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 Fig.7.. 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. However, as seen in Fig.7., 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 this error, after the voxels are identified, the related surface or boundary should be computed to further distance calculation between the opposite surfaces or points.

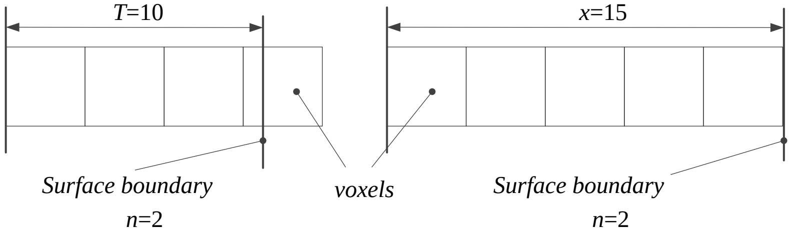

Fig. 7: Computation error.

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, based on the voxelization, the positive features and negative features whose related negative model is proposed, which enable that 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 easily. Besides, the method is based on constraint size, which decreases the computation a lot.

References

[1] Chen, Y.; Xu, X.: Manufacturability analysis of infeasible features in polygonal models for web-based rapid prototyping, ICMA 2010, Xi'an, CHINA, 2010, 120-127. https://doi.org/10.1109/ICMA.2010.34

[2] Inui, M.; Umezu, N.; Shimane, R.: Shrinking sphere: A parallel algorithm for computing the thickness of 3D objects, Computer-Aided Design and Applications, 13(2), 2016, 199-207. https://doi.org/ 10.1080/16864360.2015.1084186

[3] Moylan, S.; Slotwinski, J.; Cooke, A., et al.: Proposal for a standardized test artifact for additive manufacturing machines and processes, SFF 2012, Austin, TX, USA, 2012: 902-920.

[4] Meisel, N.; Williams, C.: An investigation of key design for additive manufacturing constraints in multi-material three-dimensional printing, Journal of Mechanical Design, 137(11), 2015, 111406. https://doi.org/ 10.1115/1.4030991

[5] Nelaturi. S; Kim, W.; Kurtoglu, T.: Manufacturability feedback and model correction for additive manufacturing, Journal of Manufacturing Science and Engineering, 137(2), 2015, 021015. https://doi.org/ 10.1115/1.4029374

[6] Patil, S.; Ravi, B.: Voxel-based representation, display and thickness analysis of intricate shapes, CAD/CG 2005, Hong Kong, CHINA, 2005, 415-420. https://doi.org/ 10.1109/CAD-CG.2005.86

[7] Subburaj, K; Patil, S; Ravi, B.: Voxel-based thickness analysis of intricate objects, International Journal of CAD/CAM, 6(1), 2009, 105-115.

[8] Telea A, Jalba A.: Voxel-based assessment of printability of 3D shapes, ISMM 2011, Verbania-Intra, ITALY, 2011, 393-404. https://doi.org/10.1007/978-3-642-21569-8_34

[9] Tedia S, Williams C B.: Manufacturability analysis tool for additive manufacturing using voxel-based geometric modeling, SFF 2016, Austin, TX, USA, 2016.