Title:
A New Adaptive Slicing Algorithm Based on Slice Contour Reconstruction in Layered Manufacturing Process

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Introduction and background:

This paper addresses the problem of reducing build times in Layered Manufacturing (LM) technologies in which 3D parts are constructed by depositing a series of planar layers.

Most commercial LM systems use a multi-stage processing pipeline [4]: 3D modeling, Data conversion, Pre-processing, Model slicing, Part deposition and Post-processing. The 3D model of the mechanical product is created by a CAD system and converted into a tessellated format (STL). The quality of the prototype is determined by several key process variables including the part orientation, the layer thickness, the deposition speed and environmental noise such as temperature and humidity variations. The quality may be measured in terms of the part strength, dimensional accuracy, surface finish, build time or the material utilization. Common approaches to achieve better quality include [6]: (i) optimal part orientation, (ii) slicing strategy, (iii) process parameter optimization, (iv) post-treatment. The determination of the slice thickness is a key parameter involving the trade-off between part accuracy and deposition time. Due to stair-step (or staircase) errors, smaller slice thickness leads to lower surface roughness but requires at higher build time. Several researchers have explored methods for ***Adaptive Slicing,*** [13] in which they allow for using layers of different slice thickness at different heights along the build direction. However, a big issue with this approach is that practically no existing RP machine provides this option. In this paper, we explore an approach for improving the layer accuracy even when layer thickness remains constant over the build.

Different measures have been used to estimate build errors: volumetric deviation[10], *cusp height*[5], surface roughness[14], area deviation[19], circumference difference and gravity deviation[12]. Among these, the first three approaches are most popular in adaptive slicing. Intuitively, the *volumetric error* is defined as the volume difference between the built-up part V_P and the original CAD model V_O; it is computed at each layer and summed over the entire part, using Eqn. (2.1).

$$\Delta'_V = (V_O \cup V_P) - (V_O \cap V_P) \tag{2.1}$$

Roughness is a traditional measure for surface quality; it was used for evaluating LM part in [14]. In the LM context, *cusp height* is the error associated to the staircase effect [5].

Proceedings of CAD'20, Barcelona, Spain, July 6-8, 2020, 374-380

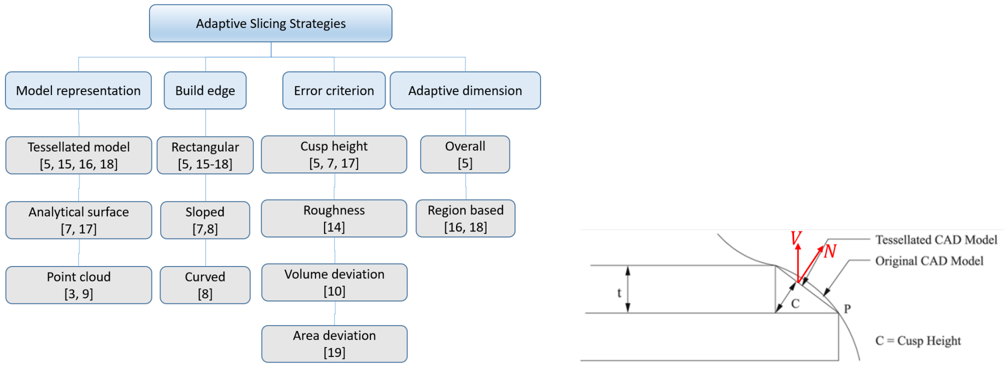

Fig. 1: (a) Classification of adaptive slicing approaches (b) Cusp height measurement

The total deposition time for a part increases approximately linearly with the number of slices. Therefore, using different layer thicknesses at different heights along the build direction has been studied by several researchers to achieve a good compromise between part accuracy and deposition efficiency. These algorithms are classified into different categories from different points of view (see Fig. 1), and details of each approach can be found in [5], [15], [16], [18], [19], [17], [7], [8], [3], and [9] We present a new adaptive slicing algorithm for tessellated models. Our method does not rely upon varying the slice thickness, so it can be adapted to all RP machines. Quality measured in terms of real volumetric deviation and maximum horizontal distance error. We use robust and efficient computational geometric techniques.

The Proposed Approach:

Commercial RP machines use the slice contour at the nominal height of the model to construct the next layer. Local geometry variations and machine specifications dictate the magnitude of layer thickness. In our proposed scheme, for each slice, we proceed to search an alternative contour based on the geometry of the zone between the top and bottom planes. The contour is computed to yield an error no worse than the traditional strategy. The efficacy of this approach is first demonstrated by selecting an actual contour at an appropriately chosen height between the heights of the bottom and top of the slice. Next, a more general strategy is introduced, which computes a contour by considering a silhouette of the slice.

To establish viability, we measure the volumetric error, from the tessellated model relative to a square-edge layered geometry, to search for the optimal height. In objective function (Eqn. 2.2), V_O and V_E are the geometry volume of the original slice and the extruded slice respectively, where the volume of extruded slice is the function of height $h \in [h_{lower}, h_{upper}]$, so is the volume deviation error ΔV. This is computed via a simple script running in CATIA^{TM}.

$$\begin{aligned} min \;\; \Delta V(h) = V_O \cup V_E(h) - V_O \cap V_E(h) \\ s.t. h_{lower} \leq h \leq h_{upper} \end{aligned} \tag{2.2}$$

Fig. 2(b) presents the original slice geometry and the extruded slice geometry taken from particular height of model in Fig. 2(a). By Boolean operation on these two slices, the corresponding volume deviation is calculated via a mass measurement tool. The objective function is non-convex and discontinuous. A Simulated Annealing search algorithm is used to solve this. Two examples, respectively from height range $[5mm, 6mm]$ and $[8mm, 9mm]$, illustrate the volume deviation along the height. In this example, by replacing the lower cross-section curve with a contour at some height between the layer, the volumetric

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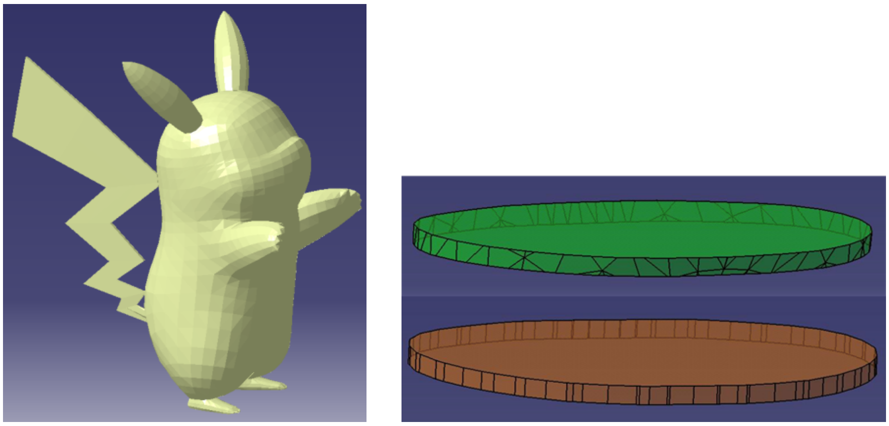

Fig. 2: (a) The pre-experiment model (Pikachu) and (b) an original and extruded slice

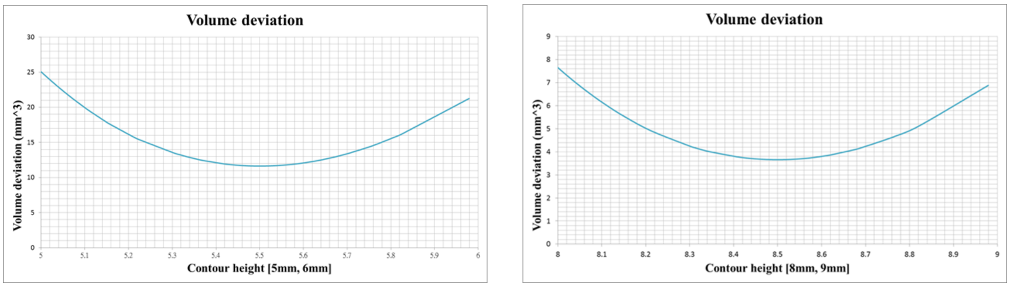

Fig. 3: Volume deviation $\Delta V(h)$ (a) $h \in (5mm, 6mm)$ and (b) $h \in (5mm, 6mm)$

error can be reduced by 50%.

Unfortunately the optimizer is slow, taking over 1.5 min for each common slice. So we seek an alternate and improved approach, where the replacement contour path is not restricted to remain in a particular intermediate plane. We shall use an approximation of the centerline of the silhouette of the slice. An edge incident to two facets that are front-facing and back-facing with respect to the viewing direction is a *silhouette edge*. If we look at the slice mesh (Fig. 4) from the direction perpendicular to the build direction, the outermost and innermost boundary are composed of full or partial silhouette edges, as well as full or partial edges on the two contour curves. The upper and lower contour curves may intersect with each other, and silhouette edges within the layer may also intersect two contour curves.

0.1 Centerline

For the purpose of computing distance error, We focus on the two-dimensional planar polygonal domain, in the shape of ***strip***, formed by the union of the projection of all or partial faces that compose the slice mesh surface. To minimize the horizontal distance between the vertical-walled surface and the original surface, we wish to find the "centerline" of the polygonal strip, in particular, by modifying its Medial axis (MA) Bium[1]. For a polygon, the medial axis edges are either straight segments or parabolic curves. It can be computed in $O(nlogn)$ time [11]. To avoid parabolic segments and for efficiency, we adopt

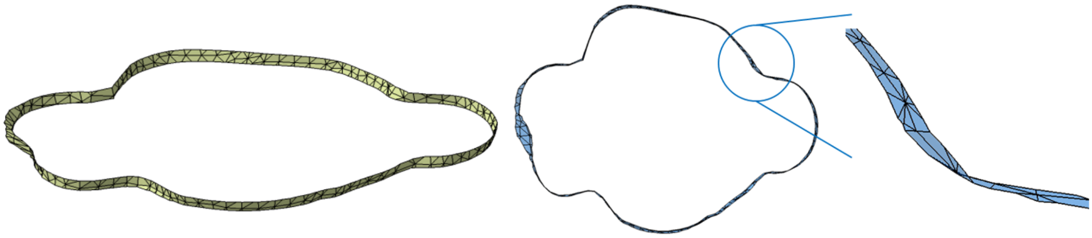

Fig. 4: A 3D slice mesh (a) slice mesh (b) Projection view of the slice mesh

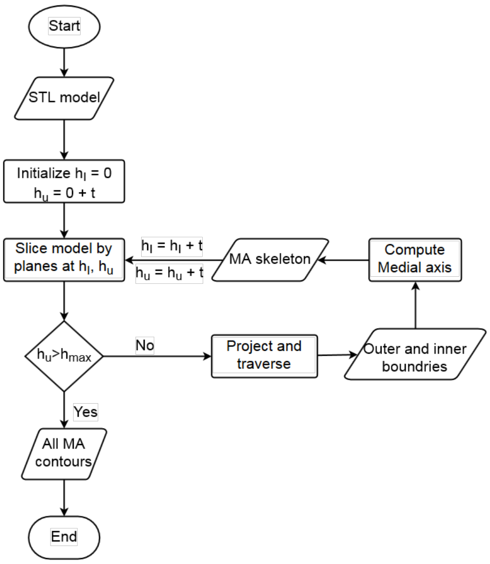

Fig. 5: Algorithm Flowchart

an approximate approach of computing the MA via the Voronoi diagram of a sampling of points from boundaries. As shown in [2], as the sampling density of the contour increases, the subset of Voronoi vertices converge to the MA.

0.2 Contour reconstruction algorithm

Our proposed adaptive slicing algorithm is outlined in Fig.5; we use the STL format as the input and measure both volume deviation and maximum horizontal deviation to evaluate its accuracy improvement. Given an input CAD model and a pre-selected layer thickness t, the model is then sliced from bottom to top iteratively. For each slice, the 2D outermost and innermost boundaries, termed as *boundary pair*, are computed after projecting 3D mesh surface onto the horizontal plane. The Medial axis skeleton is finally extracted from the Voronoi graph of sampling points from the computed boundary pair.

The Stanford bunny model in Fig.6, is used to illustrate the key ideas. The uniform slicing stage is the trivial intersection operation and by Euler's formula, computing the intersection curves and updating the slice mesh information can be done in $O(n)$ where n is the number of vertices. The slice meshes at several height are shown in Fig.6. The processing is in two stages: *boundary computation* finds the silhouette

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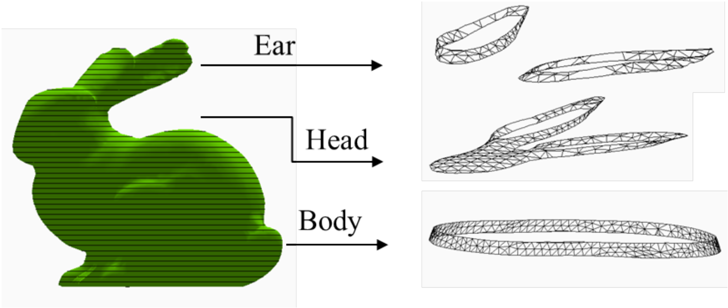

Fig. 6: Slice meshes at several height

outer and inner boundary curves for all topological cases (Fig.6), and the MA contour extraction samples the edges and computes the MA. Details are in the extended version of the paper. The MA is post-processed to smooth out sampling artifacts and further error reduction. The actual error is measured by comparing the extruded, refined MA curve with the corresponding later of the original model via a standard CAD software. The overall algorithm time complexity is $O(\frac{h}{t}\frac{l_{max}}{\delta}nlogn)$ for a model of height h and layer thickness t.

Case Study:

To evaluate the improvement in terms of part accuracy and deposition efficiency, a Stanford bunny model is taken as the benchmark. Several key parameters are given: Height ($5cm$), Length ($5.21cm$), Width ($3.97cm$), model components (5036 vertices, 30204 edges, and 10068 faces), and total volume ($28.148cm^3$).

An typical FDM machine (e.g., UP Plus 2) provides layer thickness range from $0.15mm$ to $0.4mm$ with step $0.05mm$. We firstly adopt the minimum thickness $0.15mm$ to evaluate part accuracy improvement. The distance errors of the lower contour and the MA contour at each layer are visualized in the scatter chart in Fig.7. The traditional strategy presents an average $0.0307cm$ and maximum $0.160cm$ distance error while the MA contour gives an average $0.0178cm$ and maximum $0.107cm$. Hence, average 47.3% distance error reduction is achieved. A subset of slice samples are taken to verify the volume deviation, shown in the histogram of Fig.8. Among the slice samples, the volume deviation reduction ranges from 14.3% to 49.1%, 42.4% on average. With the average error reduction more than 40%, we are allowed to use a larger layer thickness under the MA contour strategy while keeping the accuracy within the tolerance. Using the distance error of $0.15mm$ under the traditional strategy as the benchmark, Fig.9 shows that our approach allows a slice thickness of $0.25mm$ at equivalent model accuracy level.

Conclusions:

In this paper, a novel adaptive slicing strategy based on contour reconstruction is implemented based on traditional uniform slicing system. The approach adopts simple, efficient and robust geometric techniques to construct new contour for each slice on the model. The results of case studies show the MA contour yields around 40% error reduction over the traditional approach at same slice thickness. Alternatively, it yields 20%-30% time reduction by implementing the new contour with the slices of larger layer thickness, at the same model quality. The new contour data, or a new constructed model based on the new contours, can be directly feeding into the LM system for fabrication.

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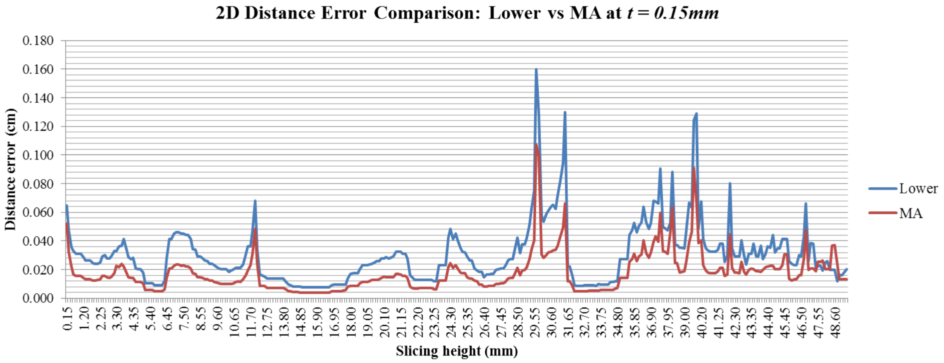

Fig. 7: 2D distance error: Lower vs MA at 0.15mm

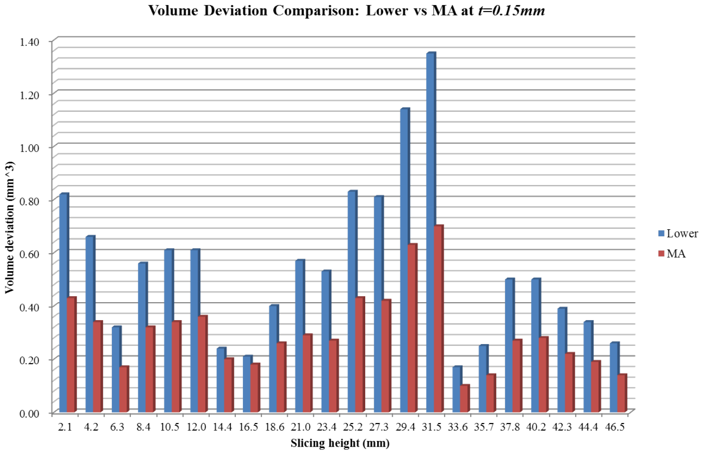

Fig. 8: Volume deviation: Lower vs MA at 0.15mm

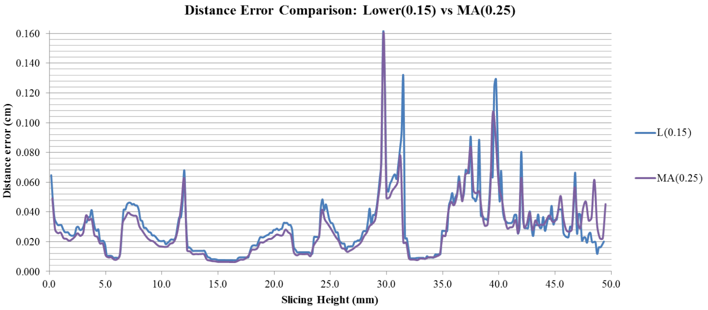

Fig. 9: Distance error: Lower(0.15mm) vs MA 0.25mm

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