# Mass Customization: Reuse of Topology Information to Accelerate Slicing Process for Continuous Liquid Interface Production

**Hang Ye**[1], **Chi Zhou**[1,*], **and Wenyao Xu**[2]

[1]Department of Industrial and Systems Engineering
[2]Department of Computer Science and Engineering
University at Buffalo, The State University of New York, Buffalo, NY 14260

Email: hye2@buffalo.edu, chizhou@buffalo.edu, wenyaoxu@buffalo.edu

*Additive manufacturing (AM), also known as 3D printing, constructs a 3D object in a layer by layer fashion. Comparing to traditional manufacturing technologies, it can build objects with complex individualized features with little extra effort. This characteristic endows additive manufacturing with the potential to realize mass customization. Continuous Liquid Interface Production (CLIP), a newly emerged Stereolithography Apparatus (SLA) based AM process, can create a solid object by using video projection as the energy source to cure the liquid photo-sensitive polymer resin. This process works in a continuous fashion, so it can achieve extremely high productivity that is crucial to mass customization. CLIP adopts a great number of images which are corresponding to cross-sectional geometric patterns as input, but this poses a challenge regarding to slice generation. The slice computation procedure for a single customized model can take hours to complete, and the time consumption becomes more prominent in mass customization, which fabricates numerous models in the same batch. Based on the observation that similarities exist among most customized products, we proposed a new slicing paradigm. This slicing paradigm reuses topology information obtained from the template model for other customized products of the same category, and the idea of topology information reuse is implemented in three levels, including self reuse, intra-model reuse, and inter-model reuse. Experimental results show that the proposed slicing paradigm can significantly reduce the time consumption on pre-fabrication computation.*

**Keywords:** *Mass Customization, Additive Manufacturing, Topology, Slicing, CLIP.*

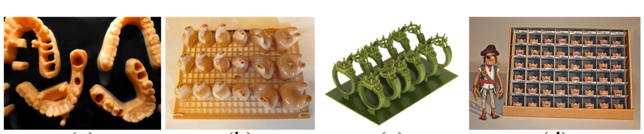
*Corresponding author. Phone: (716) 645-4706 Fax: (716) 645-3302

## 1 Introduction

The prevailing "mass production" is an important propeller of the rapid development in human material civilization after the industrial revolution, and it is also a significant source of the nation's economic strength in last century. The characterized scale effect from mass production results in reduced cost and easiness to obtain a product, so it improves quality and sustainability of human life. However, it is also because of the highly developed material civilization, any product could have countless substitutions on the market sharing similar functions. Customers are no longer satisfied with just realizing the basic function, in addition, they would prefer to purchase the products that can better meet their specific tastes. It is apparent that traditional mass production is not capable of handling this tremendous diversity in customer needs. Innovative practitioners are thinking about lifting their way to a new paradigm, mass customization, to meet the ever changing turbulent market environment. The initial idea about the principle of "mass customization" can be traced back to early 1970's [1], and Davis coined this phrase in 1987 [2]. According to Tseng and Jiao, mass customization was defined as "the technologies and systems to deliver goods and services that meet individual customer's needs with near mass production efficiency" [3].

However, highly customized products are very challenging to be mass-produced in the traditional way. Both the tangible and intangible costs of making personalized products are usually very high, and this is especially apparent for human-centered products, e.g., tooth aligner, hearing aid, artificial limb etc. Therefore, the business has to wait for today's technology advancement to enable profitable customization. Over the last 30 years, additive manufacturing emerges as a new type of manufacturing process. It is a collection of techniques to fabricate solid objects directly from a three-dimensional (3D) model created in Computer Aided Design (CAD) without the need for object-specific tooling and fixtures [4]. In traditional manufacturing process, a commercialized setup can only handle very limited types of products if not only one. Even a tiny local feature change from the product may lead to a re-design of the whole setup and process. Comparing to traditional manufacturing techniques, an important advantage of AM is that it provides "complexity for free" [4]. This property offers high flexibility and shortened product life cycle without extra penalty, thus AM has the potential to be the technical foundation for profitable customization.

Some innovative companies have already embraced the new mass customization paradigm by taking advantage of the unique design freedom offered by AM process. These companies spread in various fields, such as medical, aerospace, automotive, and consumer industries [5]. The Walter Reed National Military Medical Center utilizes AM to produce customized cranial plates and cutting guides for bone grafts [6]. Several automotive manufacturers, such as Ford and BMW, offer their customers an option to select additively manufactured features, including trims and inlays [7]. Computer game peripheral is another field where AM process has been adopted. The FigurePrints allows the players of World-of-Warcraft to purchase miniature models of their game characters which are built by full color AM [5]. Align Technology, which is running business of providing orthodontic treatment devices, utilizes reverse engineering and AM technology to progressively fabricate transparent dental braces that are worn on patients' teeth to gradually move the misplaced teeth to the desired positions. The orthodontic treatment usually lasts for 2 to 3 years, and during each treatment period, a patient receives a pair of new aligners every 2 weeks. It is reported that the company run the 3D printer (SLA-7000) 24 hours and produces 40,000 unique aligners per day. Therefore, the handling of many different complex shapes in a tight time frame is a big challenge, and requires mass customization to be involved. Siemens Hearing Instruments Inc. applies Selective Laser Sintering (SLS) based AM process to fabricate shells of hearing aids, and more than 10 million customized hearing aid shells have been created by AM. The company reports that the customer satisfaction has been improved after it started to offer better-fitted products [8]. Several applications that utilize AM technology to enable mass production of highly customized products are shown in Fig.1.



(a) (b) (c) (d)

Fig. 1. Mass Customization Applications based on Additive Manufacturing [9]: (a) dental industry, (b) medical industry, (c) jewelry industry, (d) entertainment industry.

AM technology holds the advantages of affordability and customizability, but the key challenge in applying it for mass customization is how to reduce the product lead time [4]. The time of building a 3D object is comprised of two components: the pre-fabrication computation and the manufacturing process. The later used to be the bottleneck of AM. Although this technology is also named as "rapid prototyping", it was not that fast before. For example, a single hearing aid shell used to take tens of minutes or even hours to be created. Comparing to this, the time spent on pre-fabrication computation seemed trivial as it usually takes only a few minutes or even seconds. However, recently Tumbleston *et al*. proposed a Continuous Liquid Interface Production (CLIP) approach to continuously grow an object from a vat of liquid material rather than printing them layer-by-layer [10]. This revolutionary breakthrough has proven to be 25-100 times faster than what is available on the market today. As a matter of fact, complex products can be finished in minutes instead of hours by CLIP nowadays. On one hand, the emergence of CLIP provides us with fully ready hardware support to apply AM on mass customization. But on the other hand, it poses a great challenge for the pre-fabrication computation, and makes it the bottleneck that hinders the realization of industrial revolution introduced by AM. In fact, the continuous mode is an indication of using extremely small layer thickness or extremely great number of layers. Adopting this extremely thin layer increases the input size of pre-fabrication computation dramatically, and the computation cost also rockets up drastically.

In this study, we proposed a new slicing paradigm based on the observation that similarities exist among most customized products from the same category. The proposed slicing paradigm reuses topology information obtained from the template model for the same category of customized products, and the idea of topology information reuse is implemented in three levels, including self reuse, intra-model reuse, and inter-model reuse. The remainder of the paper is organized as follows: In Sec.2, we overviewed the existing slicing method, the similarity among customized products, and the property of STL file. We also briefly described the proposed slicing paradigm in this section. In Sec.3, we proposed an improved slicing algorithm which took advantage of topological continuity. Intra-model topology information reuse was presented in Sec.4. And in Sec.5, we introduced inter-model topology information reuse which was capable of handling local feature add-on and/or removal. The conclusion and discussion were presented in Sec.6.

## 2 Background

### 2.1 Existing Slicing Algorithm

Many novel AM processes incorporate different technologies, such as laser, nozzle, jetting, electron beam, and cutter etc. [4, 11, 12]. From the late 1980s, some of the above have been successfully commercialized [13], e.g., StreoLithography Apparatus (SLA), Selective Laser Sintering (SLS), Fused Deposition Modeling (FDM), and 3D printing. All those techniques were developed based on the layered based additive principle [14]. Almost all AM techniques build the 3D object in a layer by layer fashion, so they take the cross-sectional profile derived from the 3D CAD model as the input, and this information is used to direct the energy or material deposition. The common practice for obtaining the cross-sectional information is intersecting the 3D model with a number of horizontal planes. A de facto standard input for additive manufacturing process is the STL (STereoLithography) format, which is also known as Standard Tessellation Language. STL file format was originally developed for the stereolithography CAD software, and nowadays most CAD system, such as AutoDesk, Catia, ProEengineer, and SolidWorks, can export the native CAD format as STL file. STL file is essentially a triangulated surface representation for a given object. It uses a set of orientable triangular facets to approximate the shape of the object. Each triangle facet is defined by three vertices which are saved according to the right-hand rule, and its orientation is represented by a unit normal.

Originally, the intersection, if exists, between a 3D object and a plane should be a 2D planar area (a single point or a line/curve can be viewed as the degeneration of a 2D planar area). Because of the adoption of STL format, which represents a 2D surface embedded in 3D space, the intersection becomes a 1D object embedded in 2D space. This 1D object is the boundary/contour of the previously mentioned 2D planar area, and it consists of a set of segments, each of which is defined by two end points. For a manifold mesh model, this 1D object must be one or more simple closed polygons with consistent orientations. The orientation of the polygon is used to indicate whether the area it encloses is solid or hollow. The process to obtain these intersections is usually called "slicing".

The calculation of end point coordinates for segment is straightforward. We traverse all triangle facets, and for each triangle facet we evaluate whether or not it intersects with current slicing plane ($Z = Z_k$). This can be done by simply checking the minimal vertical coordinate ($Z_{\min}$) and maximal vertical coordinate ($Z_{\max}$) of three vertices from the triangle. If $Z_{\min} < Z_k$ and $Z_{\max} > Z_k$, the triangle will intersect with current slicing plane. Then each end point can be calculated by using Eqn.(1), where $V_1(X_1,Y_1,Z_1)$ and $V_2(X_2,Y_2,Z_2)$ are two end points of the intersected edge from the triangle. The outcome of this computation is a set of unordered segments, and the connectivity/adjacency among these segments has not been explored yet. For most AM setup, it is necessary to know the connectivity for tool path planning, e.g., polygon offsetting, G-code generation etc., so we should arrange these segments in the right order to form one or more closed polygons. Closest point method [4] and marching algorithm [15] are two classic slicing algorithms. The former one calculates the coordinates of intersection points first, and retrieves the connectivity afterwards. The later one explores the topology by sorting first, and then calculates the intersection coordinates in order according to the adjacency.

$$
\begin{aligned}
X &= \tfrac{(Z_k-Z_1)\times(X_2-X_1)}{Z_2-Z_1} + X_1 \\
Y &= \tfrac{(Z_k-Z_1)\times(Y_2-Y_1)}{Z_2-Z_1} + Y_1 \\
Z &= Z_k
\end{aligned}
\qquad (1)
$$

At a specific layer, assume there exists $n$ triangle facets intersected with current slicing plane. The closest point method calculates coordinates for $2n$ end points from $n$ segments, and the time complexity is $O(n)$. However, in order to determine which point is connected to a given point, the distances between this point and all points from un-explored segments have to be computed, and this process increases the time complexity to $O(n^2)$. In contrast, marching algorithm propagates the contour from one triangle to its neighbor until getting back to the initial one, so it only calculates coordinates for $n$ points, and the connectivity is exactly the same as the sequence of marching. Although marching algorithm seems more time-efficient than closest point method, it is necessary to know the adjacency information of the triangle facets in advance. This adjacency information does not come with the STL format model automatically, and its construction is also time-consuming.

### 2.2 Similarity among Customized Models and Mesh Property

AM process can construct 3D objects with very complex geometric features, therefore, input models can be arbitrary. As mass customization intends to fabricate individualized products with near mass production efficiency, numerous models with distinct features present a huge challenge to the pre-fabrication computation. Although some models are derived from the same template by simple transformations, such as translation, rotation, scaling etc., they still need to be processed separately. Fortunately, an important observation is that customized models from the same category usually share the characteristics of high similarity, and this high similarity exists in both geometry and topology. In order to work properly, the topological similarity among customized functional products is especially prominent. For example, the artificial human heart implant, as shown in Fig.2, needs to have left atrium, right atrium, left ventricle, right ventricle, veins, and arteries connected properly, and have them isolated from one another if necessary. In other words, all human heart implants have to be homeomorphic, although they may have different customized sizes for some local features. Fig.3 shows another example of two aligners from the same customer but for different phases. Those two aligner models are homeomorphic and share 99% similarity in geometry. This high similarity has already been utilized in the product design, e.g., two different models can be derived from the same template by local modification and/or deformation. However, the existing pre-fabrication paradigm treats each model independently, and each model needs to go through every single step separately, e.g., slicing, tool path planning etc.

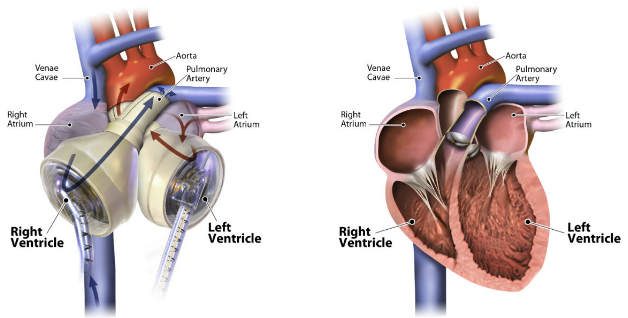



Fig. 2. Artificial Heart Implant. The left is the total artificial heart, and the right is human heart [16].

Fig. 3. Two tooth aligner models share the same topology and 99% similarity in geometry. The left is for Phase 0-30 days, and the right is for Phase 31-90 days.

STL file, as the de facto file format for AM, is the simplest polygonal mesh. It consists of three types of mesh elements: vertices, edges and faces [17]. The information to describe the mesh property includes mesh topology and mesh geometry. The mesh topology describes the incidence relations among mesh elements [17], such as for each vertex the incident edges, and for each edge the incident triangular facets. The mesh geometry describes the position (coordinate) of each vertex. It is noteworthy that two models with the same mesh topology but different mesh geometries can be different, and two models with the same mesh geometry but different topologies can be totally different as well. Fig.4(a) shows two different models share the same mesh geometry but are different in mesh topology, and Fig.4(b) shows two different models have the mesh topology in common but are different in mesh geometry. With both mesh topology and mesh geometry the mesh can be unambiguously defined.

In STL file each triangular facet is defined by three vertices which are saved according to the right-hand rule, and its orientation is represented by a unit normal. Each facet is represented as follows:

**facet normal** $N.X$ $N.Y$ $N.Z$
**outer loop**
**vertex** $V_0.X$ $V_0.Y$ $V_0.Z$
**vertex** $V_1.X$ $V_1.Y$ $V_1.Z$
**vertex** $V_2.X$ $V_2.Y$ $V_2.Z$
**endloop**
**endfacet**

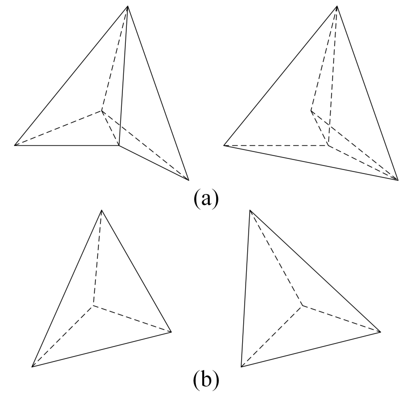



Fig. 4. Mesh Topology and Mesh Geometry: (a) meshes with same geometry but different topologies, (b) meshes with same topology but different geometries.

For efficient rendering purpose, saving each facet in this format can make face enumeration very simple. However, the connectivity/adjacency is implicit which is undesirable for geometric algorithms. As mentioned in [18], explicit mesh connectivity will make many geometric algorithms much easier to be implemented. Inspired by this, if we can make mesh topology of a single product more predictable by taking advantages of piecewise continuity and the high similarity among customized products, the pre-fabrication computation of this product can be more efficient.

### 2.3 Proposed Method

In this study, we assume there exists a template mesh model, and customized models can be derived by modifying the template. Because of the high similarity among customized products, this customized modification can at least persist a large portion of the mesh connectivity from the template. With the same mesh connectivity, the customized product is guaranteed to be homeomorphic to the template which is crucial to proper functioning. Individualized shape can be achieved by modifying the mesh geometry, as shown in Fig.4(b), and this kind of modification is already available in some softwares, such as Maya, MeshMixer, and Magics. In order to make mesh topology more predictable, we first explore the mesh connectivity of the template. During this exploration, piecewise continuity is utilized to reduce the redundant computation. The explored template mesh connectivity will be reused for customized products as they have the mesh topology in common. For local feature add-on/removal, we will take care of this local feature independently, so the topology inherited from the template can keep intact and be reused in future.

## 3 Self Topology Information Reuse

In this section, the idea of topology information reuse will be incorporated in a single model by utilizing piecewise continuity in mesh connectivity. The classic closest point method is implemented in two steps: 1) calculating intersection coordinate; and 2) connecting each segment in the right order. The second step is based on the observation that the closest point to a given point is the point itself, and the flow chart of this step is shown in Fig.5 [4, 19]. It is the second step that dominates the time complexity, and at each layer the connectivity of each segment is explored separately. Because each segment is the intersection between the slicing plane and a triangular facet, two segments are connected if and only if their incident triangular facets are adjacent in space. Therefore, if both of the two adjacent triangular facets cross more than one layers (the edge shared by both facets crosses more than one layers), the connectivity among their corresponding segments will persist at all crossed layers.

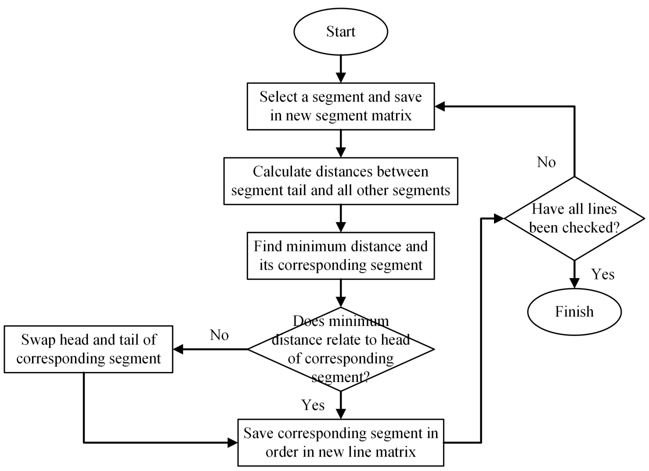



Fig. 5. Flow Chart for Connecting Segments in Order

An example is shown in Fig.6. Triangular facet $T_p$ and $T_q$ have an edge in common, both facets cross $i^{th}$, $i+1^{th}$, and $i+2^{th}$ layer, and the corresponding segments $L_p^i$ and $L_q^i$, $L_p^{i+1}$ and $L_q^{i+1}$, $L_p^{i+2}$ and $L_q^{i+2}$ are connected. The closest point method does not utilize this piecewise continuity in mesh connectivity, and conducts idle computations.

The idea of self topology information reuse takes advantage of this piecewise continuity in mesh connectivity, and explores the adjacency between two triangular facets only once. The explored necessary facet adjacency information is stored in a table, and in later layer if two segments are incident with the same facet pair, they will be connected automatically. Using Fig.6 as an example, if we slice the model from the bottom to the top, the adjacency between $T_p$ and $T_q$ is explored at layer $i$. At layer $i+1$, these two facets still get involved, and we can march from $L_p^{i+1}$ to $L_q^{i+1}$ (or from $L_q^{i+1}$ to $L_q^{i+1}$) directly without computing the distances between the tail of $L_p^{i+1}$ (or $L_q^{i+1}$) and all other segments on this layer.

Since in a manifold mesh model each triangular facet

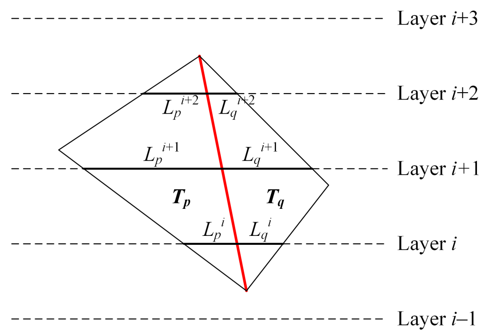



Fig. 6. Piecewise Continuity in Mesh Connectivity

has three edge-connected neighbors, a $t \times 3$ matrix is created to save the adjacency information, where $t$ is the total number of facets from the model. Each row is corresponding to a facet, and each entry saves the neighboring facet of a given facet. For instance, the value of the entry $[i, j]$ (for $0 \leq j \leq 2$) being $k$ means the $j^{th}$ neighbor of facet $T_i$ is facet $T_k$. It is apparent that the adjacency between two facets is commutative, therefore, the value of the entry $[k, l]$ (for $0 \leq l \leq 2$) must be $i$. For a given triangular facet, we save the adjacency according to the vertex sequence. Assuming three vertices from a specific facet are $V_0$, $V_1$ and $V_2$, the neighboring facet which is opposite to $V_0$ is saved at the first entry, the facet opposite to $V_1$ is saved at the second entry, and that is opposite to $V_2$ is saved at the third entry. Fig.7 shows an example.

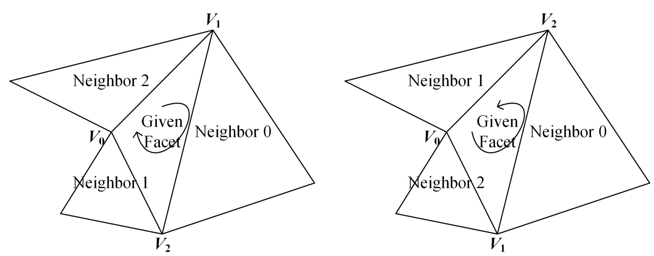



Fig. 7. Neighbor Numbering of A Given Triangular Facet

Initially, all entries of the adjacency table are set as -1. At a specific layer, we start from a facet and march from one facet to another according to the known adjacency until arriving at a facet with -1 value in the entry corresponding to the neighbor in marching direction. This marching results in a polyline instead of a segment, and the polyline consists of one or more connected segments. Fig.8 shows the flow chart of polyline computation.

When all polylines are generated, we only need to investigate the connectivity among polylines by the same idea of the closest point method, and the outcome of this investigation will be used to update adjacency matrix afterwards. The flow chart of this process is shown in Fig.9. Comparing to Fig.5, there are only three differences:

1. In this process we investigate the connectivity among polylines rather than segments;

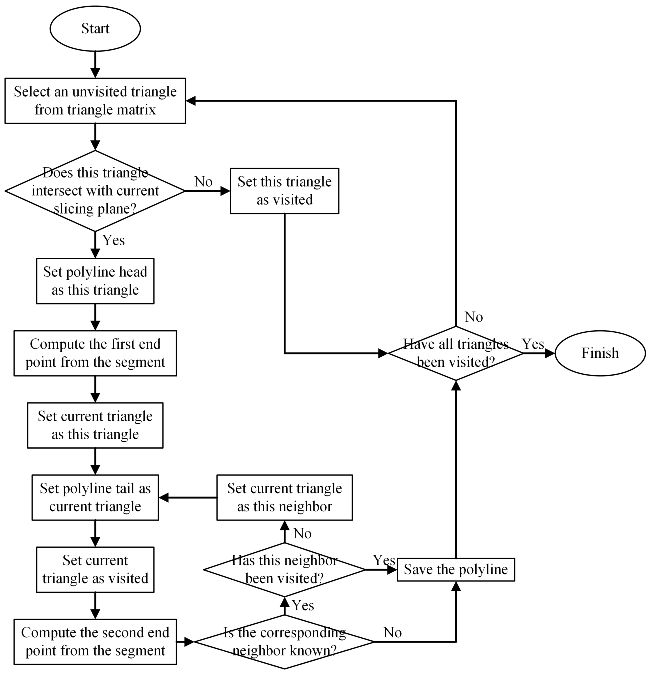



Fig. 8. Flow Chart for Computing the Polylines

2. The distance between the head and tail from the same polyline needs to be compared as well, because it is possible that a single polyline is a closed polygonal contour;
3. The adjacency table is updated according to the minimum distance check.

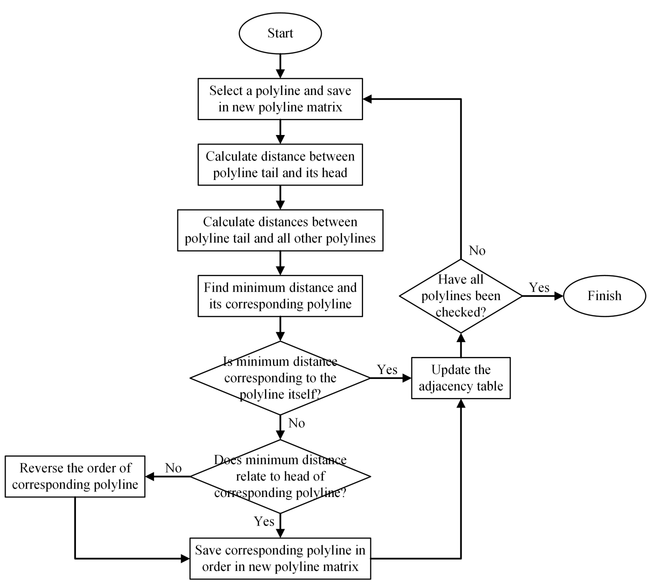



Fig. 9. Flow Chart for Connecting Polylines in Order

Fig.10 shows the intersection between a model and the $i^{th}$ slicing plane, and two contours, $L_1L_2L_6L_8L_{11}L_{10}L_3$ and $L_4L_7L_9L_5$, are included. The area enclosed by the interior contour is hollow, and the area nested between the interior contour and the exterior contour is solid. Assume that from the calculation for the previous layers, the connectivities of $L_1L_2L_6$, $L_4L_7L_9L_5$, $L_{11}L_{10}L_3$ are already known, and the incident facet of $L_8$ just starts to get intersected with current slicing plane. After traversing all facets, four polylines will be generated, and the details are shown in Table 1 (Assume the index of a facet is identical to the segment which is incident to this facet. i.e., Segment $L_i$ is incident to triangular facet $T_i$). When we finish this layer, the connectivity between $P_1$ and $P_2$, $P_2$ and $P_4$, $P_3$ and itself, $P_4$ and $P_1$ can be determined. The adjacency table needs to be upgraded accordingly and Table 2 shows the adjacency before and after this update.

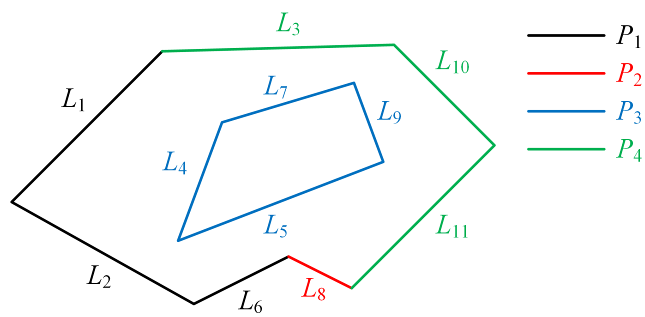



Fig. 10. An Example of Self Topology Information Reuse

Table 1. Polyline Information

| Polyline | Member Segment | Head | Tail |
|---|---|---|---|
| $P_1$ | $L_1, L_2, L_6$ | $T_1$ | $T_6$ |
| $P_2$ | $L_8$ | $T_8$ | $T_8$ |
| $P_3$ | $L_4, L_7, L_9, L_5$ | $T_4$ | $T_5$ |
| $P_4$ | $L_{11}, L_{10}, L_3$ | $T_{11}$ | $T_3$ |

Typical layer thickness used by existing AM processes is usually between 50 $\mu m$ and 100 $\mu m$, but as a continuous AM process, CLIP can have a layer thickness as small as 1 $\mu m$ [10]. After adopting such a tiny layer thickness, on one hand, the possiblity that the same facet adjacency information can be reused for many layers is high; on the other hand, the effect of reusing this adjacency information is significant comparing to the closest point method. Three models, tooth aligner (Fig.11(a)), hearing aid (Fig.11(c)) and vertebral column (Fig.11(e)), are selected as test cases to go through both the classic closest point method and the proposed slicing method with topology reuse. These models are also typical human-centered products which have great demands for mass customization. The test environment is: 64 bit Windows 10 Pro system laptop with Intel(R) Core(TM) i7-4600U, CPU @ 2.10GHz 2.69 GHz and 8GB RAM, and the layer thickness is set as 1 $\mu m$. The results are shown in Table 3. It is apparent that by reusing the topology infor-

Table 2. Adjacency Table Update

| Facet | Neighbor Before Update | Neighbor After Update |
|---|---|---|
| 1 | 2 | **3**, 2 |
| 2 | 1, 6 | 1, 6 |
| 3 | 10 | 10, **1** |
| 4 | 7 | **5**, 7 |
| 5 | 9 | 9, **4** |
| 6 | 2 | 2, **8** |
| 7 | 4, 9 | 4, 9 |
| 8 | | **6**, **11** |
| 9 | 7, 5 | 7, 5 |
| 10 | 11, 3 | 11, 3 |
| 11 | 10 | **8**, 10 |

mation, the time consumed for slicing can be dramatically reduced.

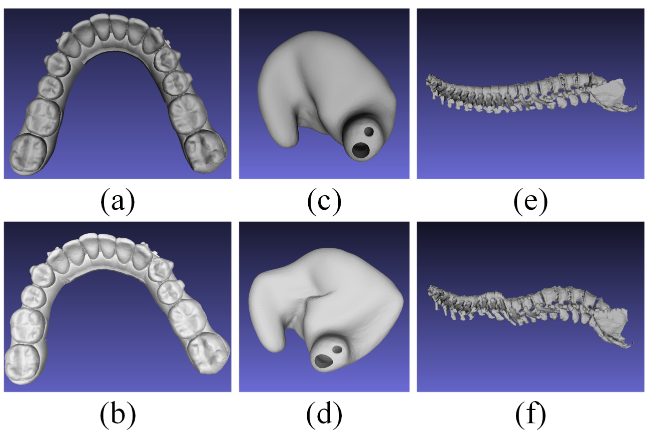


Fig. 11. Test Cases: (a) original tooth aligner, (b) deformed tooth aligner, (c) original hearing aid, (d) deformed hearing aid, (e) original vertebral column, (f) deformed vertebral column.

## 4 Intra-model Topology Information Reuse

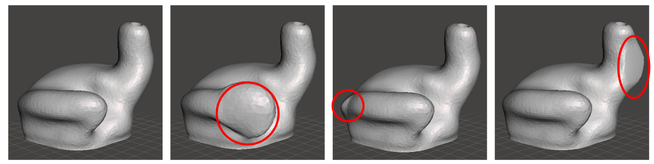
In previous section, we introduced an improved slicing method, which takes advantage of the piecewise continuity in mesh topology. It can be applied on a template model to obtain contour files. Due to the similarity existing among customized products, we can derive other models by modifying the template. This modification can be any arbitrary change on the mesh geometry (vertex position), and the mesh topology is expected to be held. Fig.12 shows three deformed hearing aid models, and they all share the same mesh topology with the original one.

During the slicing for the template, each necessary adjacency is explored only once, and it is saved in the adjacency table. To enable the intra-model topology information reuse, this adjacency table is exported after template slicing. It is loaded first when we start to slice the customized model. Therefore, at least part of necessary adjacency is known for the customized models, and their slicing can be much faster comparing to the model whose connectivity is totally unknown. It is possible that the exported adjacency table still has some entries whose values are -1 (which means corresponding edges of these entries do not intersect with any slicing planes during the template slicing, e.g, parallel to the slicing planes). However, in the modified model these edges may get intersected with slicing planes, and this is because of the vertex position change and/or slicing plane position change. The same strategy as the closest point method can be applied on these edges to further accomplish the adjacency table.

Table 3. Time Statistic Comparison for Self Topology Reuse

| Model | Size | # Layers | $t_{CP}$ | $t_{SR}$ |
|---|---|---|---|---|
| Aligner | 545k | 14k | 67m8s | 3m55s |
| Hearing Aid | 327k | 8.8k | 5m25s | 43s |
| Vertebral Column | 549k | 10k | 55m56s | 1m37s |

The “Size” shows the number of facets, and “# Layers” is the number of layers. Time units are in minute (m) and second (s). “$t_{CP}$” and “$t_{SR}$” are the time consumed for closest point method and self topology reuse, respectively.



(a) Original (b) Deformed 1 (c) Deformed 2 (d) Deformed 3

Fig. 12. Deformed Models Derived from the Template

Three test cases, deformed tooth aligner (Fig.11(b)), deformed hearing aid (Fig.11(d)) and deformed vertebral column (Fig.11(f)), are selected to demonstrate the efficiency from intra-model topology information reuse. The test environment is the same as Section 3, and the layer thickness is also set as 1 $\mu m$. The time statistics are report in Table 4.

Table 4. Time Statistic Comparison for Intra-Model Topology Reuse

| Model | $t_{CP}$ | $t_{SR}$ | $t_{IAR}$ |
|---|---|---|---|
| Deformed Aligner | 68m6s | 3m54s | 1m37s |
| Deformed Hearing Aid | 5m27s | 43s | 34s |
| Deformed Vertebral Column | 54m17s | 1m39s | 1m14s |

“$t_{IAR}$” is the time consumed for intra-model topology reuse slicing, and the time for loading the adjacency table is included.

## 5 Inter-model Topology Information Reuse

Sometimes modifying the template model only by changing the vertex position cannot generate desired customized feature, and local feature add-on and/or removal might be necessary. For example, a customer or a manufacturer may want to add a unique monogram on a specific customized product to differentiate this product from others. The monogram can be numbers, characters, or even QR code, and it is not easy to be achieved by changing the mesh geometry only.

Adding a feature to a mesh model can be accomplished by Boolean union, and some commercial softwares, such as Magics, can do this without any difficulty. The union operation merges two manifold mesh models into one, and the resultant model has to be manifold as well. During this process, the facets at or near the conjunction have to be merged, cut, or deleted. For mass customization, the impacted facets may only be a small part of the whole model, but the original mesh topology has been changed. If the impacted facets can be identified, we can edit the adjacency table accordingly to make it still reuseable. Unfortunately, this topology change occurred during the modification is not traceable for most mesh processing softwares.

In order to reuse the template topology, the add-on feature is saved as a separate manifold mesh model, and it is placed at the designated position relative to the template model. In the following slicing process, the template and the add-on feature are sliced independently, therefore, the topology information for the template can still be reused. After both parts have been sliced, the contour profiles from both parts are combined together to convert into binary images. Fig.13 is a hearing aid model with 3D personalized monogram, and we use this model as an example to illustrate the details.

(a) (b) (c)

Fig. 13. Hearing Aid with Monogram: (a) hearing aid model, (b) monogram, (c) resultant model.

For the original hearing aid model (Fig.13(a)), the adjacency table derived from template slicing still can be used. Comparing to the hearing aid model, any add-on feature usually has a smaller size in terms of number of facets. In this example, the hearing aid model has 327,428 triangles, whereas the monogram only contains 6,932 facets. Along this line, whether the connectivity of add-on feature is known is insignificant. Because the monogram is an add-on feature, the polygonal area enclosed by the contour of template and that enclosed by the contour of monogram must have some overlap (That is to say they have to at least share some segments in order to be connected to each other). This overlap results in intersection of the contours, and leads to invalid loops. Because CLIP is a mask projection based SLA process, we can skip the process of invalid loop identification and removal, which is usually required in planar polygon offsetting problem, to generate a valid image directly from contour with invalid loops.

In this paper, the concept of winding number [20] is used to generate aforementioned valid images. If we adopt the convention that the exterior contour is oriented counterclockwise (CCW) and the interior contour oriented clockwise (CW), the winding number is defined as following [20]:

**Definition 1:** Let $P \subset R^2$ be a set of oriented polygonal contours, $q \subset R^2$ be a point, and $r \subset R^2$ be any ray from $q$ to infinity that intersects no vertex of $P$. The winding number $\omega(r,P)$ of $r$ with respect to $P$ is:

$$\omega(r,P) = \sum_{e_i \in P} \Psi(r,e_i)$$

where for each edge $e_i$, $\Psi(r,e_i)$ is defined as follows:

$$\Psi(r,e_i) = \begin{cases} 0 & \text{if } r \text{ does not intersect } e_i; \\ 1 & \text{if } e_i \text{ crosses } r \text{ in CCW as view from } q; \\ -1 & \text{if } e_i \text{ crosses } r \text{ in CW as view from } q. \end{cases}$$

In order to determine whether a single connected region is solid or hollow, positive winding rule is selected. If the winding number for this region is positive, it is classified as solid, and the pixels on the image it covers are set as foreground. Otherwise, the region is identified as hollow, and its corresponding pixels on the image are set as background. Fig.14(a) represents the contour at a specific height for the hearing aid model with monogram, and the calculated winding number is shown in Fig.14(b). Fig.14(c) is the binary image after conversion which can be used for CLIP directly. It is noteworthy that this method is also capable of handling feature removal, and the principal idea is the same as Boolean difference. In this application, the orientation of the contour from removing feature needs to be reversed. Fig.14(e)-(h) shows an example for feature removal.

## 6 Conclusion and Discussion

In this paper, we embraced the idea of reuse in the computational field for additive manufacturing. The emerging CLIP technology can dramatically reduce the fabrication time, and now the pre-fabrication computation becomes the bottleneck. By taking advantage of the high similarity existing among customized products, we proposed reusing the topology information to accelerate slicing process. This reuse was implemented in three levels, including self reuse, intra-model reuse, and inter-model reuse. Self reuse is based on the piecewise continuity in mesh connectivity, and it reuses the topology information explored from the calculation for previous layers. This improved slicing algorithm does not aim at decreasing the order of asymptotic time complexity, instead it is trying to reduce the size of input by

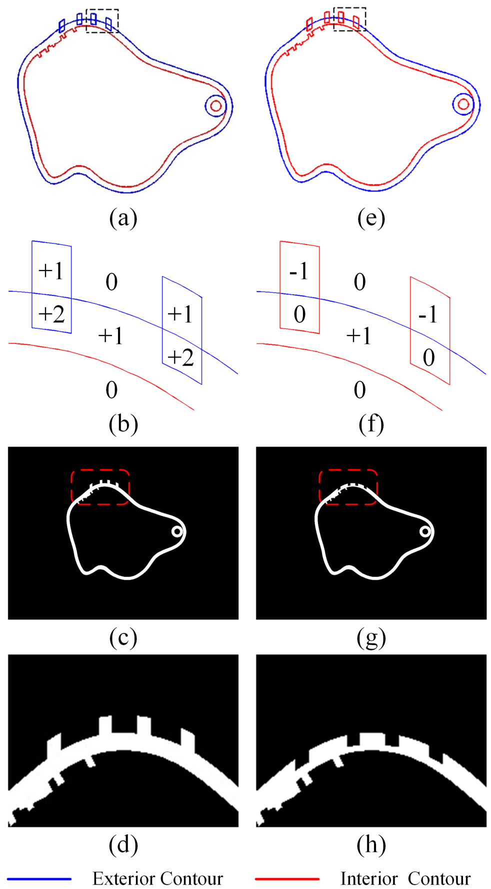



Fig. 14. Hearing Aid with Monogram: (a) contour with feature add-on, (b) winding number for feature add-on, (c) image for feature add-on, (d) zoom-in image for feature add-on; (e) contour with feature removal, (f) winding number for feature removal, (g) image for feature removal, (h) zoom-in image for feature removal.

eliminating redundant calculations. Comparing to the classic closest point method, time saving is significant, but this method consumes more storage. For a given model and a specific layer thickness, the total number of connectivity needed to be explored is a constant. If all necessary connectivity is known, the asymptotic time complexity is linear. Intra-model reuse utilizes the topology information obtained from template slicing, and expects to attain a near linear time complexity. Customized model which is suitable for intra-model reuse can be derived from the template by applying vertex position change on all three dimensions as long as the mesh topology persists. And inter-model reuse was also proposed to take care of local feature add-on and removal, which is also very common in practice. It treats the add-on/removal feature independently to keep the mesh topology from template intact, so this information can be reused. In the contour-image conversion, Boolean operations are adopted to render a valid mask image. Experimental results show that prominent time saving can be achieved by adopting the proposed method.

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## References

[1] Toffler, A., 1970. *Future Shock*. Random House, New York, NY.

[2] Davis, S. M., 1987. *Future Perfect*. Addison-Wesley, Reading, MA.

[3] Salvendy, G., ed. *Handbook of Industrial Engineering: Technology and Operations Management*, 3rd ed. John Wiley & Sons, New York, NY, Chap. 25, pp. 684–687.

[4] Gibson, I., Rosen, D. W., and Stucker, B., 2009. *Additive Manufacturing Technologies: Rapid Prototyping to Direct Digital Manufacturing*, 1st ed. Springer, New York, NY.

[5] Fogliatto, F., and da Silveira, G., 2010. *Mass Customization: Engineering and Managing Global Operations*. Springer Series in Advanced Manufacturing. Springer.

[6] Scott, J., Nayanee Gupta, C. W., Newsome, S., Wohlers, T., and Caffrey, T., 2012. Additive Manufacturing: Status and Opportunities. Tech. rep., Science and Technology Policy Institute.

[7] Ford, S. L. N., 2014. "Additive manufacturing technology: Potential implications for u.s. manufacturing competitiveness". *Journal of International Commerce and Economics*.

[8] Froehlich, M., 2013. Insio: A New Standard in Custom Instruments. Tech. rep., Siemens.

[9] Envisiontec, Inc. `http://envisiontec.com/`.

[10] Tumbleston, J. R., Shirvanyants, D., Ermoshkin, N., Janusziewicz, R., Johnson, A. R., Kelly, D., Chen, K., Pinschmidt, R., Rolland, J. P., Ermoshkin, A., Samulski, E. T., and Desimone, J. M., 2015. "Continuous liquid interface production of 3d objects". *Science,* **347**(6228), pp. 1349–1352.

[11] Beaman, J. J., Barlow, J. W., Bourell, D. L., Crawford, R. H., Marcus, H. L., and McAlea, K. P., 1997. "Solid freeform fabrication: a new direction in manufacturing". *Kluwer Academic Publishers, Norwell, MA,* **2061**, pp. 25–49.

[12] Jacobs, P. F., 1993. *Rapid Prototyping and Manufacturing: Fundamentals of StereoLithography*. McGraw-Hill, New York, NY.

[13] Wohlers, T., 2013. Wohlers Report: Additive Manufacturing and 3D Printing State of the Industry. Annual worldwide progress report, Wohlers Associates, Fort Collins, CO.

[14] Freedman, D. H., 2012. "Layer by layer". *Technology Review,* **115**(1), pp. 50–53.

[15] Rock, S. J., and Wozny, M. J., 1991. "Utilizing topological information to increase scan vector generation efficiency". In Proceedings of International Solid Freeform Fabrication Symposium, pp. 1–9.

[16] SynCardia Systems, Inc. `http://www.`

syncardia.com/media/multimedia-library-dp1.html.

[17] Armin Iske, E. Q., and Floater, M. S., eds., 1991. *Tutorials on Multiresolution in Geometric Modelling*. Springer, Berlin, DE, Chap. 12, pp. 319–362.

[18] Shirley, P., and Marschner, S., 2009. *Fundamentals of Computer Graphics*, 3rd ed. A K Peters, Natick, MA.

[19] Vatani, M., Rahimi, A. R., Brazandeh, F., and Nezhad, A. S., 2009. "An enhanced slicing algorithm using nearest distance analysis for layer manufacturing". In Proceedings of World Academy of Science, Engineering and Technology, Vol. 37, pp. 721–726.

[20] Chen, X., and McMains, S., 2005. "Polygon offsetting by computing winding numbers". In Proceedings of International Design Engineering Technical Conferences & Computers and Information Conference (IDETC/CIE 2005), ASME, pp. 1–11. Paper number DETC2005-85513.