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Reviewed Paper

USING SKELETONS FOR VOID FILLING IN LARGE-SCALE ADDITIVE MANUFACTURING

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Abstract

In additive manufacturing (AM), slicing software is used to generate tool paths that are then converted to G-Code, which tells the 3D printer how to build a part. Toolpaths are generated using closed-loop paths. Sometimes the space left for a closed-loop is not sized perfectly. This can lead to overfill or underfill issues. Therefore, skeletonization of a polygon seeks to resolve this issue by creating an open-loop path to fill the voids between adjacent toolpaths. A straight skeleton was used to explore this work. Straight skeletonization represents the topological skeleton of a shape through line segments. After skeletonization, the extrusion rate can be varied to adjust bead width more precisely to fill the gap.

1. Introduction

In additive manufacturing (AM), the program used to convert a 3-Dimensional (3D) model into the commands that a printer needs to make a part is called a slicer. Most modern slicers accomplish this task by taking cross sections of the 3D models and running morphological operations on the outlines in these cross sections, which generates toolpaths that are then converted into the G-Code that 3D printers use to build parts. The most common patterns for filling the outline are raster (Figure 1a. Raster Fill), honeycomb (Figure 1b. Honeycomb Fill), and concentric (Figure 1c. Concentric Fill).

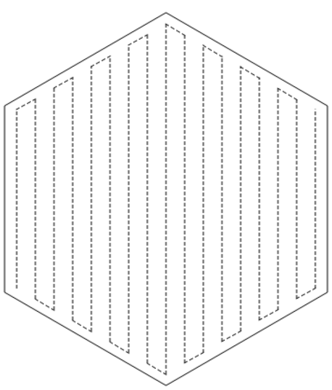

Figure 1a. Raster Fill

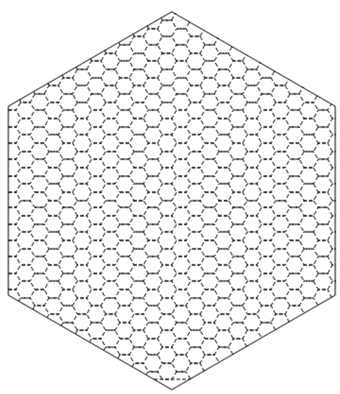

Figure 1b. Honeycomb Fill

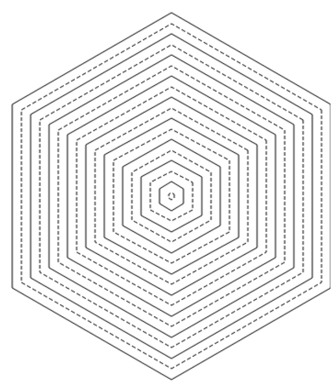

Figure 1c. Concentric Fill

Concentric fill is commonly used to create a completely solid fill. When taking the cross section at a specific layer height of a part, the result is multiple individual n-dimensional polygons. These polygons can be offset either outward to make them larger (Figure 2) or inwards to make them smaller. Concentric fill requires taking the outline of a single island and offsetting the outline inwards by the half of the size of the bead width to find the path line of the first ring (Figure 3). Offsetting the original outline by a full width gets the outline of the next bead (or ring). Concentric fill continues this process until the offset polygons get removed as the lines shrink to zero length. Because of how the polygon offsetting work, it is limited to only producing closed-loops or paths that start and end at the same point. One of the fundamental issues with the concentric fill pattern is under and over filling when a model is not designed to be an even multiple of bead widths wide. When a part is designed to be larger than an integer even multiple of bead widths wide then the outline of the final ring will exist, but the center line will not and there will be a gap in the middle. Under filling can cause future layers to sink down to fill in voids or weaknesses in the part. When a part is designed to be smaller than an integer even multiple of bead widths then the last ring overlaps on itself causing over filling. Over filling can lead to the printer head colliding with solid material potentially damaging the part, the printer, or both. While this poses a small problem for desktop 3D printers as the gaps/bumps are small, it is a much more significant problem on large-scale machines that can print hundreds of pounds of material per hour and have build volumes that are several feet in each dimension. Material bumps on large-scale machines can be rock solid, and gaps that occur are much larger. These gaps can reduce the strength of the overall part as well causing it to be weaker to whatever stresses that may be applied.

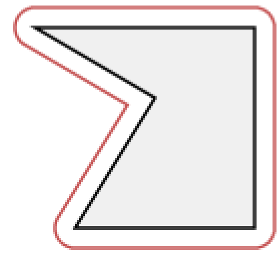

Figure 2. Polygon offsetting (Johnson)

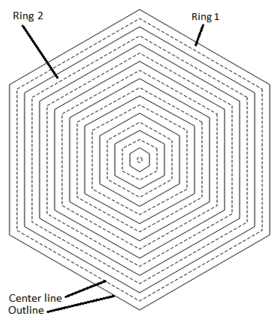

Figure 3. Annotated concentric fill

2. Prior Work

Other works such as (Agarwala, Jamalabad and Langrana) and (Eiliat and Urbanic) have discussed this problem. One suggested solution required the designer to define the part's width using an even integer multiple of bead widths. While this is possible to implement with a simple geometric part, it is not an ideal solution for organic shapes. Another solution mentioned involved adjusting the output speed of the extruder to decrease the width of the bead. This is only possible with some printers. Also, the bead width is not linearly proportional to extruder output speed as other factors, such as gantry or robot speed and layer height, are involved in the volumetric flow rate. For these reasons, the solution detailed below was explored.

3. Method

When the width of a part is an inconvenient size, two undesirable things can occur. Either the final ring will overlap upon itself, leading to an overfilled center, or a gap will be left. Using skeletonization eliminates these errors. This is done by first detecting the regions that would cause the under/over filling, then applying a skeletonization algorithm to generate the topological skeletons of the region. Topological skeletons are collections of open paths that form connected line segments throughout the interior of the polygonal area. They work as an open-loop path, or a path that starts and ends at separate points, through the center of a polygon. Some post-processing is then performed to connect the skeleton segments to the boundary polygon to eliminate small voids at the ends of the paths. If the original outline has a hole, then the skeleton has the possibility of being a closed-loop (Figure 6).

3.1 Detecting Voids

Detecting the possibility of under filling or over filling is done by erosion and dilation, a common technique for smoothing in image processing, of the outline (not the center path) of a ring by the bead width and then taking the difference of this result from the original outline (Figure 4).

Algorithm 1: Void Detection

Procedure

outline ← cross-section outlines as a list of polygons
while outline.size() **do**
inline ← outline.offset(- beadwidth / 2)
non_skeleton_region ← outline – inline.offset(beadwidth / 2)
skeleton_region ← outline – non_skeleton_region

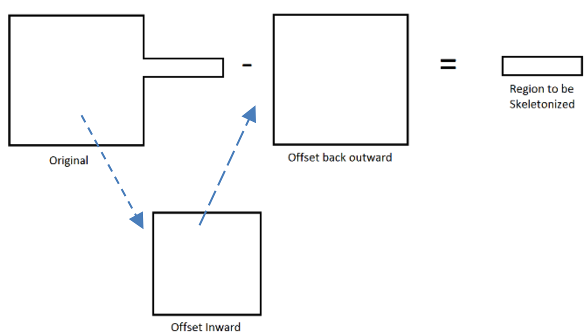

Figure 4. Void detection

3.2 Skeletonization

Once the skeleton region is detected, a straight skeleton algorithm is applied to create the central path of the region.

3.2.1 Straight Skeleton

First defined for simple shapes by (Aichholzer, Aurenhammer and Alberts) and later defined for arbitrary 2-Dimensional inputs by (Aichholzer and Aurenhammer), the straight skeleton, also known as an angular bisector network, is a method for representing a topological skeleton. The straight skeleton is defined through a continuous shrinking process in which each of the edges of the shape are moved inwards parallel to the previous edge at a constant speed (Figure 5). Each vertex moves along the angle bisector of its incident neighbors. Each edge continues to shrink until either its length is reduced to nothing and its vertices merge into one or another vertex runs into it, which splits the shrinking edge.

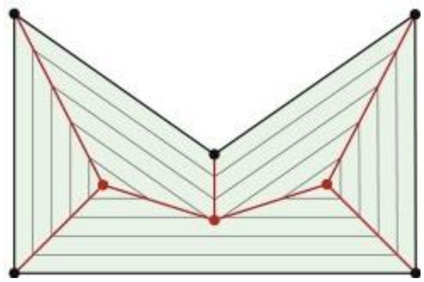

Figure 5. Straight Skeleton (Cheng, Devadoss and Risteski)

3.3 Post-Processing

Once the skeleton (See red lines in Figure 6) is generated, the end points usually form a triangle with one of the polygon edges. An angle bisector of this triangle is used to connect each end with the midpoint of the edge to eliminate a small gap (See blue lines in Figure 6).

As mentioned before, if the outline contains a hole, then it is possible that the skeleton is a closed-loop (Figure 7) or a closed-loop with a tail. The loop is closed or connected to a tail piece during post-processing.

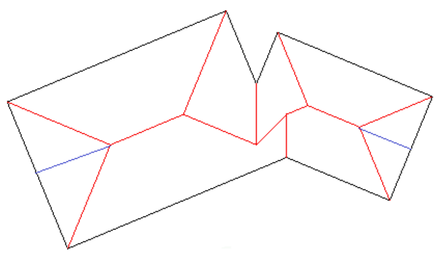

Figure 6. Straight skeleton of polygon without holes

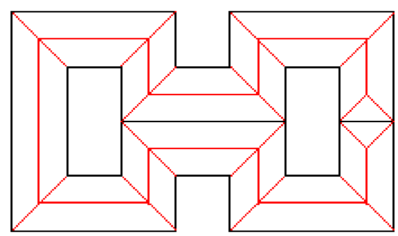

Figure 7. Straight skeleton of polygon with holes (Cacciola)

3.4 Variable Extrusion

One of the other solutions previously proposed for over/under filling was varying the rate of extrusion. Combining this solution with skeletonization increases the ability of the printer to correctly fill a shape with a perfect concentric fill. For the straight skeleton, as the vertices and edges are removed, this is used to determine the approximate width of the gap, which then creates a bead as close to the width of the gap as possible.

4. <u>Results</u>

The results of this work were tested with Oak Ridge National Laboratory's (ORNL) experimental, large-scale polymer printer using ORNL Slicer software (Love and Duty). The build space of this machine is 8' x 8' x 8'. The layer height for this work is 0.15", and the bead width is 0.34". Carbon Fiber ABS is used for the experiment.

Without any type of skeletonization, gaps are left by the polygon offsetting process as shown in Figure 7 and Table 1. In Figure 7, the number written on the build sheet is the multiple of bead widths. As the number gets further from an even integer multiple (2) the gap gets larger spanning from 0.162 bead widths to 1.391 bead widths on the lines and 0.209 bead widths to 1.079 bead widths on the loops. As the number gets close to the next even integer multiple (4), overfilling is observed on the 3.75 bead width line and loop.

(a)

(b)

Figure 7. Printed Test Pieces without Skeletons

Table 1. Gap Data of Printed Test Pieces without Skeletons

Thickness (bead widths)	Lines Gap (bead widths)	Loops Gap (bead widths)
2	0	0
2.25	0.162	0.209
2.5	0.371	0.379
2.75	0.621	0.450
3	0.794	0.876
3.25	1.138	1.041
3.5	1.391	1.079
3.75	0	0
4	0	0

Adding skeleton paths removes most of the gaps (Figure 8) by filling them with a single open path bead for the lines and a single closed-loop path bead for the loops. Most remaining gaps, such as those on the 2.25 and 2.5 bead width lines and loops, were smaller than the amount the extruder could vary in width. The machine can reduce the bead to 50% of its original size and expand to 150% of its original size. Therefore, the gaps were left unfilled by the void detection.

(a)

(b)

Figure 8. Printed Test Pieces with Straight Skeletons

Table 2. Gap Data of Printed Test Pieces with Straight Skeletons

Thickness (beadwidths)	Lines Gap (beadwidths)	Loops Gap (beadwidths)
2	0	0
2.25	.170	0
2.5	.368	.381
2.75	.630	.446
3	0	0
3.25	0	0
3.5	0	1.038
3.75	0	0
4	0	0

On the print with skeletons, some gaps were too thin for a skeleton to resolve them, but they were still larger than the same gap on the print without skeletons. This was caused by the inertia of the extruder reducing the positional accuracy.

5. <u>Conclusion</u>

Concentric filling is a type of infill pattern used in 3D printing in which a 2D island is filled with shrinking contours through polygon offsetting. Polygon offsets is limited to only being able to create a closed-loop or polygon. When the cross-section of a part is not an even multiple of beads width under or over filling can occur. A solution for these limitations is proposed in which the final ring is used to detect if it will create an overlap (for over filling) or a void (for under filling). Skeletonization generates an open path that goes through the center of a polygon. This is used to replace the overlap or gap with a skeleton path that can be open-loop for a polygon without a hole or a closed-loop for a polygon with a hole. The success of this approach was verified on a large-scale polymer printer to remove gaps and replace overfill.

6. References

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