A novel approach for adaptive skeleton toolpath generation

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Abstract

Large-format additive manufacturing is a key component of Industry 4.0, revolutionizing production through automation and real-time data sharing in cyber-physical systems. However, voids in printed parts can cause mechanical defects, especially in large-format printing. This research presents an adaptive methodology for skeleton toolpath generation to better fill void spaces. Developed by researchers at Oak Ridge National Laboratory, this novel approach consists of seven subprocesses: Void Identification, Smoothing, Chamfering, Voronoi Diagram Generation, Pruning, Path Consolidation, and Path Adaptation. By integrating these subprocesses, the method significantly enhances the structural integrity of complex parts, ensuring comprehensive void filling while minimizing both underfilling and overfilling.

Void Identification

The use of skeleton toolpaths to produce a completely dense part requires the identification of all void geometries. Voids can occur in two scenarios. First, when the geometry width is not an even multiple of the bead width, resulting in closed loop paths (CLPs) that cannot completely fill the geometry. Second, when parts of the geometry are lost during the offsetting procedure, as CLPs in regions less than two beads wide self-intersect or overlap, creating invalid portions. To identify these voids, the valid portions of the CLP are offset outward by half the bead width and subtracted from the original bounding geometry.

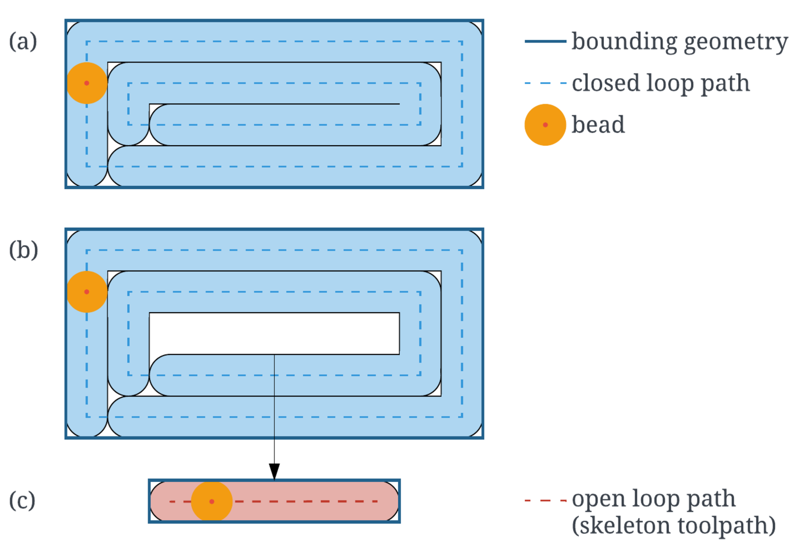

Fig. 1. (a) A rectangular geometry that is four beads wide is completely filled by two closed loop paths. (b) A rectangular geometry that is five beads wide is partially filled by two closed loop paths and contains a void that cannot be filled by an additional closed loop path of the same bead width. (c) The void featured in (b) is filled by an open loop path (skeleton toolpath).

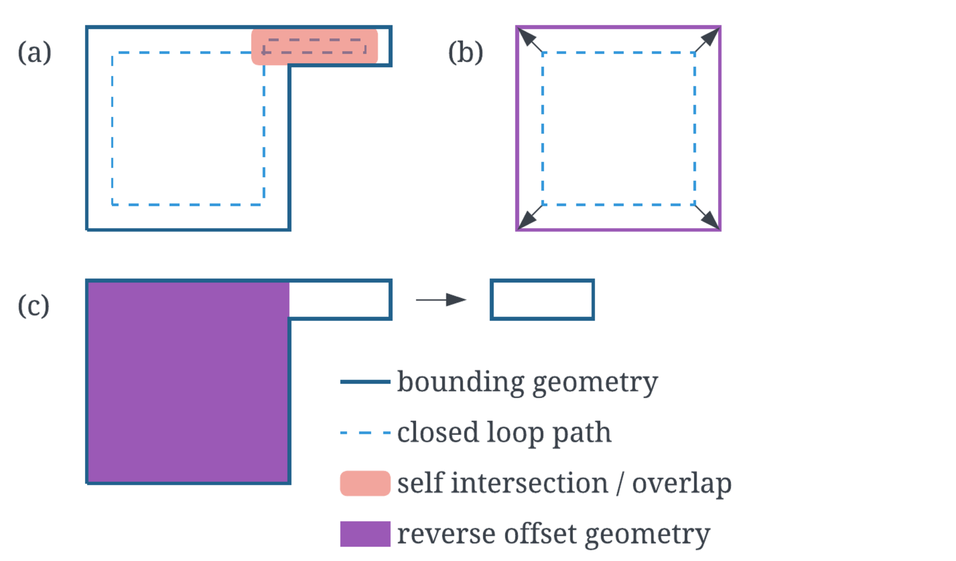

Fig. 2. (a) A square geometry with an extension that is 1.5 beads wide generates a closed loop path with a self-intersection/overlap. (b) The self-intersection/overlap is discarded and the remaining closed loop path is offset outward to produce the reversed offset geometry. (c) The reversed offset geometry is subtracted from the original bounding geometry to produce the lost geometry.

Smoothing

To maximize the stability of skeleton toolpaths, it is essential to smooth the boundaries of the identified voids. This is because the region's boundary is often subject to small deformations due to multiple polygon offset and clipping operations. The smoothing process is performed by removing vertices between adjacent near-colinear segments, based on a specified tolerance, δ. The algorithm applied for this process is similar to Lang's Polyline Simplification algorithm but without a fixed search region.

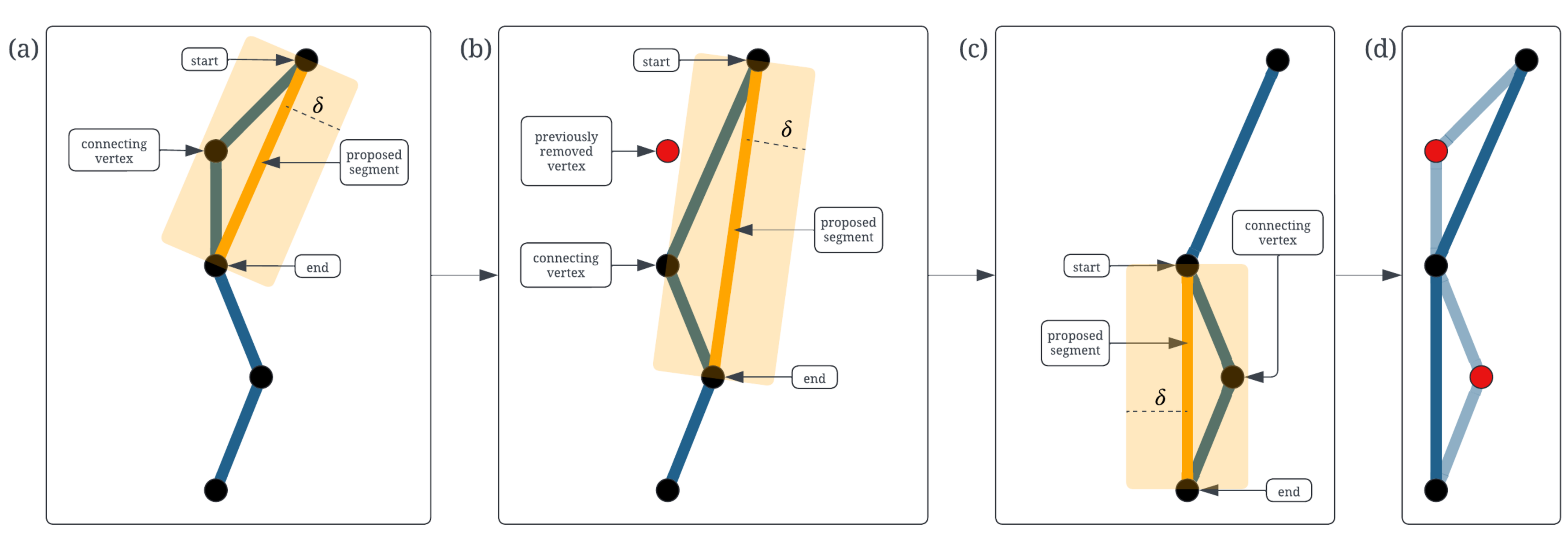

Fig. 3. (a) The connecting vertex is within the specified tolerance, δ, so the first two segments will be combined and the search region will expand to include the next segment. (b) The previously removed vertex is not within the specified tolerance, δ, so the third segment will not be combined with the first two. Instead, the search region will shift to the end point of the last search region and restart. (c) The connecting vertex is within the specified tolerance, δ, so the last two segments will be combined and the smoothing process will finish. (d) The smoothed polyline superimposed on its original form.

Chamfering

Through the post-generation pruning process, all skeleton branches intersecting the generating boundary are removed, including those bisecting the vertices of acute regions. To retain as much of the skeleton toolpaths as possible in acute regions, these regions are chamfered prior to skeleton generation. Acute vertices are split into two phantom vertices separated by a minimum distance, resulting in the generation of three skeleton segments. After the pruning process, only the segment running the length of the acute region remains.

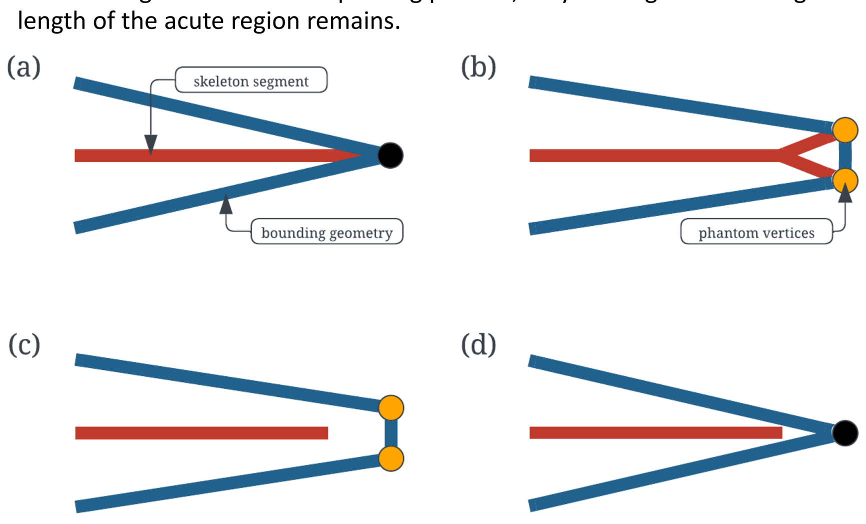

Fig. 4. (a) An acute region with a bisecting skeleton branch. (b) A chamfered region with two new phantom vertices and three skeleton branches. (c) A chamfered region with all bisecting skeleton branches removed. (d) The remaining skeleton branch with respect to the real geometry of the acute region.

Voronoi Diagram

To generate skeleton paths, Voronoi diagrams are created for each void geometry after the identification, smoothing, and chamfering processes. Voronoi edges within these diagrams serve as the foundation for the skeleton toolpath. Although Voronoi diagrams are typically created using points as generating objects, line segments can also be employed. When line segments are used, Voronoi edges are particularly suitable for approximating a geometry's topological skeleton.

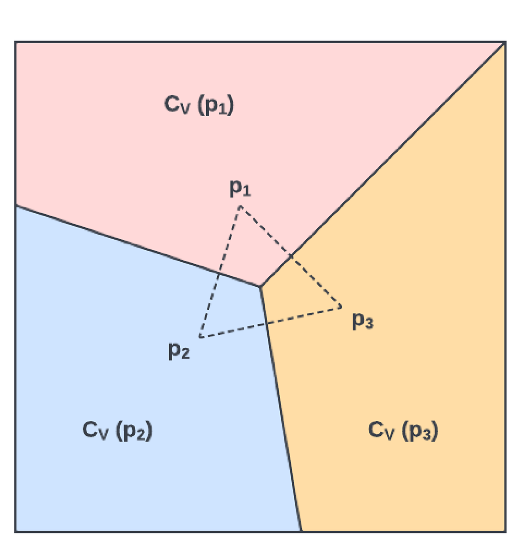

Fig. 5. A Voronoi diagram of points p_1, p_2, p_3 showing a partitioning on the plane into cells $C_v(p_1)$, $C_v(p_2)$, $C_v(p_3)$.

Skeleton Pruning

Skeleton pruning is an essential step in the skeletonization process that aims to remove unimportant peripheral branches while preserving the connectivity of the skeleton. In the context of toolpath planning, a pruning process specifically designed for this application is developed. To maintain positional accuracy in large-format 3D printers, the skeleton toolpath should consist of a minimal number of continuous line segments and be entirely contained within the region without boundary intersections. The pruning process involves two activities: removing all boundary-intersecting branches and smoothing the remaining skeleton polylines. The effectiveness of this process is largely due to the preceding boundary smoothing and chamfering processes.

Path Consolidation

After pruning, the skeleton is decomposed into a set of paths to minimize the number of travel movements required during printing. Travels are motions of the system from one area of construction to another and are considered detrimental to manufacturing time. To achieve this, the skeleton is treated as a connected, undirected graph, with the objective to find the minimum number of Eulerian trails that cover the graph. The process follows a modified version of Hierholzer's algorithm for finding Euler cycles, involving repeated random walks and consolidation of trails until all edges of the graph are covered. This approach results in a more efficient toolpath with reduced travel movements.

1. Starting at a vertex of odd degree, a random walk of unvisited edges is initiated. Each time an edge is traversed, it is labeled as visited, and the degree of the two vertices it joins is reduced by one. The walk continues until a vertex of degree one is entered. The collection of traversed edges is set aside as a candidate trail.
2. Step 1 is repeated until there are no vertices of odd degree left within the graph.
3. If the graph still contains unvisited edges, a vertex is located with both visited and unvisited edges. A candidate trail containing that vertex is then broken and a random walk of unvisited edges is initiated from that vertex. Since no vertices of odd degree are left within the graph, the walk will eventually return to the vertex where it started. The Eulerian trail then continues along the remaining edges of the broken trail, thereby prepending additional edges to the broken trail without increasing the total number of trails.
4. Step 3 is repeated until all edges of the graph are covered.

Path Adaptation

Skeleton toolpaths must be assigned a bead width before printing. Using a fixed bead width is not suitable for skeletons as they fill irregular regions of varying width, which can result in over- or under-filling. To address this issue, each skeleton segment is divided into adaptable subsegments based on the segment length and discretization distance. The bead width of each subsegment is determined by its minimum distance to the region boundary and is implemented through a linear relationship between bead width and toolpath speed. The result is an adapted toolpath that eliminates overfilling and minimizes underfilling.

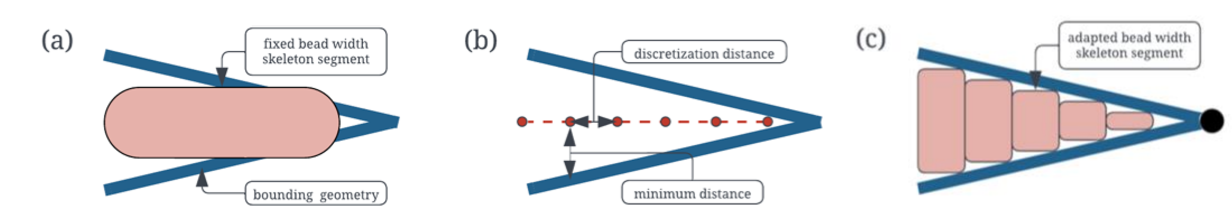

Fig. 6. (a) A fixed bead width skeleton segment in an acute region both overfills and underfills the geometry. (b) A skeleton segment is discretized into smaller subsegments with varying bead widths. (c) The adapted skeleton toolpath completely fills the acute region.

Results & Discussion

To demonstrate the practical application of adaptive skeletons, multiple parts were sliced for manufacturing on a 3D Platform WorkCenter 500. The printer has a build volume of 1m x 2m x1m and a nozzle diameter of 6mm with a feasible bead width range from 3mm to 12mm. Generated skeletons segments with bead widths lower than 3mm are discarded, and segments with bead widths higher than 12mm are assigned 12mm as their bead width. When manufacturing solid parts, a critical success factor is to achieve maximum solidity, which entails extruding as much volume as the calculated part volume. The total extruded volume can be approximated by summing the individual volumes of each extruded segment by multiplying the cross-sectional area of a segment by its length. The slicing results with and without the use of adaptive skeletons are summarized in Table 1 for an ellipse column, impact column, irregular column, and turbine blade. Additionally, single layers of both the impact column and turbine blade were printed using a clear polymer filament.

Part	Part volume (mm^3)	6mm Perimeters (mm^3)	6mm Perimeters & Adaptive Skeletons (mm^3)	Volume Increase (%)
Ellipse Column	7.11×10^6	4.12×10^6 (57.90%)	6.17×10^6 (86.74%)	28.84%
Impact Column	4.35×10^7	2.57×10^7 (59.06%)	3.80×10^7 (87.40%)	28.34%
Irregular Column	3.96×10^8	3.52×10^8 (88.89%)	3.54×10^8 (89.42%)	0.53%
Turbine Blade	4.86×10^7	4.34×10^7 (89.24%)	4.39×10^7 (90.44%)	1.2%

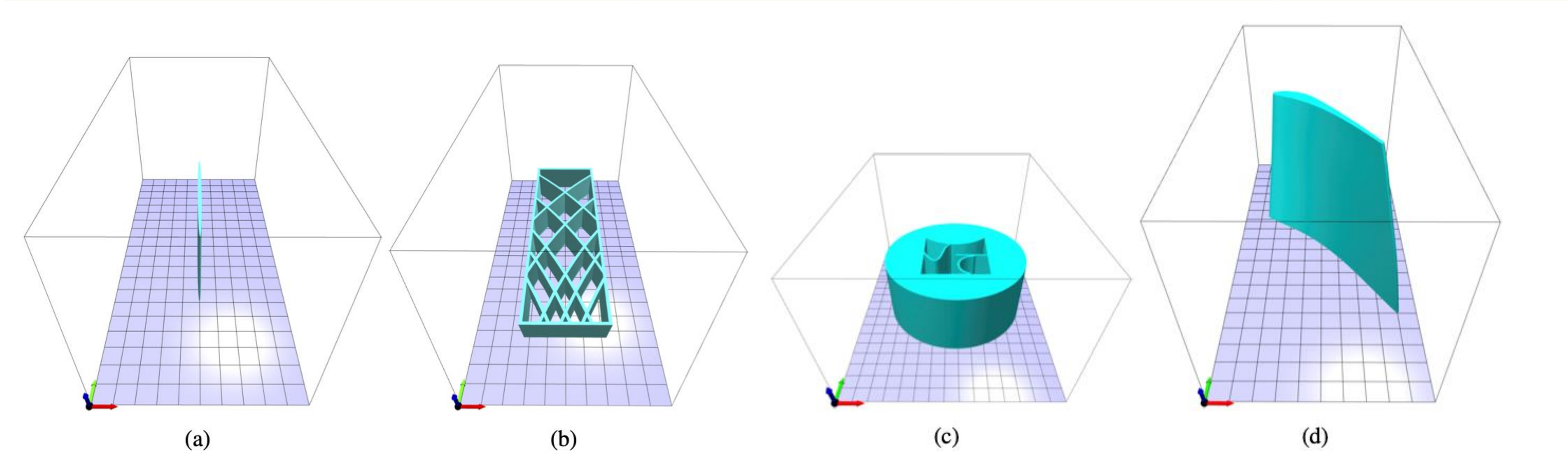

Fig 7. (a) An ellipse column with a volume of 7.11 × 106mm^3. (b) An impact column with a volume of 4.35×107 mm^3. (c) An irregular column with a volume of 3.96 × 108mm^3. (d) A turbine blade with a volume of 4.86 × 107mm^3.

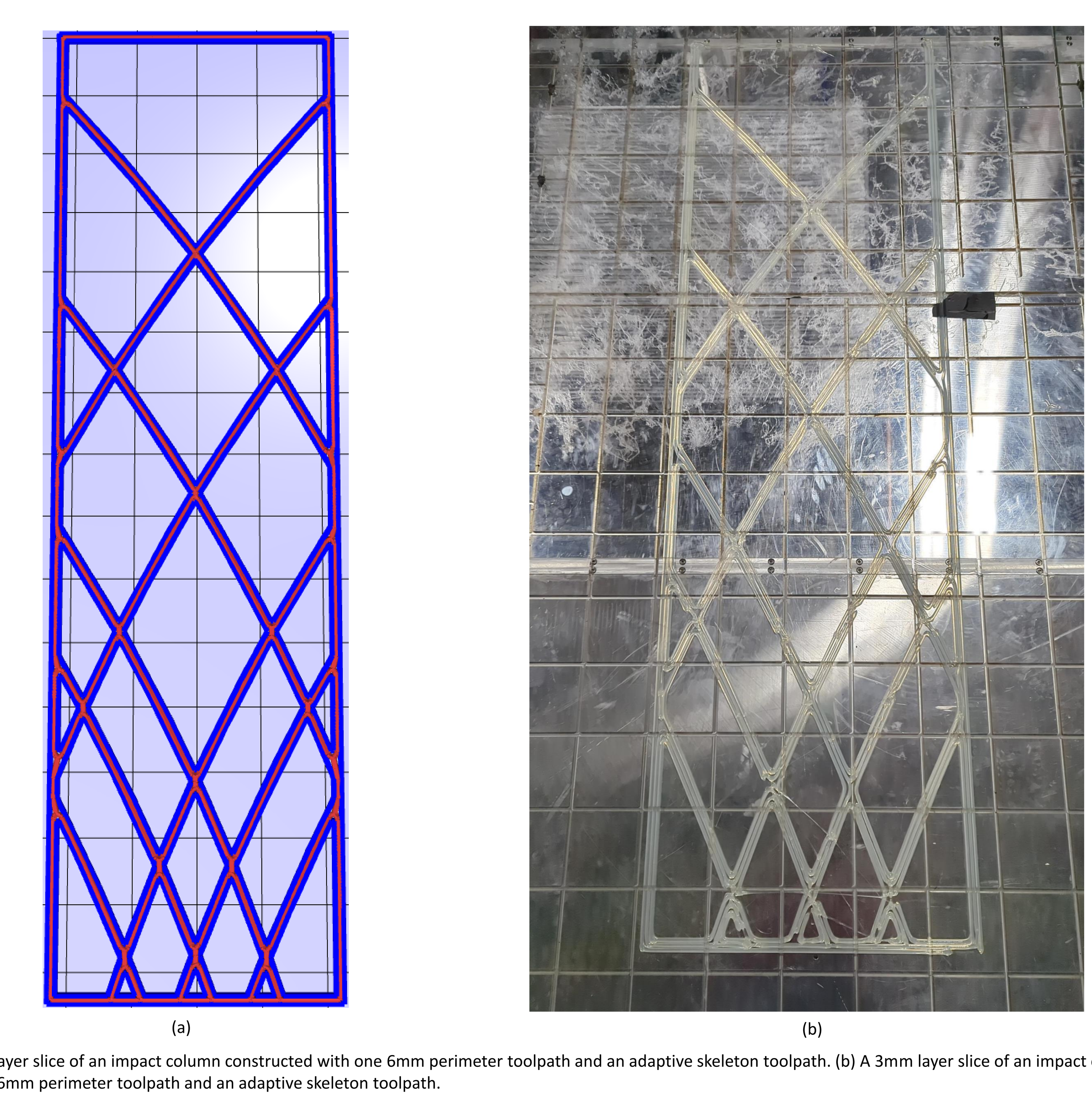

Fig 8. (a) A 3mm layer slice of an impact column constructed with one 6mm perimeter toolpath and an adaptive skeleton toolpath. (b) A 3mm layer slice of an impact column printed with one 6mm perimeter toolpath and an adaptive skeleton toolpath.

Conclusion

This study has demonstrated the potential of adaptive skeleton toolpath generation for enhancing large-format AM by effectively filling void geometries that arise due to part design constraints and discrete offset operations. By adapting the bead width of skeleton toolpaths and implementing chamfering techniques for acute regions, the proposed approach enables the generation of toolpaths that fill complex and irregular regions, thereby improving the quality and strength of the printed parts.

The method not only minimizes overfilling and underfilling but also reduces manufacturing time by producing continuous toolpaths and minimizing the number of required travels. This approach proves particularly valuable for applications in industries such as aerospace and automotive, where the manufacturing of high-quality and robust components with intricate geometries is crucial.

In conclusion, adaptive skeleton toolpath generation offers a significant advancement for large-format AM, addressing the challenges associated with irregular and complex void geometries and ensuring the production of high-quality, structurally sound parts. Future work will explore the automation and optimization of the algorithm's parameters to increase its robustness, versatility, and applicability to a wider range of geometries, further enhancing the performance and capabilities of large-format AM systems.

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