CREATING TOOLPATHS WITHOUT STARTS AND STOPS FOR EXTRUSION-BASED SYSTEMS

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Abstract

Toolpath generation for extrusion-based additive manufacturing systems, called slicing, involves operations on polygonal contours that are derived from an STL file. Slicing generates multiple paths per layer (both closed-loop and open-loop) that are designed to optimally fill the space outlined by the polygon(s). In the course of printing a layer, the extruder must start and stop, the tip must be wiped, and the extruder must travel between paths without printing. Any amount of time the printer spends moving without printing is considered wasted time because the part isn't being constructed. In addition, the start/stop point, known as the seam, is often a blemish on the surface of the part that contributes to weaker material properties. Therefore, a single path for creating multi-bead walled structures is desirable because it would save machine time and create parts with better surface finish. This paper will cover one method of modifying the CAD file and slicing engine to allow for parts to be printed without starting and stopping the extruder.

Introduction

Fused Deposition Modeling (FDM) is an extrusion-based 3D printing process [1] that can be used to additively manufacture objects by extruding metal [2], polymer [3], and concrete [4]. Extrusion-based systems use toolpaths to direct the deposition head to deposit material, layer by layer, in desired locations. When printing simple geometries, the process is straightforward. The tip of the printer head has to be wiped in between layers to clear excess material, but otherwise, printing is continuous. However, when more complex geometries are printed, it is not uncommon for toolpaths to contain multiple starts and stops. For example, any holes or gaps within the printed part are often achieved by printing the contour of the hole, so that the area surrounding the hole has a smooth surface finish. The contour of the hole is usually separate from the outer edge of the part. Therefore, the printer head has to stop printing, move to the edge of the hole, and start printing again. The higher the number of distinct edges and contours a geometry contains, the more starts and stops are introduced into the toolpath. These starts and stops necessarily increase print time, as all the time spent not printing is time spent not producing the part. Therefore, to increase the efficiency and appeal of FDM, it is necessary to develop a way to continuously print complex geometries while preserving surface finish with minimal starts and stops.

The standard method for generating extrusion-based system toolpaths is a purely geometric-based approach called "slicing" [5,6]. The name slicing comes from the process of slicing the file to be printed into layers. The part, which originates in CAD (computer aided design) software (such as Solidworks or Autodesk Fusion 360), is exported from the CAD software as an STL (stereolithography) file. An STL file represents the surface geometry of the CAD file using triangles to approximate all curves and features [7]. This STL is loaded into the slicing software to be sliced into layers.

Slicing works by intersecting a horizontal plane (in plane with the build surface) with the STL file and then incrementing the height by the desired printing layer height. Each slice becomes a layer represented as a polygon or polygons to show the boundaries. The next step of slicing is to fit toolpaths to the layer to optimally fill the layer. Toolpaths are generated specific to the user-defined settings in the slicer such as bead width, infill density, and number of perimeters. Closed-loop paths are generated first by polygon offsets of the layer's bounding polygon. Once all closed loop paths are generated, usually called perimeters and insets, skins and infill are used to fill the remaining void. These can be generated in many different ways, but the simplest approach is to apply a grid across the region to be filled and apply toolpaths to the grid.

The final step of slicing is to output the toolpaths as G-Code, which is code that represents the instructions for the machine about how to print the desired part. G-Code has some standardizations for common codes but is largely machine-specific. Each machine has its own unique hardware i/o that can be enabled and disabled as needed during the print. The slicing software must know about each system's capabilities and format the G-Code output accordingly.

Starts and Stops

Starts and stops occur when one toolpath ends and the extruder stops extruding to move to the next toolpath. The time spent moving between the end of one path and the start of the next, called traveling, slows down the print and therefore necessarily wastes time. Travel time is considered wasted time for manufacturers because the machine is not adding material to grow the part. While some part geometries and some manufacturing systems require travel time to ensure the part is successfully printed, minimizing unnecessary travel time is always ideal [citation?]. Therefore, the challenge for any system is to develop approaches that achieve successful prints while minimizing starts and stops.

The start and stop point, known as the seam (Figure 1), creates a non-uniform region on the surface of the part where the extruder must stop and the tip must be wiped off to clear excess material from the nozzle. This seam is not only rough, but it creates a weak "joint" in the part [8]. At the start/stop point, the bead of polymer is disconnected. It's a butt joint where fibers don't flow across the joint, causing a significant loss of strength.
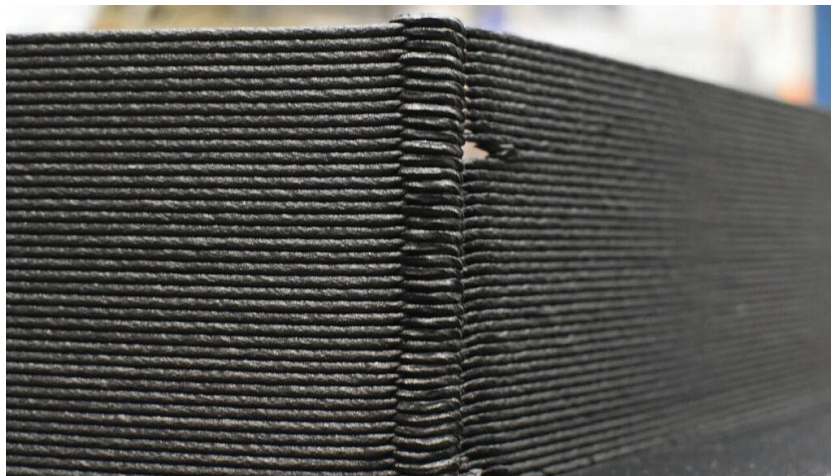

Figure 1: Starts and stops, a weak point on Big Area Additive Manufacturing (BAAM) prints

The start of a path for a pellet-based extruder requires a pause, or a slow movement, to build up pressure in the extruder so that the initial extrusion will bond to the substrate or previous layer. The end of the path has the opposite problem. The release of pressure as the extruder slows down causes material to drool out of the extruder nozzle. This can be corrected by moving slowly for the last few moves of the path or wiping the tip across the part, both of which take time.

The Single Path

Currently, single path printing exists through a method called spiralizing [9]. Spiralizing works by removing the independent closed loop paths of a layer to make just one continuous closed loop path for each layer. This is done by taking the layer polygon and offsetting the outer boundary inward by one bead width. The result is a single closed loop path to represent the external geometry of the layer. Figure 2 shows a circle and the resultant toolpath when spiralizing.
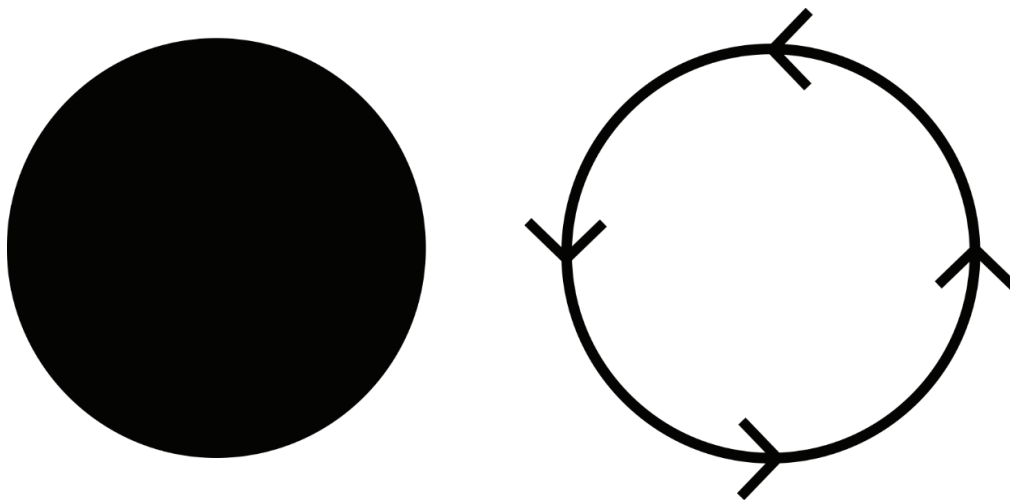

Figure 2: A circle and the spiralize toolpath that it generates

If every layer of a spiralize print is planned so that the start and stop is at the same location, then the start and stop can be removed by continuing the print from one layer to the next. This is done by slowly incrementing the Z height throughout the layer so that after one full layer has been traversed, the Z height has changed by one-layer height. Figure 3 below shows a chair that is printed with spiralize.

Figure 3: A chair printed without starts and stops, called spiralizing

Spiralizing doesn't work for dense structures because there can be no starts and stops, which means no infill or solid regions and no two-bead wall objects. It also means printing just one object at a time. Because of these constraints, spiralizing is often called spiral vasing because it's used to print vase-like objects that just need the outer contour without internal spars or support structures.

The spiralize approach can be taken a step farther to encompass a full layer, if the extruder has a path to traverse the layer without crossing itself or starting and stopping. Take for example a simple square with the center removed, Figure 4. The standard tool pathing approach for this results in the toolpaths seen in Figure 5. This object has three distinct paths that require starting and stopping the extruder and traveling. If the extruder got to a corner and turned around and traveled back on itself, it could return to the start point while tracing all paths and never starting/stopping (Figure 6).
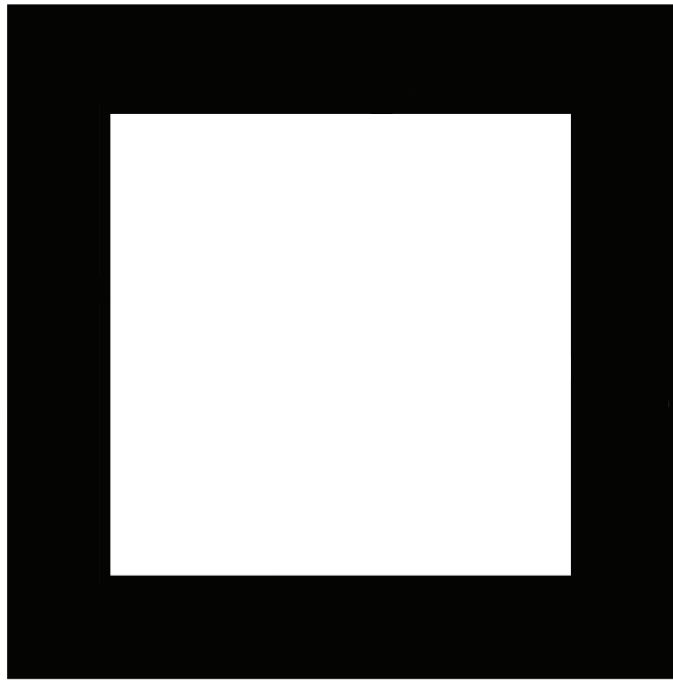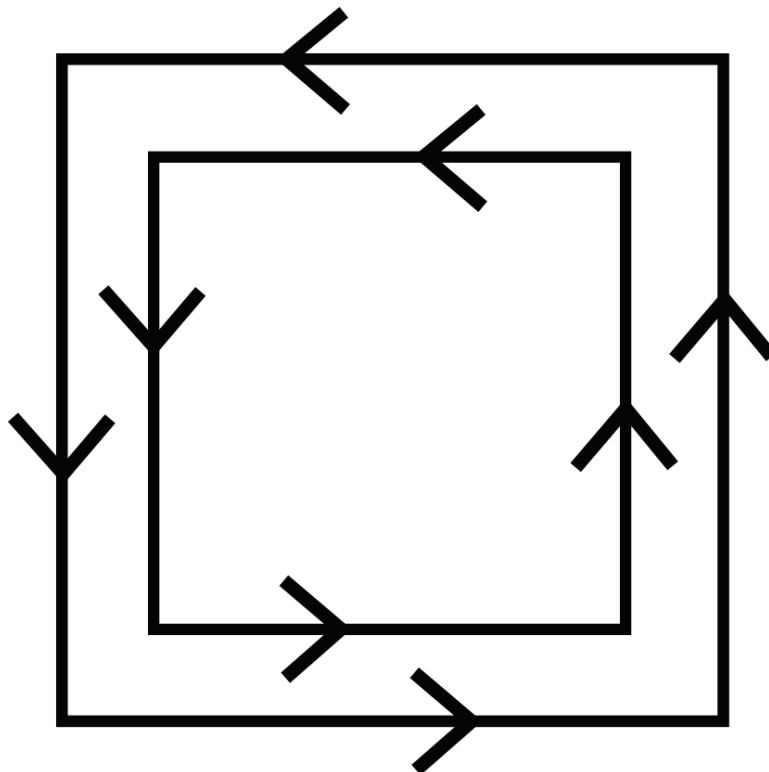
Figure 4: A square with hollow center

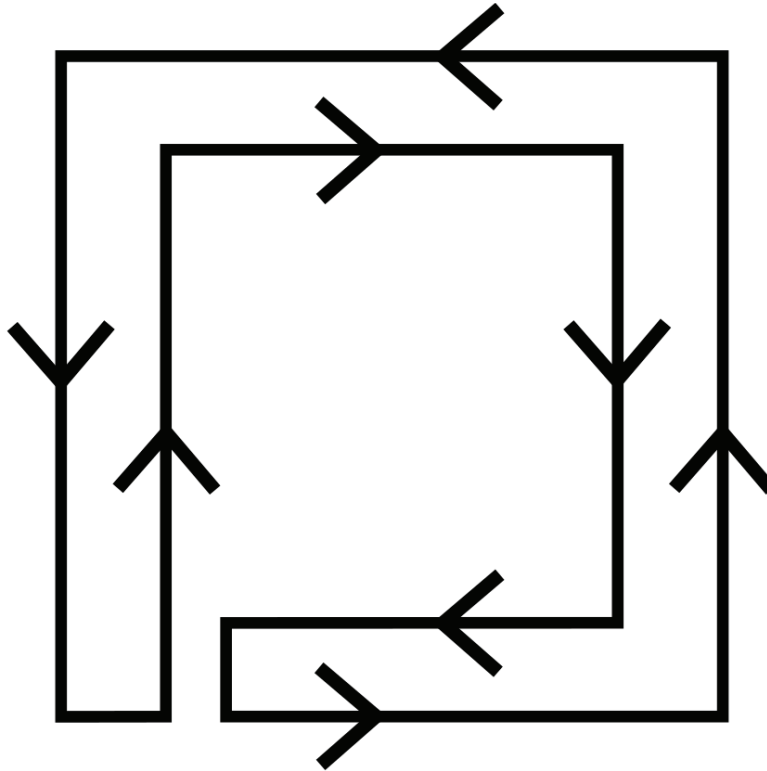Figure 5: Standard tool pathing for a hollow square with two bead wall

Figure 6: Square with tool pathing forced to double back to create a single path

This same approach can be applied to larger structures, like trusses, that can be constructed with multiple closed loop paths. The number of times the extruder must turn around on itself is the number of closed loop paths minus one. If the part is designed such that every layer starts and stops at the same location, a spiralize approach can be implemented. Figure 7 below shows a figure eight with two cuts to reduce the print from three paths to one path.
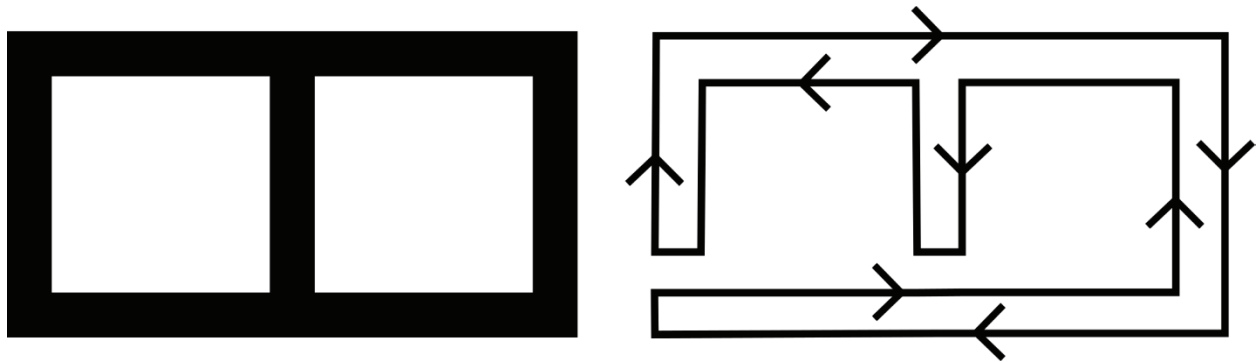

Figure 7: A figure eight printed as one single path

Single Path STL

The simplest method of creating a single path is to simply design the object to be printed as a single path. This can be done by inserting small cuts along the wall sections to break up the closed loop paths and force the extruder to double back on itself (Figure 8). These cuts are very small, just 0.02inches (0.5mm) wide, which is $1/15^{th}$ the size of the nozzle diameter. A cut this small prevents the trusses in the structure from being connected in the tool pathing (when optimization is disabled) but doesn't leave a gap during the actual print. This forces the extruder to double back on itself and create one large closed loop instead of individual paths.
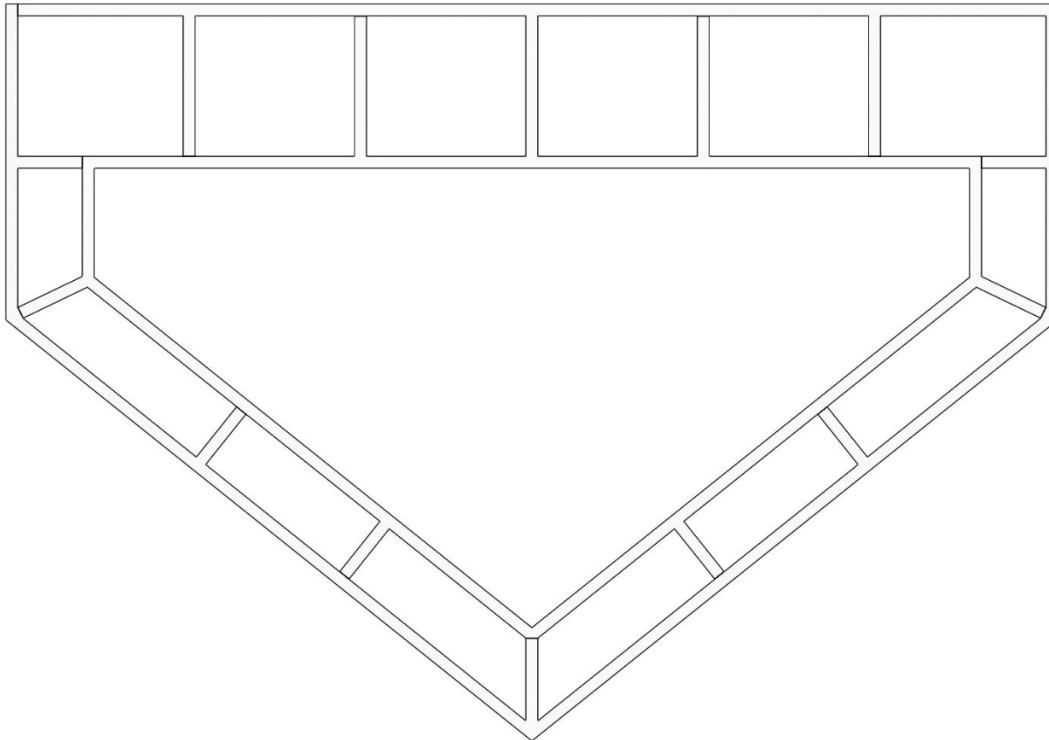
Figure 8: An object with small cuts to force the travel in a single path

Slicer Unoptimization

In order for printing to be as fast as possible, tool paths are automatically optimized by the slicer to save time and eliminate unnecessary moves. For example, paths of a length smaller than the nozzle diameter can't be printed and should be eliminated. The same goes for holes that are smaller than the nozzle diameter; they get eliminated because the holes add more time to the print than they remove [10].

This removal of small holes creates a problem for the small slices that were added to the STL to create a single path. The slices are removed by default during the optimization step because the slicer thinks it's saving time and optimizing out something that won't work. Figure 9 shows what happens when the STL from Figure 8 is sliced with the optimization enabled. The small cuts get ignored, or optimized out, and the layer is printed normally by breaking up all the sections into small closed loop paths. To fix this, a setting was added to the ORNL Slicer that allows the user

to skip the optimization step during inset generation. Figure 10 shows the resultant G-Code generated from the STL in Figure 8.
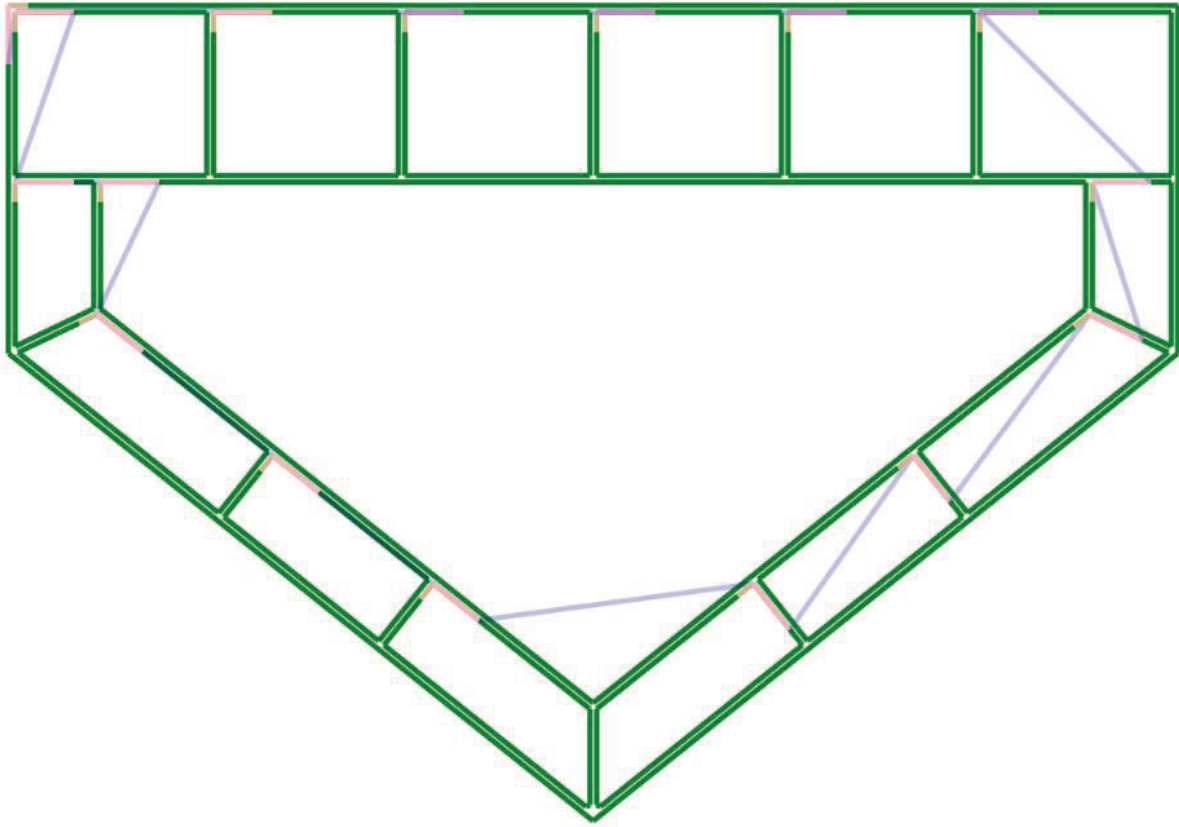

Figure 9: The result of slicing software optimizing out all the small cuts. The pink areas are starts/stops and the light blue lines are travel moves.
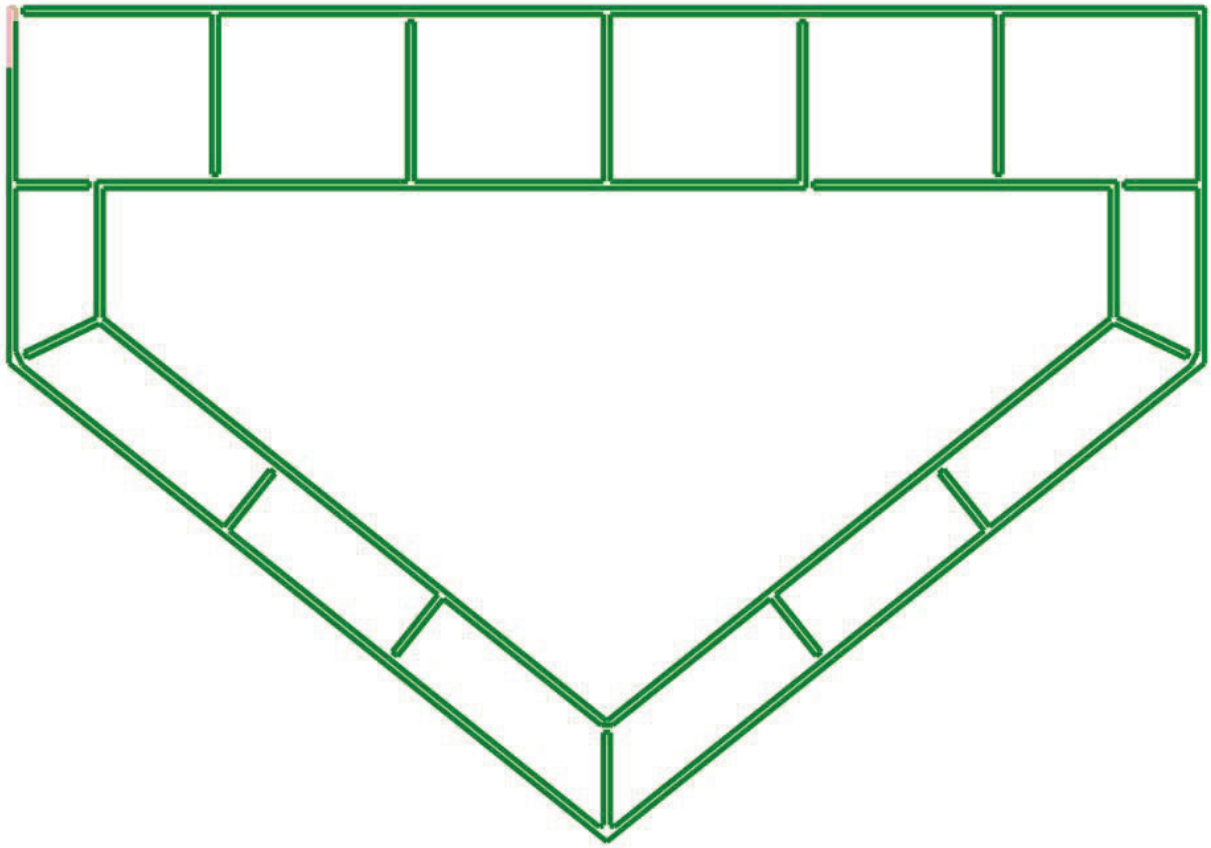
Figure 10: The resultant toolpaths when optimization is disabled

Results

To compare the two approaches, printing the traditional way with starts and stops and the single path approach, the object seen in Figure 8, a representative boat hull, was printed both ways on a Cincinnati BAAM system. The object is 60" long and 42" wide. The objects were made with a 0.3" nozzle and a 3" long tip wipe. Figure 11 below shows the print with traditional pathing including starts and stops. Figure 12 is a closeup of the starts and stops to show the roughness of each seam. Figure 13 shows the single path print and Figure 14 shows a closeup of the cuts where the extruder doubles back on itself. The cuts are small, just 0.02" wide, but Figure 14 shows that the beads still have a small amount of overlap preventing an actual gap from occurring during printing.
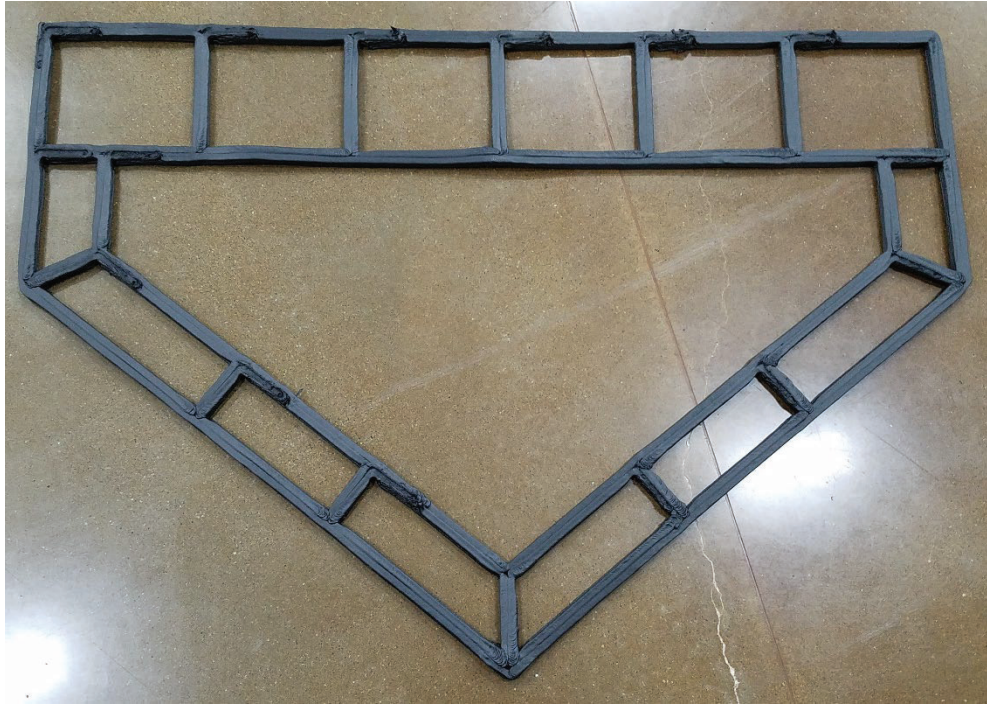
Figure 11: Print with traditional pathing

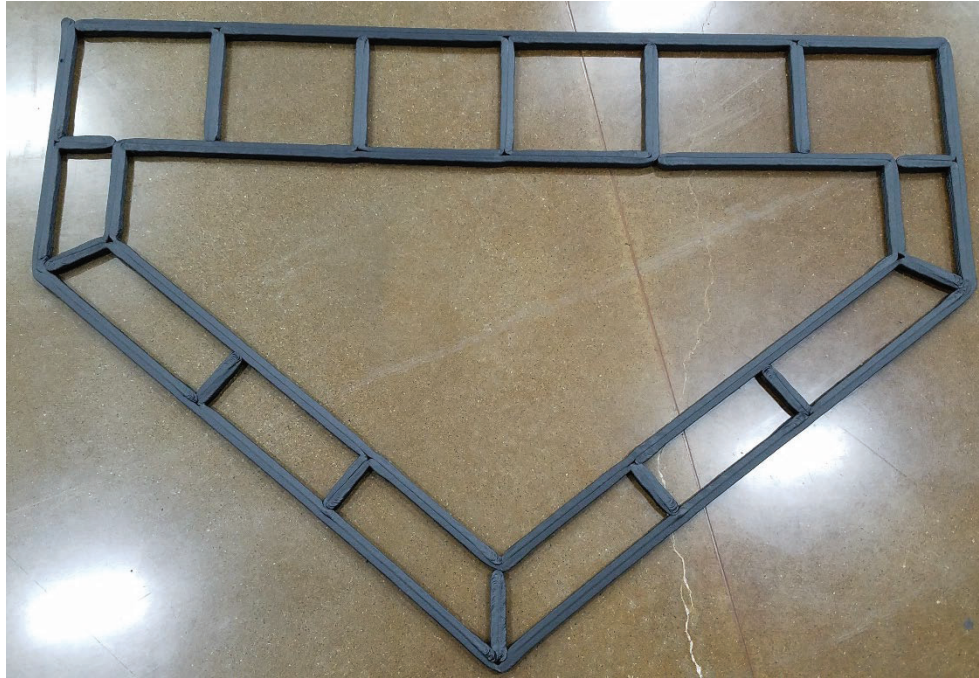Figure 12: Closeup of the starts and stops in Figure 11

Figure 13: Print with a single path, no starts and stops

Figure 14: Closeup of the inserted cuts to create the single path

Table 1 shows a data comparison of the two prints. The travel distance for the traditional pathing is the XY distance between the start and stop of each move including the transition to the next layer. The single path only has one travel move, from the end of the tip wipe in a path to the start point of the next layer.

Table 1: Comparison of printing with traditional pathing using starts and stops and a new approach using a single path

	Traditional Pathing	Single Path
Number of Printing Paths	16	1
Number of Travel Moves	16	11
Travel Distance (in)	158.88	3
Layer Time (s)	129.36	109.57

Conclusion

An approach for creating a single path to traverse a layer of a 3D printed part was presented. This approach is meant to save time during the printing process by eliminating starts and stops and non-printing moves. There are geometric limitations that prevent this method from being applied to all 3D printed objects, but the methodology is very applicable to large format processes such as BAAM. For the test print of a boat hull, the single path approach saved more than 15% (19.79 seconds per layer) of the time the traditional path took. This time savings is geometry-dependent, so not all prints will see 15%-time savings. Based on the results of this study, it can be inferred that objects with a lot of individual short paths will see a large time savings and parts with less paths will see less time savings. Further studies investigating the use of this method on a wider variety of part geometries are required to conclusively demonstrate the proposed time savings. Additionally, future work will entail mechanical testing, to see if there are differences in material strength, and software algorithm development to remove the manual slicing in CAD.

Acknowledgements

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