TOOLPATH PLANNING FOR CONTINUOUS EXTRUSION ADDITIVE MANUFACTURING
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Abstract
Recent work in additive manufacturing has introduced 3D printers that extrude slurries and viscous mixtures such as silicone, glass, epoxy, and concrete, but it is difficult to control extrusion once the print has begun. Conventional toolpath generation for 3D printing assumes that the flow of material can be controlled precisely and the resulting paths include instructions to disable extrusion and move over the print. A continuous extrusion printer cannot disable material flow, and so these toolpaths produce low quality prints with wasted material. We outline a greedy algorithm for post-processing toolpaths that employs a Traveling Salesperson Problem (TSP) solver to reduce the distance traveled between subsequent space-filling curves and layers, which reduces unnecessary extrusion by at least 20% for simple object models on an open-source 3D printer.

Algorithm 1 Greedy Minimization

```
Ci = {ci, 1, ci, 2, ... ci, mi}

for each layer i
    Add an edge for each pair of curve endpoints with Euclidean distance cost
    d(i,j) = \sqrt{(x_j - x_i)^2 + (y_j - y_i)^2}

    Select path that gives minimal total Euclidean distance between curve endpoints
    minpath(i) ← Tsp-Concorde(L)
    mincost(i) ← totalcost(minpath(i))

    Save the best path and cost for each layer
end for
```


Reordering the Toolpath
A toolpath for additive manufacturing can be described as an ordered set of n layers, L = (l1, l2, ..., ln). Each layer in L consists of a sequence of space-filling curves Ci = {ci, 1, ci, 2, ... ci, mi} over which material is extruded. We define a minimization problem to reduce the total Euclidean distance between endpoints of curves by reordering curves:

\[
\minimize \sum_{i=1}^{n-1} \sum_{j=i+1}^{n} d(c(i,j), c(i+1,j)) + d(c(mi), c(1,1))
\]

We represent each layer as a fully-connected graph with a node for each curve. A continuous extrusion printer cannot disable material flow, and so post-processing toolpaths that employs a Traveling Salesperson Problem (TSP) solver to reduce the distance traveled between subsequent space-filling curves and layers, which reduces unnecessary extrusion by at least 20% for simple object models on an open-source 3D printer.

Toolpath Improvements
Star prism, cube, cylinder, and octopus models were sliced with Slic3r to generate toolpaths for 3D printing.

Extrusion Reduction with Greedy Minimization
Reduction in cumulative distance between endpoints of curves after applying greedy reordering algorithm. Improvement is expressed as a percentage of original toolpath cost.

Structure and material both impact the mechanics of stretchy silicone parts. Characterizing the relationship between material placement geometry and mechanical output can improve insight into toolpath planning for elastomeric extrusion printing.

Printing with Silicone
The mechanisms for additive manufacturing of viscous fluids differ significantly from the operation of a thermoplastic printer.

Our open-source silicone printer is shown above left. Pumps push the fluid through tubing and a nozzle (right), and pressure accumulates so that the viscous material flows. The pressure built up in the pump and the nature of the fluid make it difficult to retract once it starts to flow.

In contrast, thermoplastic material extrusion (shown left) relies on a motor to pull the filament down into a heated extruder head so it flows and prints, and filament extrusion pauses when the motor stops.

Unaltered toolpath with streaky material infill and print head transitions that cut across layer

Material extrusion during layer transition creates ridges

Continuous extrusion silicone printing presents challenges in toolpath generation. Toolpaths that cut across the partially-printed object or through concave outlines place excess silicone that detracts from the visual appearance of the object.

The geometry of space-filling curves that the print head traverses to place material and the order in which these curves are traversed has a noticeable impact on the texture and quality of printed parts.

Toolpath Space-Filling Curves
The goal of toolpath optimization for continuous extrusion is to minimize the distance traveled along any curve that is not intended to place material. We assume that the print head speed and extrusion rate are constant.

Our approach identifies discontinuities in the space-filling curves generated by a slicer (such as Slic3r) and reorder the continuous regions to minimize total distance between their endpoints. Examples of space-filling curves and discontinuities are shown below.

First layer of a rectilinear infill toolpath. Extrusion should stop before travel moves, indicated with black dots.

Two Hilbert infill toolpaths. The purple path is an in-progress layer. Left: Original toolpath that crosses print. Right: Reordered toolpath that avoids crossing print.

An example of print quality comparison for original (a,b) and reordered octopus models (c,d). The toolpath was reordered with our greedy material reduction algorithm.

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Toolpath Impacts Print Quality
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