TOOLPATH PLANNING FOR CONTINUOUS EXTRUSION ADDITIVE MANUFACTURING

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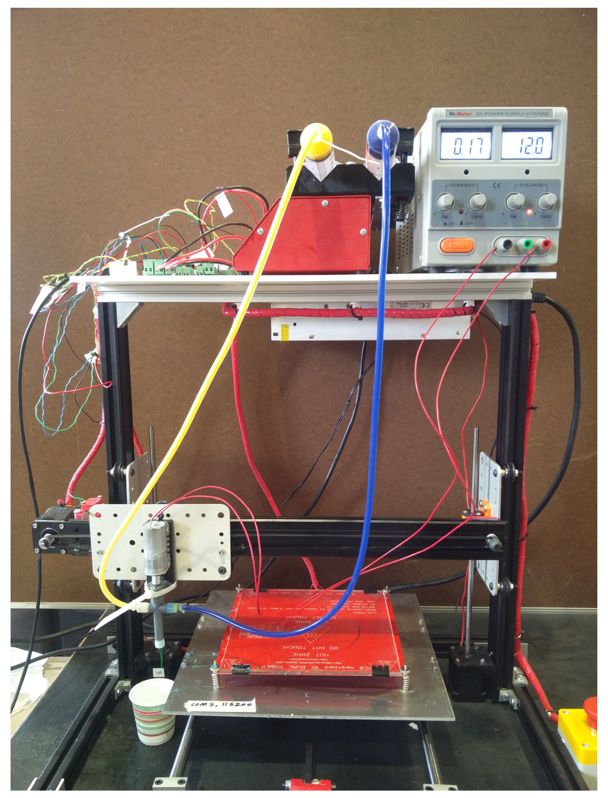
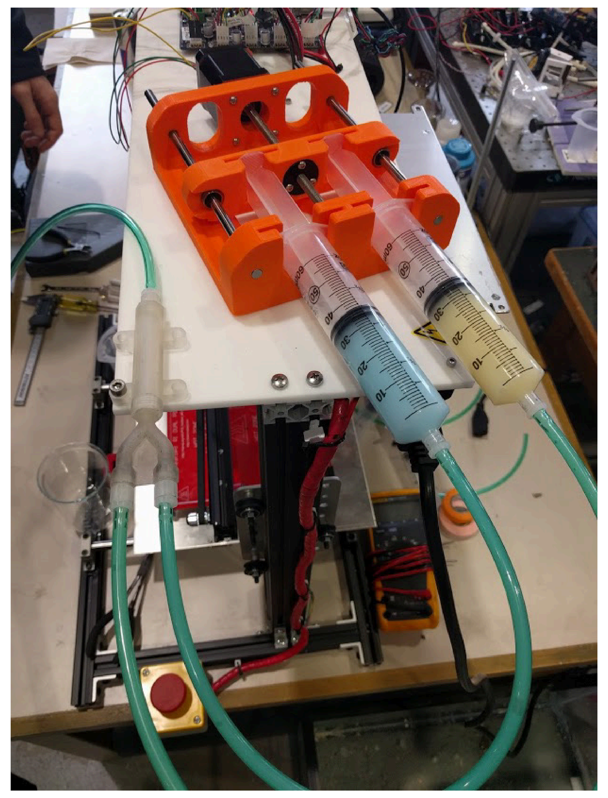
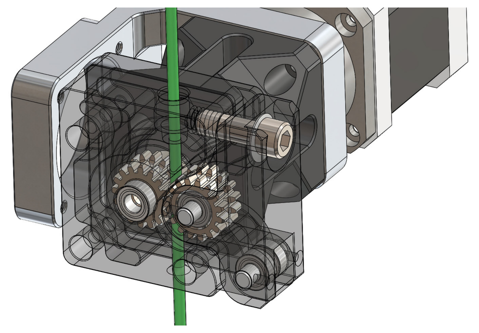
Printing with Silicone

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.

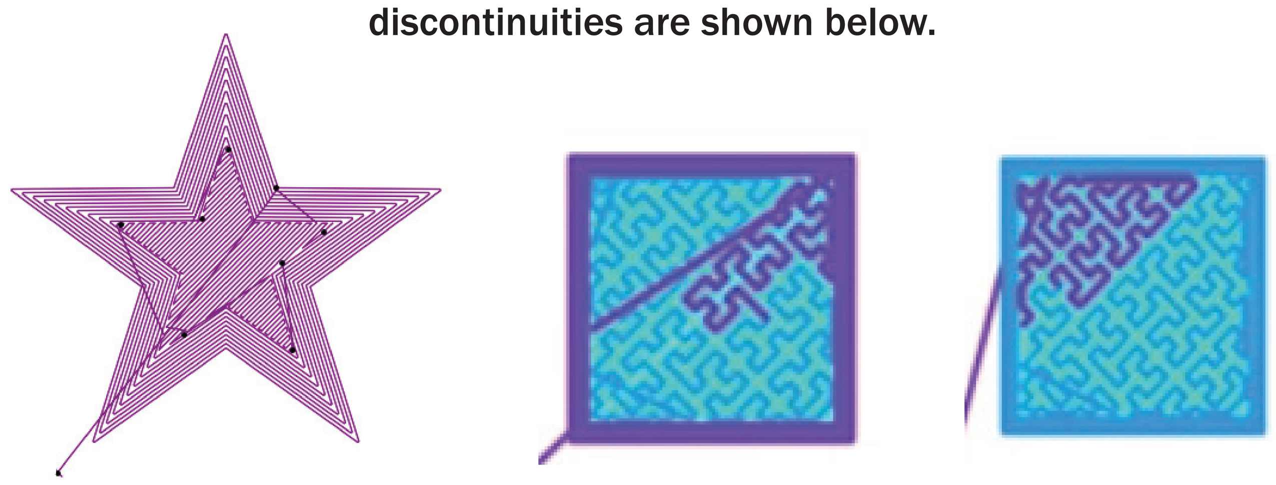
J. Morrow, S. Hemleben and Y. Menguc, "Directly Fabricating Soft Robotic Actuators With an Open-Source 3-D Printer," in IEEE Robotics and Automation Letters, vol. 2, no. 1, pp. 277-281, Jan. 2017.

Thomas J. Ober, Daniele Foresti, and Jennifer A. Lewis, “Active mixing of complex fluids at the microscale,” in PNAS 2015 112 (40) 12293-12298; published ahead of print September 22, 2015.

Toolpath Space-Filling Curves

The goal of tooplath 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 reorders 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.

Slic3r Manual. Available at: http://manual.slic3r.org/intro/overview

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.

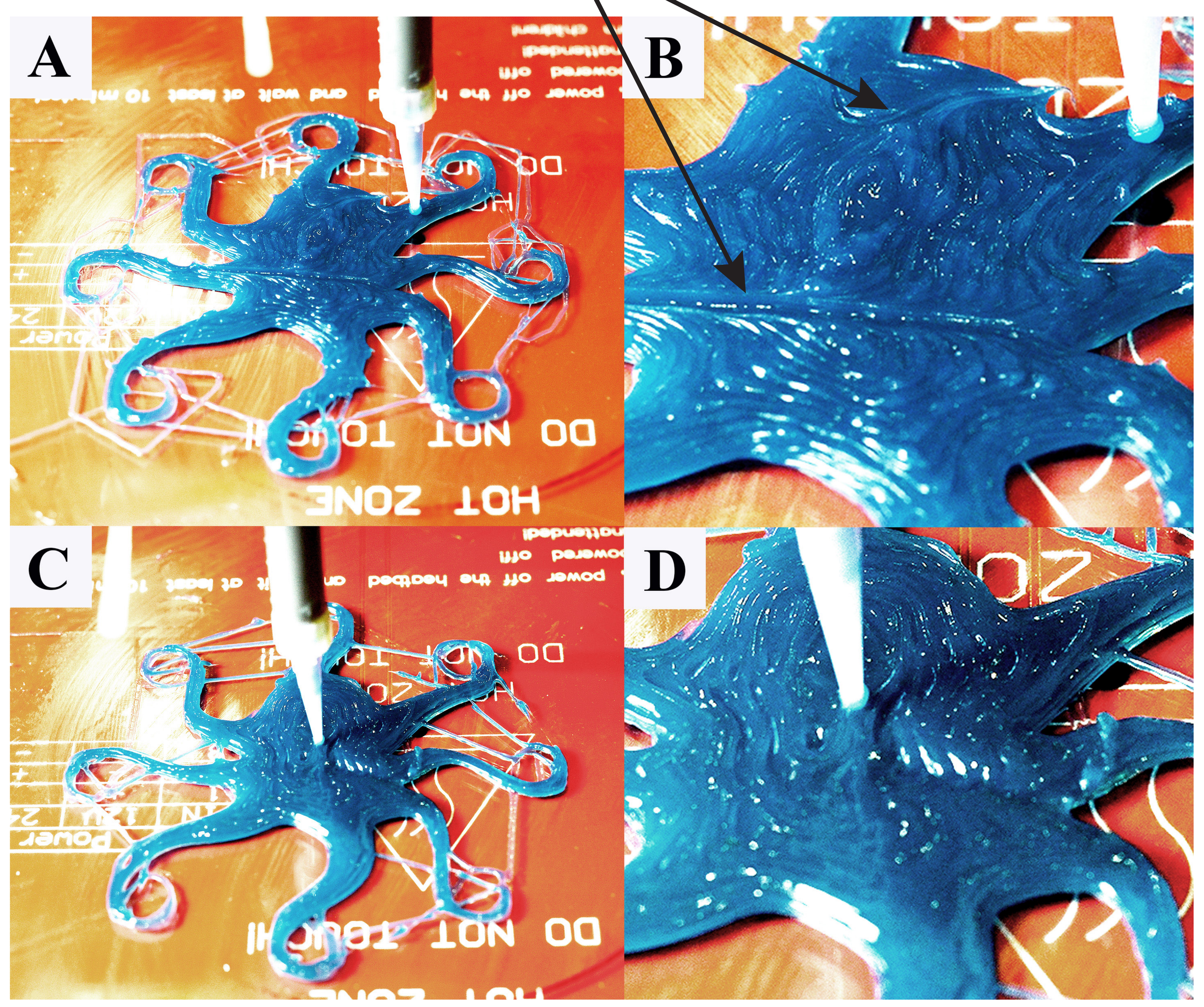
Toolpath Impacts Print Quality

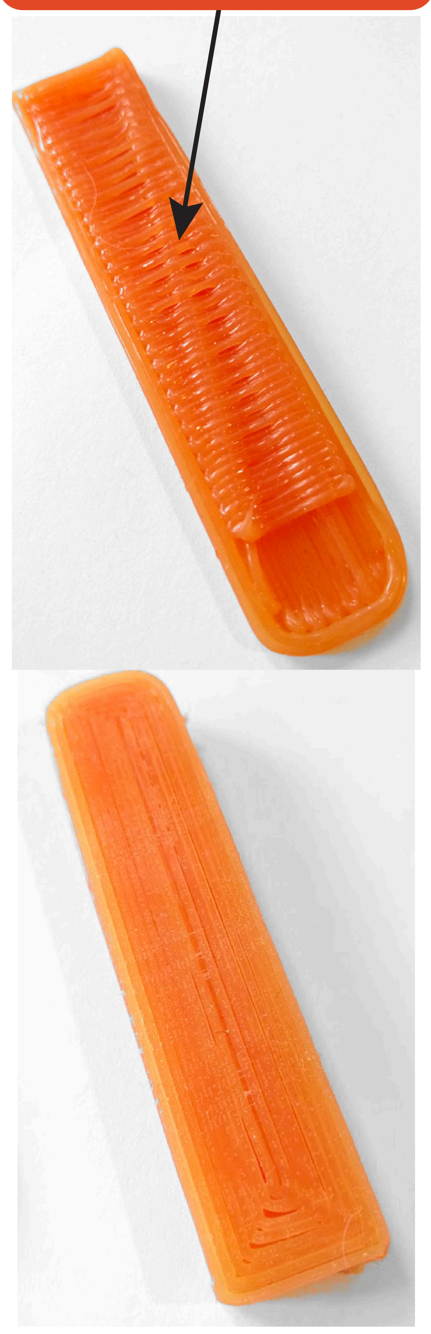
Continuous extrusion silicone printing presents challenges in toolpath generation. Toolpaths that cut across the partially-printed object or through concave outlines place excess silicone that detracts from the visual appearance of the object.

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.

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

Material extrusion during layer transition creates ridges





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.

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.

Reordering the Toolpath

A toolpath for additive manufacturing can be described as an ordered set of n layers, $L = \{l_1, l_2, \dots l_n\}$. Each layer l_i in L consists of a sequence of space-filling curves $C_i = \{c_{i,1}, c_{i,2}, \dots c_{i,m}\}$ over which material is extruded. We define a minimization problem to reduce the total Euclidean distance between endpoints of curves by reordering curves:

$$\text{minimize } J(C_i) = \sum_{i=1}^{n}\Big[\sum_{j=1}^{m_i-1} d(c_{i,j}, c_{i,j+1})\Big] + d(c_{i,m_i}, c_{i+1,1})$$

We represent each layer as a fully-connected graph with a node for each curve. The Concorde TSP solver is used to find the shortest path to visit all curves. We select an open-loop path from the TSP solution by considering the distance between layers.

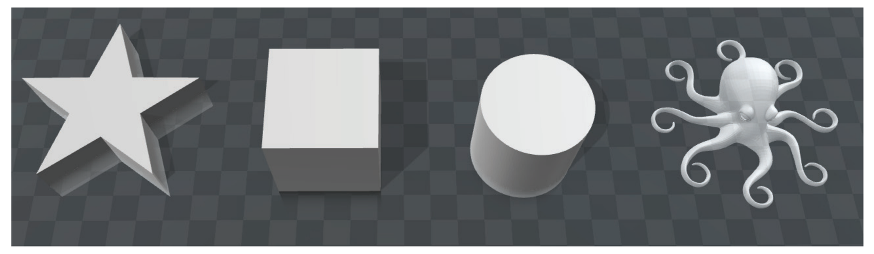
Algorithm 1 Minimize-Material-Greedy

for each layer l_i **do**
Construct-Complete-Graph(C_i) ▷ Add an edge for each pair of curve endpoints with Euclidean distance cost
  $shortest \leftarrow$ Tsp-Concorde(C_i, $c_{i,0}$) ▷ Get exact TSP solution path and cost from Concorde
  for each curve $c_{i,j}$ **do**
    $path \leftarrow$ One-Way-Subpath($shortest$, $c_{i,j}$) ▷ Select subpath from TSP cycle starting at $c_{i,j}$ without return edge to $c_{i,j}$
    $cost \leftarrow \sum^{path} d + d(minpath_{i-1}, c_{i,j})$ ▷ Calculate TSP subpath cost and add distance between $c_{i,j}$ and last layer
    if $cost < mincost_i$ **then**
      $mincost_i \leftarrow cost$ ▷ Save the best path and cost for each layer
      $minpath_i \leftarrow path$
    end if
  end for
  $totalcost \leftarrow totalcost + mincost_i$ ▷ Total toolpath cost accumulates over layers
end for

Concorde TSP Solver. Available at: http://www.math.uwaterloo.ca/tsp/concorde/index.html

Toolpath Improvements

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

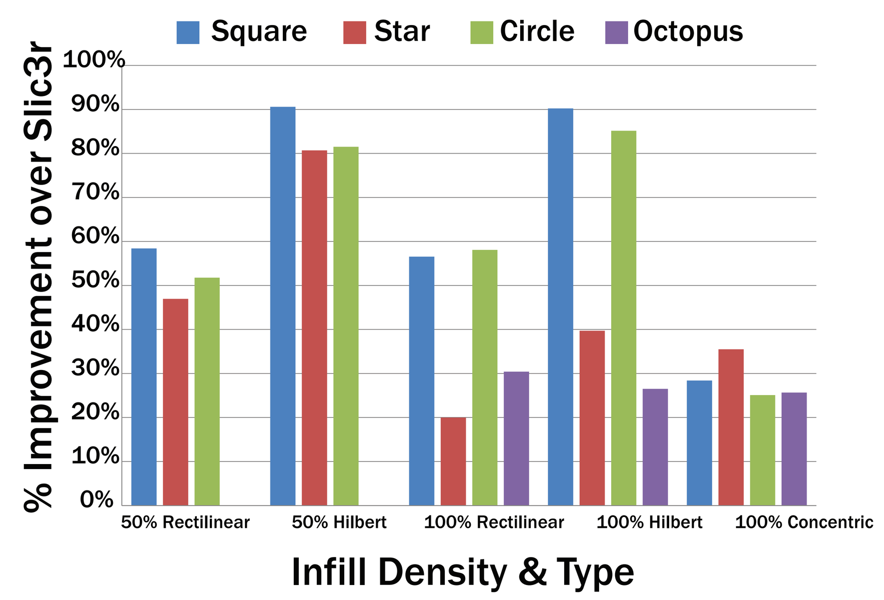


Extrusion Reduction with Greedy Minimization

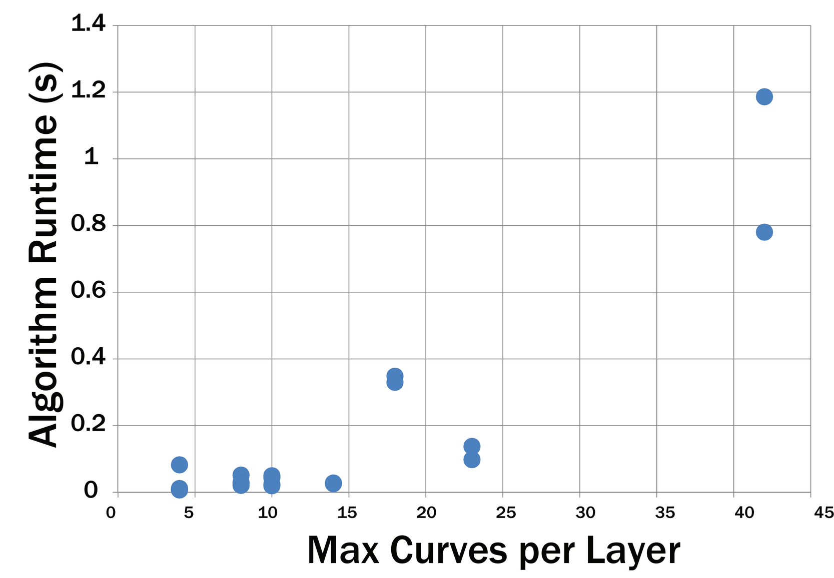
Reduction in cumulative distance between endpoints of curves after applying greedy reordering algorithm.

Improvement is expressed as a percentage of original toolpath cost.

The models above were sliced with varying combinations of infill density and pattern.



Execution Time Statistics: Simple Objects



Algorithm execution time for prism object models with varying infill pattern and density.

Runtimes are plotted against the maximum curve count in any model layer.

This metric is an indicator of the complexity of solving the TSP, the most computationally intensive portion of the toolpath reordering algorithm.