FDM 3D-printing as Asynchronous Cellular Automata

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Introduction

► **3D printing** (or Additive manufacturing)
  ■ Objects are designed by using 3D CAD.
  ■ 3D objects are printed layer by layer.
  ■ Cheap FDM 3D printers are widely used. (FDM means fused deposition modeling)

► **3D printers can generate “naturally-randomized” self-organized patterns.**
  ■ Printing conditions and process including nozzle temperature, extrusion process, air motion, etc., are fluctuated.
  ■ *Chunks* and *strings* are generated.

► **FDM 3D-printing can be interpreted as asynchronous CA** (cellular automata).
  ■ A printing head generates 1D on/off patterns.
  ■ Fluctuated patterns are similar to patterns generated by stochastic CA.
Methods for 1D CA pattern generation

▶ 1D CA-like patterns are generated by a helical motion.
  ■ No 3D CAD/CAM program prints in this way!

▶ No explicit randomization is introduced.
  ■ Velocity of filament extrusion is constant and small.

▶ This method was originally proposed by the previous paper.
Typical printed patterns -- Stripes

The layer is thick (0.3 mm). The filament cross section is 0.045 mm². PLA.

Stacked chunks and strings can be seen.

More uniform pattern
The layer is thin (0.1 mm). The filament cross section is 0.02 mm². PLA.

Less uniform pattern (Strings are torn)
Printing process using Rostock MAX 3D printer

http://youtu.be/IJ15ysJR5l8
Basic computational model

A computational model that simulates printed 1D patterns (chunks only) was developed.

- **Explicit randomization** was (random numbers were) introduced instead of “natural randomization”.
- A pattern is generated by using a probabilistic rule:
  ```java
  if extrudedFilament >= 1 /* certain amount */ then
    if cell[l−1][i] = 1 then cell[l][i] = 1 & filament cleared at probability p0
    else if cell[l−1][i+1] = 1 then cell[l][i] = 1 & filament cleared at probability p1
    else cell[l][i] = 0
  else cell[l][i] = 0
  ```

  extrudedFilament = 0;
  for layer in 1, 2, …, layers loop
    z = 0.3 * layer;
    for i in 0, 1, …, 4 * 72 loop
      cell[layer][i] = 0; // clear pattern
      if extrudedFilament >= 1 then
        if cell[layer−1][i] > 0 and random() <= p0 or
          cell[layer−1][i+1] > 0 and random() <= p1 then
          cell[layer][i] = 1; // fill the cell
          extrudedFilament = 0.0; // clear filament
        end if
      end if
      drawNextArc(cell[layer][i], z, i);
    extrusion = extrusion + e1; // extrude
  end loop
  cell[layer][steps] = cell[layer][0];
end loop
```

Explicit randomization was introduced instead of “natural randomization”.

A pattern is generated by using a probabilistic rule:

- If extruded filament is greater than or equal to 1 (a certain amount), then:
  - If the cell at the previous layer is 1, then the cell at the current layer is set to 1, and the filament is cleared with probability p0.
  - If the cell at the previous layer is 1 and the cell at the previous layer plus 1 is 1, then the cell at the current layer is set to 1, and the filament is cleared with probability p1.
  - Otherwise, the cell at the current layer is set to 0.

- The extruded filament is reset to 0, and the loop is repeated for all layers.

- The current layer's pattern is filled with the adjacent layer's pattern at the current layer's pitch, which is 0.3.

- The filament state is cleared when the extruded filament is greater than or equal to 1.

- The filament state is cleared when the cell at the previous layer is 1 and the random number is less than or equal to p0, or when the cell at the previous layer plus 1 is 1 and the random number is less than or equal to p1.

- The cell at the current layer is filled with the adjacent layer's cell state.

- The extruded filament is cleared when the extruded filament is greater than or equal to 1.

- The current layer's pattern is extruded by adding e1 to the extrusion.

- The current layer's cell state is set to the previous layer's cell state.

- The loop is repeated for all layers.

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Simulation of typical patterns

- A program written in Python generates G-code (CAM program) is used.
  - G-code execution results are visualized by Repetier-Host (a CAM tool for 3D printers).

\[
\begin{align*}
  p_0 &= 0.99, \ p_1 = 0.9, \ e_1 = 0.4 \\
  p_0 &= 1.0, \ p_1 = 0.4, \ e_1 = 0.4 \\
  p_0 &= 1.0, \ p_1 = 0 \text{ to } 1, \ e_1 = 0.4 \\
  p_0 &= 1.0, \ p_1 = 0.4, \ e_1 = 0.4
\end{align*}
\]
Various printed patterns and Simulation results

- Extinction of stripes
- Splitting and merging of stripes
- Waves and meshes
Extinction of stripes

A printed result

The layer height is 0.2 mm. PLA.

A simulation result

p1 = 0.9, p0 = 0.97, e1 = 0.6
Extinction of stripes (cont’d)
Splitting and merging stripes

► Printed results

ABS

PLA
Splitting and merging stripes (cont’d)
Computational model for splitting/merging stripes

The computational rule must be extended to simulate splitting and merging.

- if extruded filament $\geq 1$ then
  - if cell[$l$][$i-1] > 0 then cell[$l$][$i] = 1 & filament cleared at probability $p_{-1}$
  - else if cell[$l$][$i+1] > 0 then cell[$l$][$i] = 1 & filament cleared at probability $p_1$
  - else if cell[$l$][$i] = 1 then cell[$l$][$i] = 1 & filament reduced by $C$ /* $C < 1$ */
  - else cell[$l$][$i] = 0

else cell[$l$][$i] = 0
else cell[$l$][$i] = 0
Simulation results of splitting/merging stripes

$p_1 = 0.7$, $C = 0.8$,
$p_1 = 0.9$, $p_0 = 0.995$, $e_1 = 0.4$

$p_1 = 0.99$, $C = 0.9$,
$p_1 = 0.9$, $p_0 = 0.995$, $e_1 = 0.4$
Stripes are weakly connected by thick strings.

“Waves” moves across stripes.

The layer height is 0.25 mm. PLA

Strings are torn

Thick strings
Simulation of waves

► It is easy to see noises propagated across stripes.

► It is less easy to see wave propagation here.

Noises are added to the initial condition.

The observed waves and the simulated waves may be different because strings are not simulated.
Meshes

- **Stripes are strongly connected.**
- **Meshes have not yet been successfully simulated.**

The layer height is 0.15 mm. PLA

ABS
Meshes (cont’d)
Summary

► FDM 3D printers can generate self-organized patterns.
  ■ “Pure” self-organized patterns can be generated by the 1D-CA-like printing method.
  ■ Fluctuating stripes, splitting and merging stripes, waves, and meshes can be generated.

► The printed patterns can be simulated by 1D CA.
  ■ Stripes can be simulated.
  ■ Splitting and merging stripes, waves, and meshes can be “simulated”, but it is not yet certain that it is the right way.

► Web site for this presentation
  ■ http://bit.ly/1n7PJQr