A Roadmap Towards Parallel Printing for Desktop 3D Printers

Molly Aubrey Carton, Chandrakana Nandi, Adam Anderson, Haisen Zhao, Eva Darulova, Dan Grossman, Jeffrey Ian Lipton, Adriana Schulz, Zachary Tatlock

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Existing Parallel 3D Printing

Lewis et al.

Chen et al.

DLP

Polyjet

Escher
Existing Parallel 3D Printing

What about FDM Printers?
Parallel 3D Printing for FDM Printers

Can we use the extruders simultaneously to print faster by generating parallel toolpaths?

Parallel programming: multiple processes speed up compute times
How to Repurpose Existing Tools for Parallel Printing

- Hardware
- Firmware
- G-code Generator
How to Repurpose Existing Tools for Parallel Printing

Each component affects the others

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DOFs
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DOFs

Instruction set and semantics
How to Repurpose Existing Tools for Parallel Printing

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Hardware
Firmware
G-code Generator

Instruction set and semantics

DOFs

Motor Controls
How to Repurpose Existing Tools for Parallel Printing

Each component affects the others

- **Hardware**
- **Firmware**
- **G-code Generator**

- **DOFs**
- **Instruction set and semantics**
- **Motor Controls**
- **Physical constraints**
How to Repurpose Existing Tools for Parallel Printing

Each component affects the others

Hardware

- DOFs
- Instruction set and semantics
- Motor Controls
- Physical constraints

Firmware

G-code Generator
Many FDM 3D printers have multiple extruders!

None use them simultaneously to print the same object

Main uses: ditto printing, multi-color printing, multi-material printing
FDM 3D Printer Models

- N extruders moving in lockstep
- N extruders with a single independent axis
- N extruders with two independent axes
- N extruders with three independent axes
FDM 3D Printer Models

Parallelism is restricted / permitted by printer configuration (degrees of freedom)!

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FDM 3D Printer Models

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Fixed-width dual extrusion printers are the most common
Hardware Support for Parallel Printing

- N extruders moving in lockstep
- N extruders with a single independent axis
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- N extruders with three independent axes

Parallelism is restricted / permitted by printer configuration (degrees of freedom)!

Affordable
Open-source
Ease of experimentation

MPCNC 3D Printer
Cheap
Online community
Reconfigurable
Experimental Hardware: Customized MPCNC 3D Printer

70%, large print area frame
Fixed-width dual extrusion model
Custom dual extruder mount

https://www.thingiverse.com/thing:4883743
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Firmware: Interprets G-code

G1 X80.000 Y0.80 Z0.00 E2.40

Move motor to specified \(X, Y, Z\) coordinates while extruding the length of filament provided in the argument to \(E\).

Typically straight line code interpreted and executed sequentially.

How to allow firmware packages to interpret parallel G-code?
Firmware Support for Parallel Printing

- Language support
- Extend interpreter
- Ease of editability

Marlin firmware
- Use the M605 command
- Modify the interpreter
- Open-source codebase
Firmware Support for Simultaneous Extrusion

M605 S2: Dual Nozzle Duplication Mode

Enable both extruders even when inactive

M605 S2 toggles extruder duplication

< 20 LOC
Firmware Support for Simultaneous Extrusion

; Part 1
T1 ; switch to extruder T1
G1 X40.00 Y0.80 Z0.00 E2.40 ; extrude with T1 up to (40.00, 0.80, 0.00)

; Part 2
M605 S2 ; turn on dual extrusion mode
G1 X80.000 Y0.80 Z0.00 E2.40 ; extrude with both up to (80.00, 0.80, 0.00)
M605 S2 ; turn off dual extrusion mode

; Part 3
T0 ; switch to extruder T0
G1 X120.00 Y0.80 Z0.00 E2.40 ; extrude with T0 up to (120.00, 0.80, 0.00)
Firmware Support for Simultaneous Extrusion

; Part 1
T1 ; switch to extruder T1
G1 X40.00 Y0.80 Z0.00 E2.40 ; extrude with T1 up to (40.00, 0.80, 0.00)

; Part 2
M605 S2 ; turn
G1 X80.000 Y0.800 Z0.000 E2.40 ; extrude with T1 up to (80.00, 0.80, 0.00)
M605 S2 ; turn

; Part 3
T0 ; switch to
G1 X120.00 Y0.80 Z0.00 E2.40 ; extrude with T1 up to (120.00, 0.80, 0.00)
Firmware Support for Simultaneous Extrusion

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T1 ; switch to extruder T1
G1 X40.00 Y0.80 Z0.00 ; extrude with T1 up to (40.00, 0.80, 0.00)

; Part 2
M605 S2 ; turn on dual extrusion mode
G1 X80.00 Y0.80 Z0.00 E2.40 ; extrude with both up to (80.00, 0.80, 0.00)
M605 S2 ; turn off dual extrusion mode

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T0 ; switch to extruder T0
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Firmware Support for Simultaneous Extrusion

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; Part 2
M605 S2 ; turn off dual extrusion mode
G1 X80.000 Y0.80 Z0.00 ; extrude with T1 up to (80.00, 0.80, 0.00)
M605 S2 ; turn off dual extrusion mode

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G-code Generator

Mesh \xrightarrow{slicer} G-code
G-code Generator

Mesh \rightarrow \text{G-code} \rightarrow \text{Horizontal 2D slices}
G-code Generator

Horizontal 2D slices

Mesh → Slicer → G-code → 3D Printing
G-code Generator

Horizontal 2D slices

Mesh \rightarrow \text{slicer} \rightarrow \text{G-code} \rightarrow \text{infill}

Most time spent in infill
Can we parallelize?
G-code Generation for Parallel Infill

Printer and design agnostic
Works on single model
Simulate results

Early prototype parameterized by design
Parallelize infill on single model
Early simulator prototype
Early Ideas for G-code Generation for Parallel Infill

T0 and T1 are two extruders separated by $\delta$. 
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Compute start and stop points for both extruders based on ray intersections with the perimeter.

Early Ideas for G-code Generation for Parallel Infill
T0 and T1 are two extruders separated by $\delta$. Compute start and stop points for both extruders based on ray intersections with the perimeter. Generate G-code commands wrapped by `M605 S2` where both extruders should extrude.
Early End-to-End Experiments

Simulated estimates indicate up to 2x speedups possible for basic models
Going Forward from Our Exploration

Support complex models with multiple islands

Extend to support parallel perimeter

Support different printers

Analyze mesh to detect additional opportunities for parallelism

Analyze CAD to recommend more parallelizable designs

Better simulators for parallel G-code
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[Diagram with DOFs, Firmware, Hardware, Motor Controls, Physical constraints, and G-code Generator]

PAUL G. ALLEN SCHOOL
OF COMPUTER SCIENCE & ENGINEERING
MECHANICAL ENGINEERING
UNIVERSITY of WASHINGTON