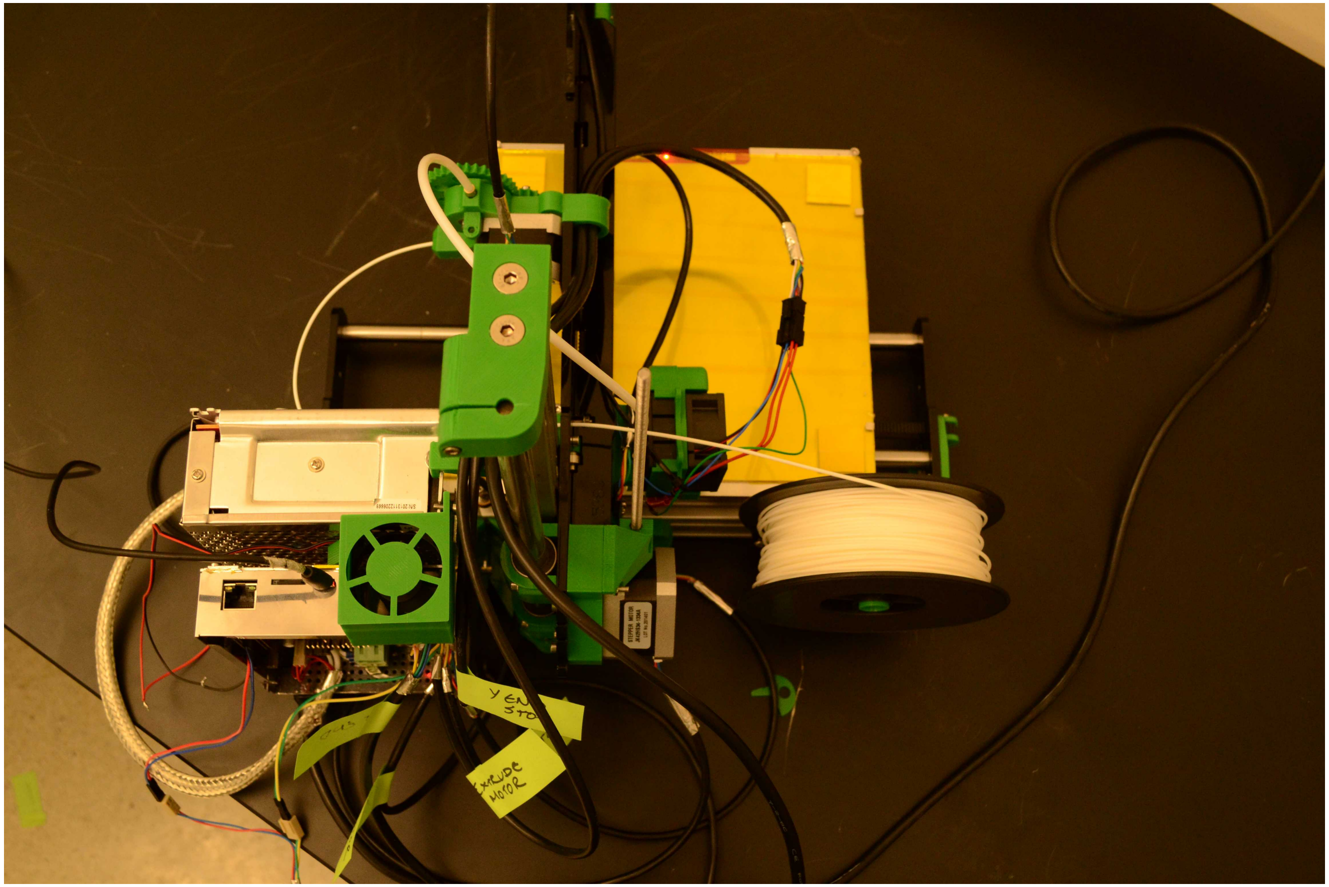
Increasing Versatility of 3D Printing

John Harakas
Advisor: Dr. Joel Rosiene
Math and Computer Science Department



Overview

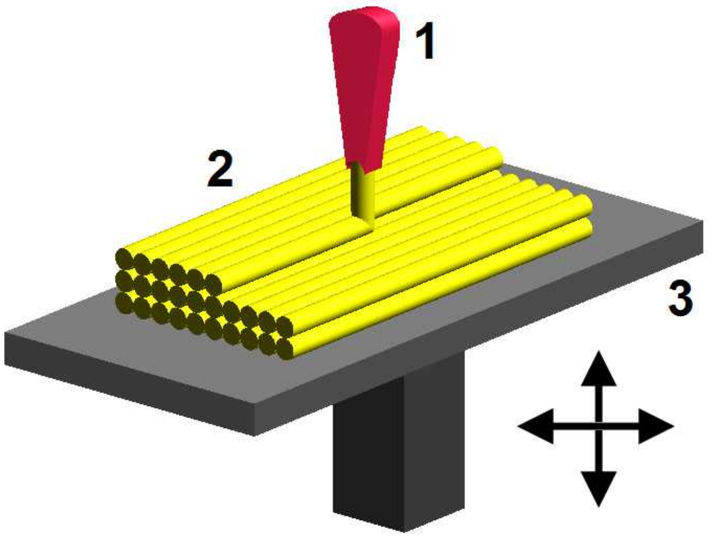
- Following research is part of a proposal to Connecticut Space Grant Consortium: NASA affiliate for a research grant over the summer
- 3D printing has permeated the consumer market
- Bringing the ability to manufacture objects on-the-fly at home is revolutionary concept

What is 3D Printing

- Printing in three dimensions...
  - From 3D computer model
- Consumer 3D printers are becoming increasingly available at lower prices
- Countless different thermoplastics for printing
  - Each have distinct physical characteristics
    - Hard, brittle, elastic
    - Extrusion temperatures,

Fused Deposition Modeling (FDM)

- Fused Deposition Modeling
  - Thermoplastic filament heated and extruded across xy-plane
  - Printed in horizontal layers
  - Most common



"FDM by Zureks" by Zureks - Own work. Licensed under GFDL via Wikimedia Commons - http://commons.wikimedia.org/wiki/File:FDM_by_Zureks.png#/media/File:FDM_by_Zureks.png

Fused Deposition Modeling (FDM)

- Use Gcode
  - Numerical control programming language
- Input 3D model into slicer program
  - Slices the object into horizontal layers 5mm thick
  - Outputs Gcode that directs the printer
- Print stacks of horizontal layers (xy-plane)
  - Print first layer on xy-plane
  - Increment z-axis to print second layer on top
- Path planning algorithm determines the build order
  - What order to traverse the xy-plane

GCode

- Numerical control programing language used for computer-aided manufacturing
  - Normally slicing software generates Gcode for an object
- Controls everything about the print
  - Axis motor movements
  - Speed and temperature
  - Extrusion increments
  - Use absolute or relative coordinate positions

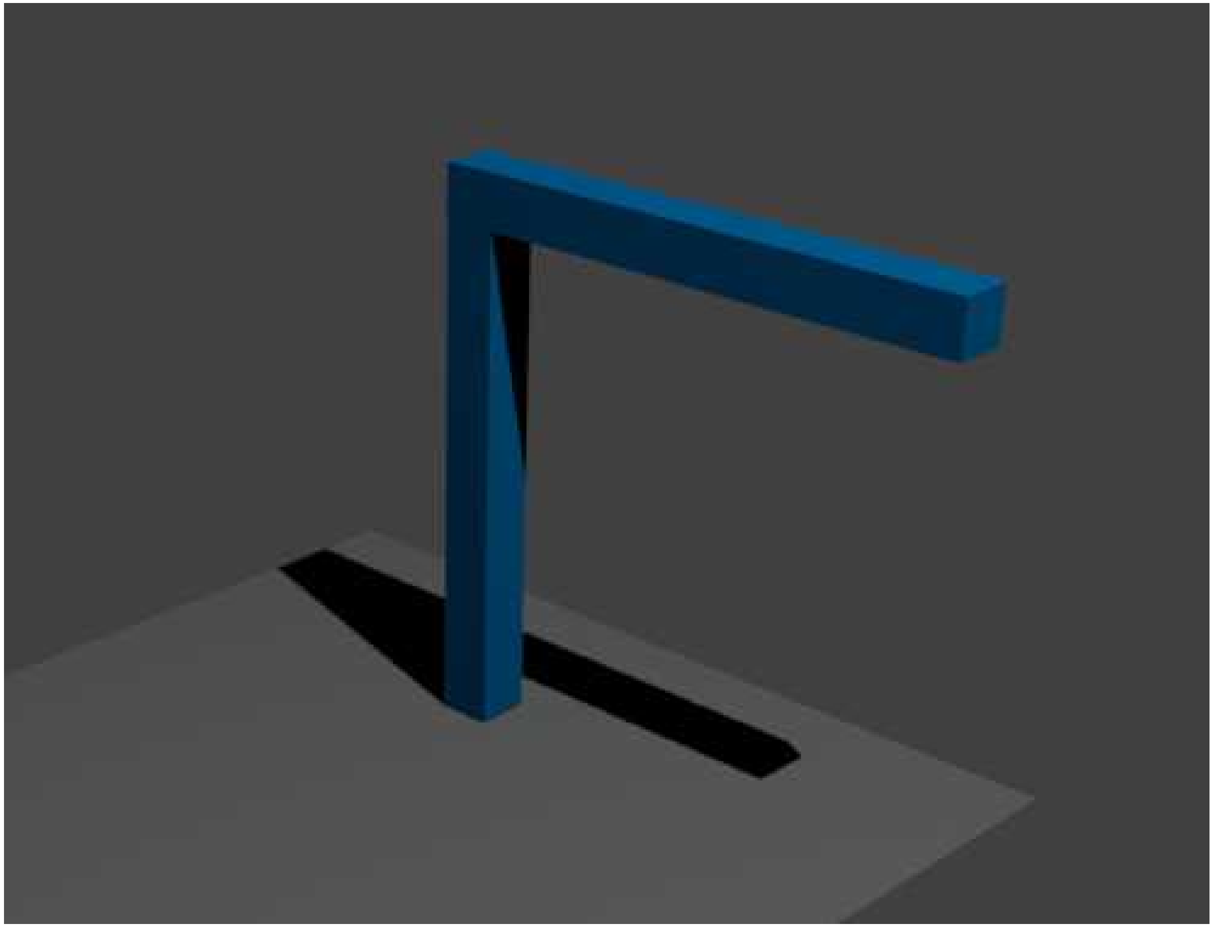
RepRap Foundation

- **Rep**licating **Rap**id-Prototyper
  - Self-copying machine
  - Open source design and code
  - Firmware follows NIST-compliant Gcode standards
  - Can analyze the source code
  - Modify source code for custom needs
  - Saves time – don't code from scratch

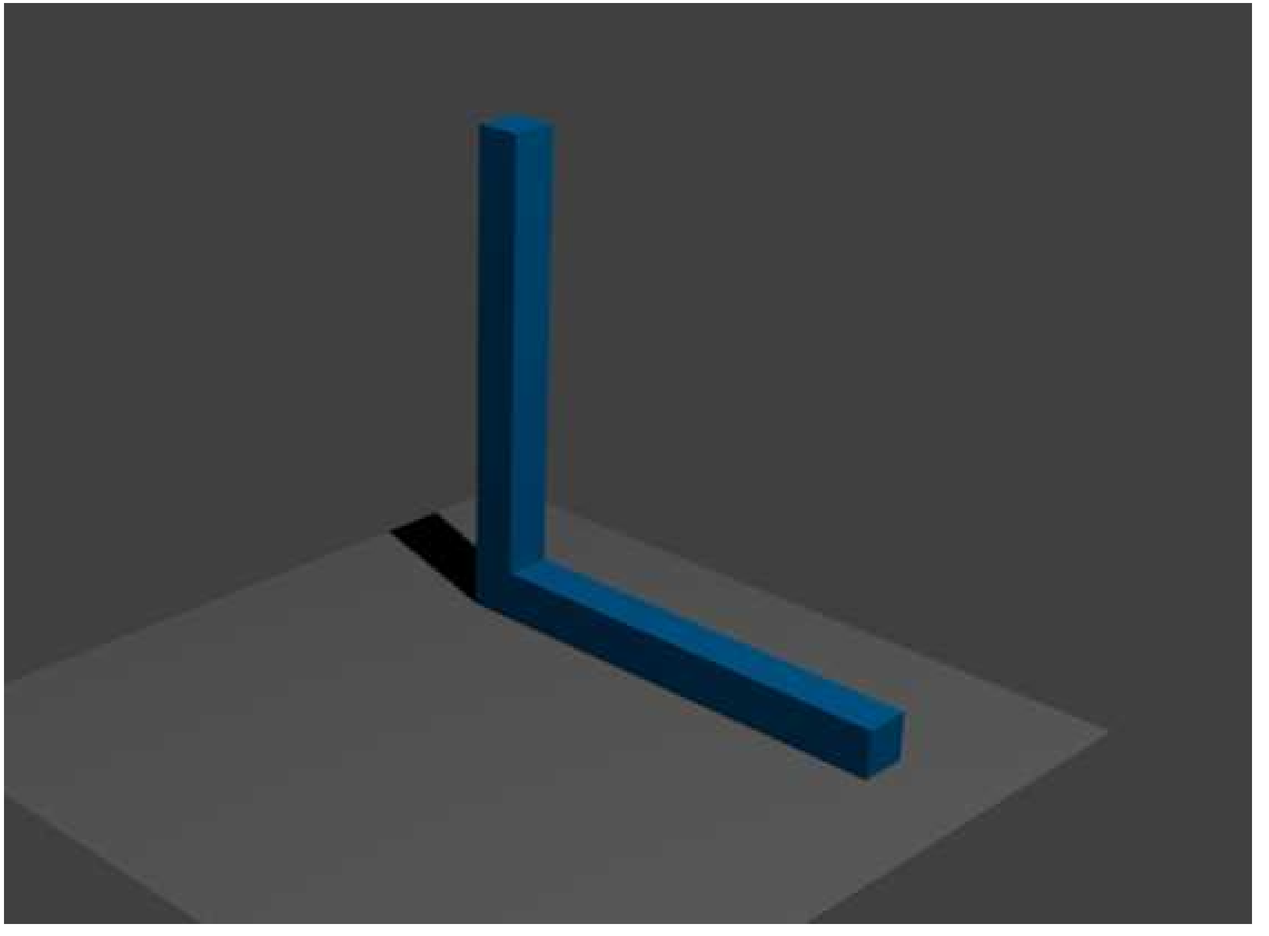
Limitations of FDM

- Temperature and speed are manually set and static throughout the print.
- Single thread thickness
  - 1.75mm filament uses .5mm extrusion nozzle
- Printing a single object with multiple properties requires multiple filaments/nozzles
- Gravity: Some objects cannot be printed well
  - Needs a foundation to print on top of

Not Printable



Printable



Research Overview

- Overcome Limitations
  - Paramaterize material properties
  - Aggregate database of material properties for common filaments
- Demonstrate proof-of-concept
- Model the polymers to be able to hit a target spec

Alter Material Properties

- Manipulate material properties with temperature and speed
- Changes in ductility
  - Material's ability to be stretched into a wire
- How a material deforms
  - Warping

Temperature

- Increasing temperature changes material properties
- Changes in ductility
- Look at changes between glass transition range to melting point

Speed

- Extrusion at higher temperatures take longer to cool
  - Slower extrusion allows previous layers to cool
- Extruding at varying speed can change rate of deformation

Deformation

Printed at higher temperature, much greater deformation

Ignore Path Planning and Slicing

- Slicer and path planning determine the Gcode generation for an object
  - Forgo slicing and path planning
- Wrote python program to handle Gcode
  - Handles serial connection and communication
  - Enqueues commands to be sent
  - Simplifies code input
  - i.e. turn off heaters:

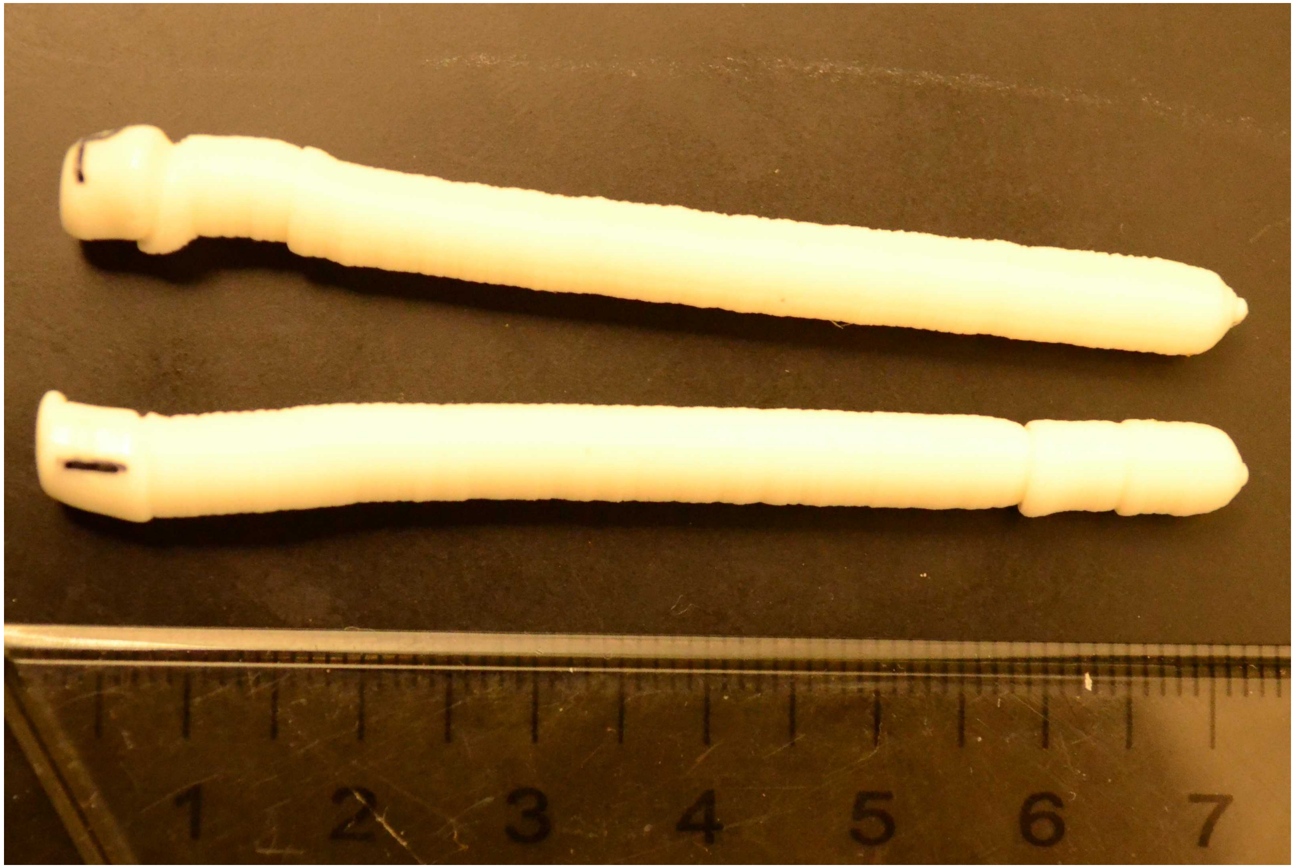
```
M104 S0 \n M140 S0 \n  → t off
```

One Filament – More Versatilty

- Achieve variable thread thickness
- Print both flexible and rigid objects
- Uniaxial printing (one dimension)
- Minimize the foundation surface to print on

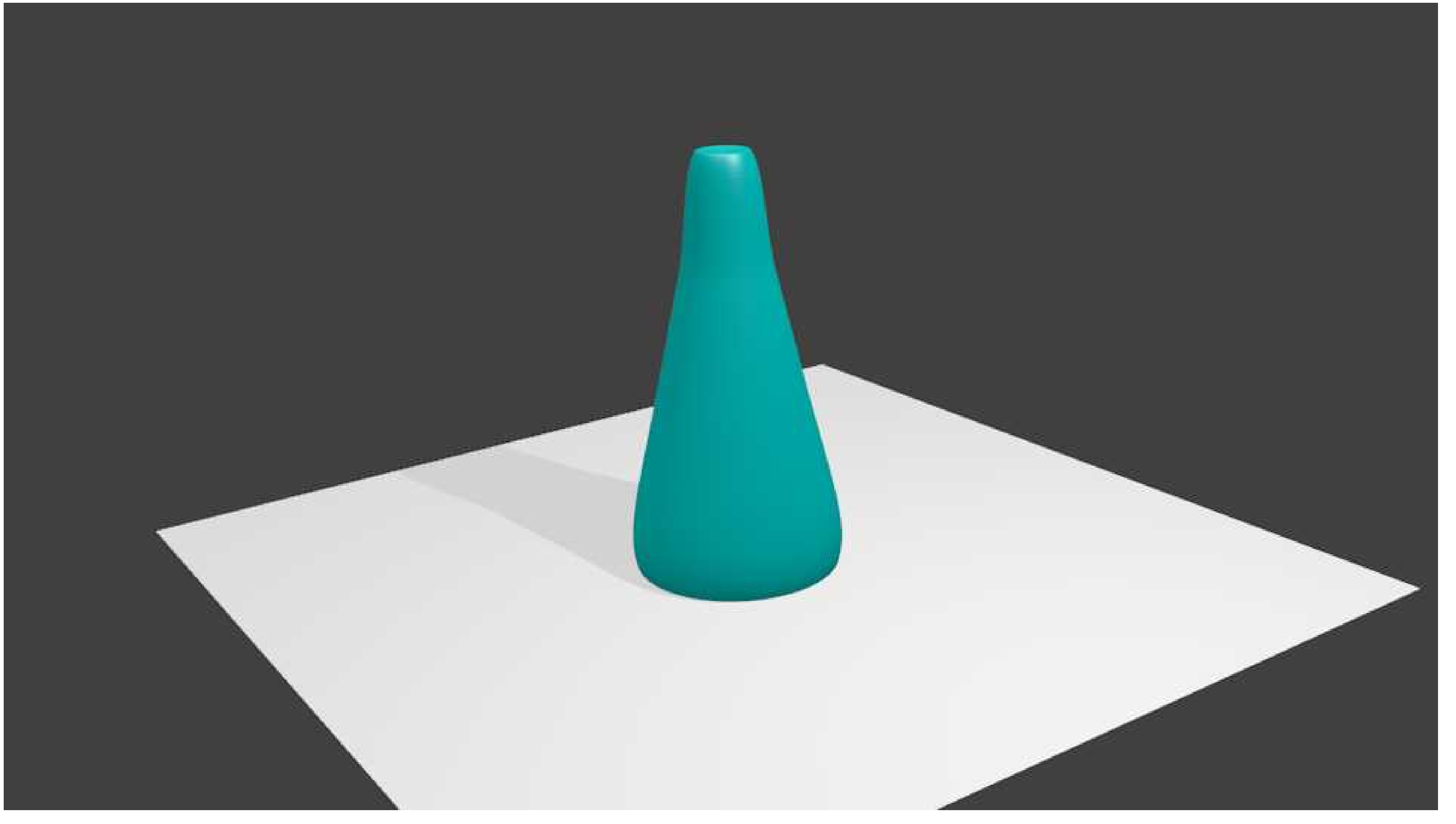
Uniaxial Printing

- Cylinders can be printed much more quickly uniaxially on z-axis
  - As opposed to slicing into horizontal layers



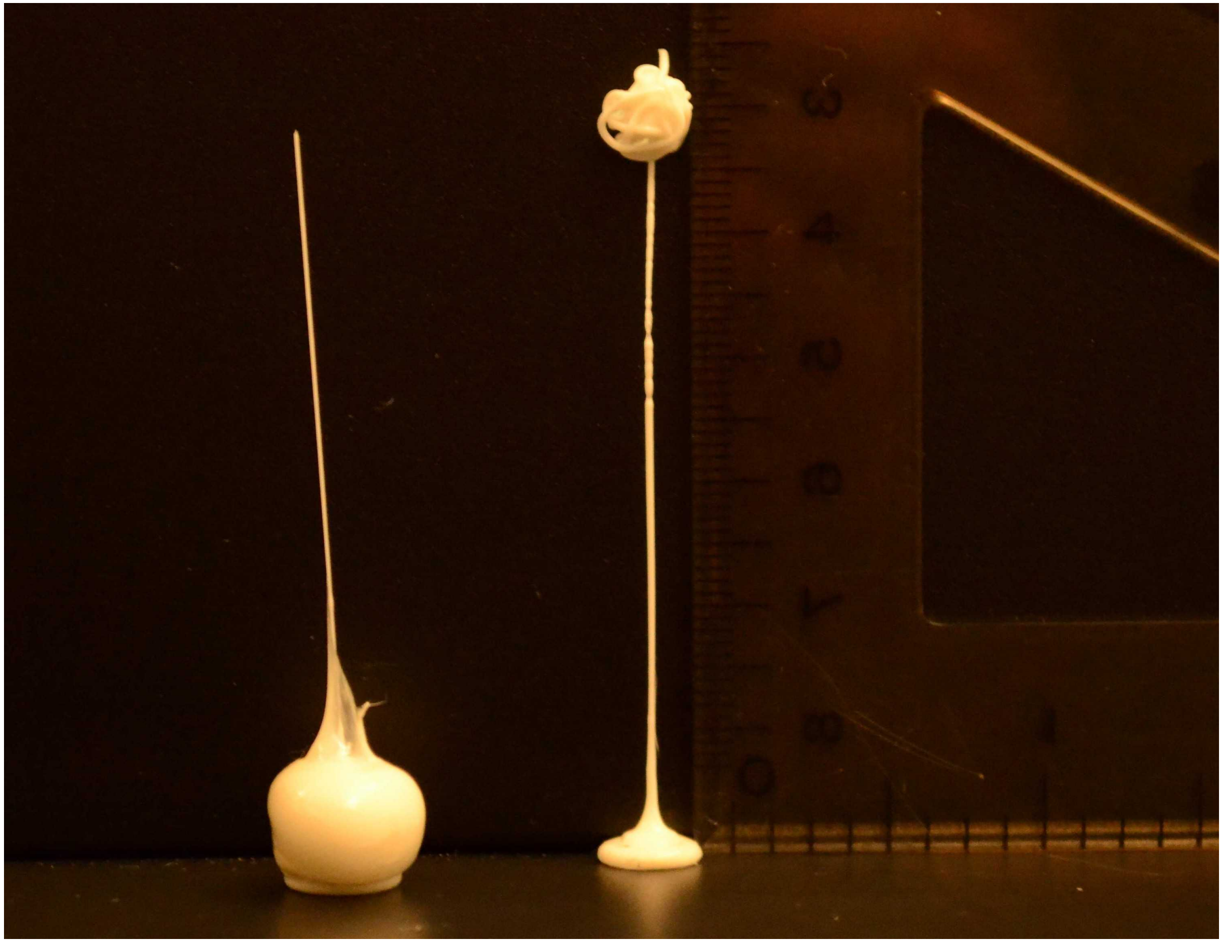
Uniaxial Printing

- Symmetric objects
  - Control the deformation (Like a Hershey's Kiss)

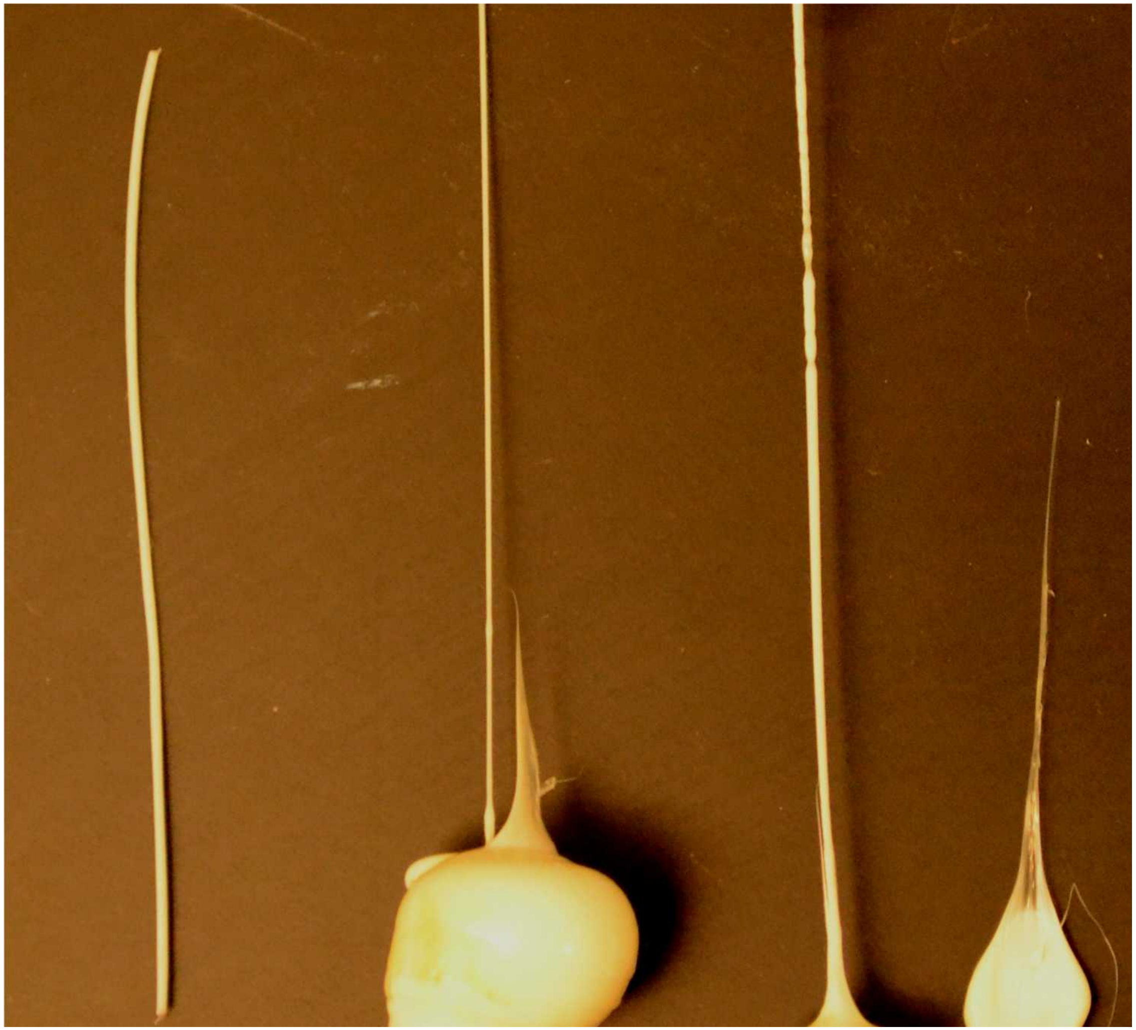


Gravity

- Minimize foundation needed to print
  - Extrude at lower temperature, cools and solidifies faster

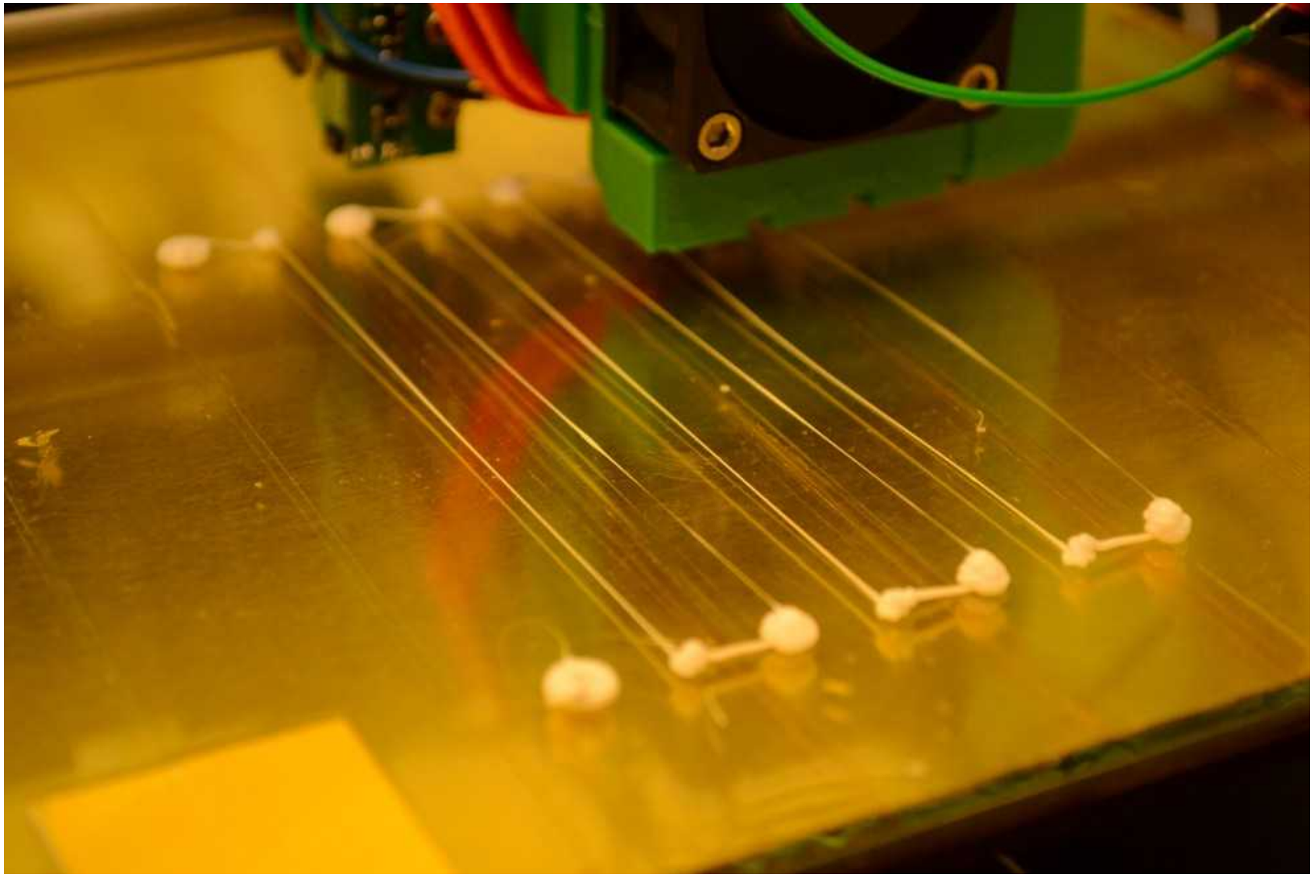


Variable Thread Thickness



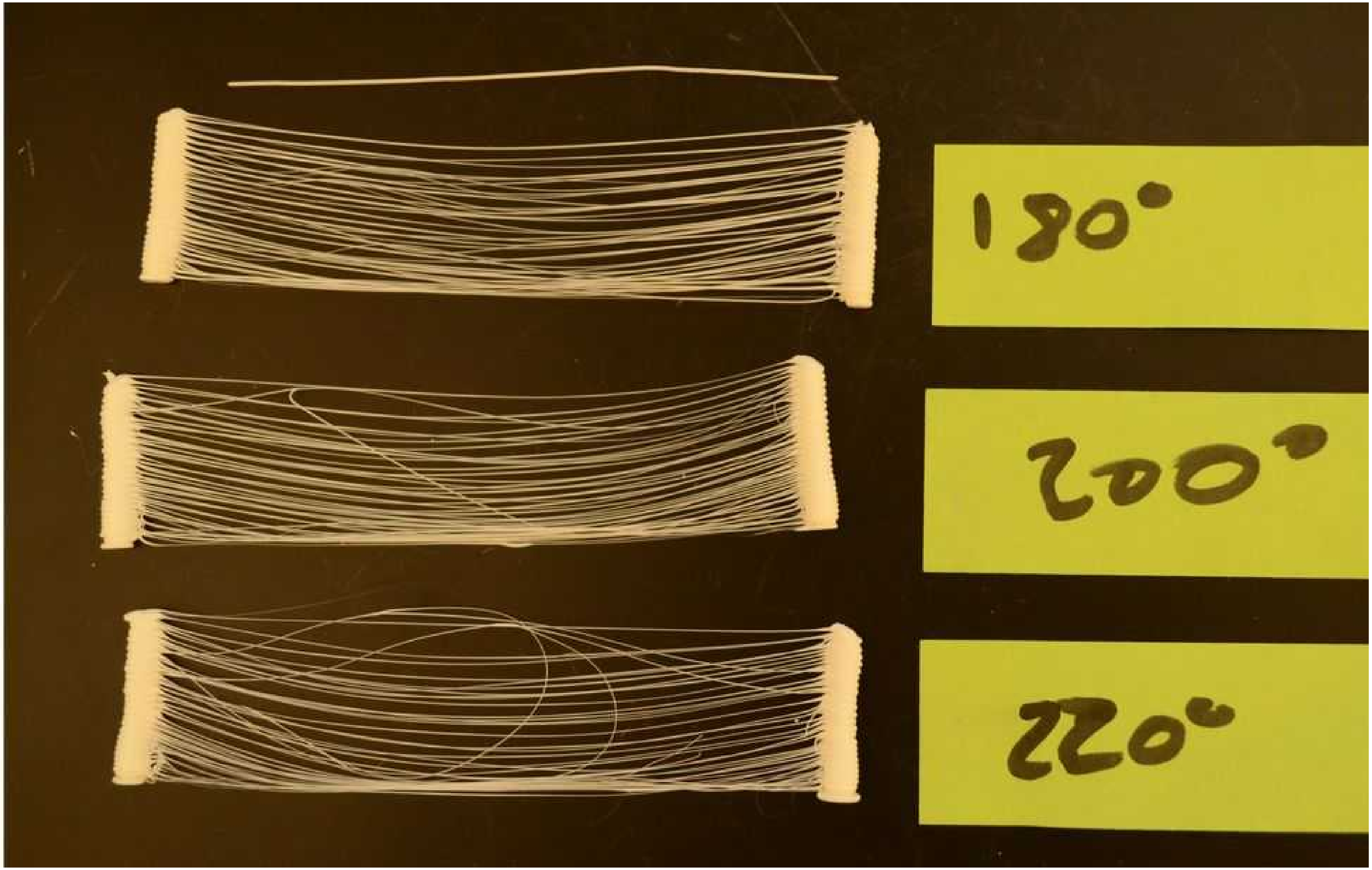
Variable Thread Thickness

- Using anchor points to print thin meshes.
  - Threads much thinner than nozzle diameter
  - Less rigid, more flexible



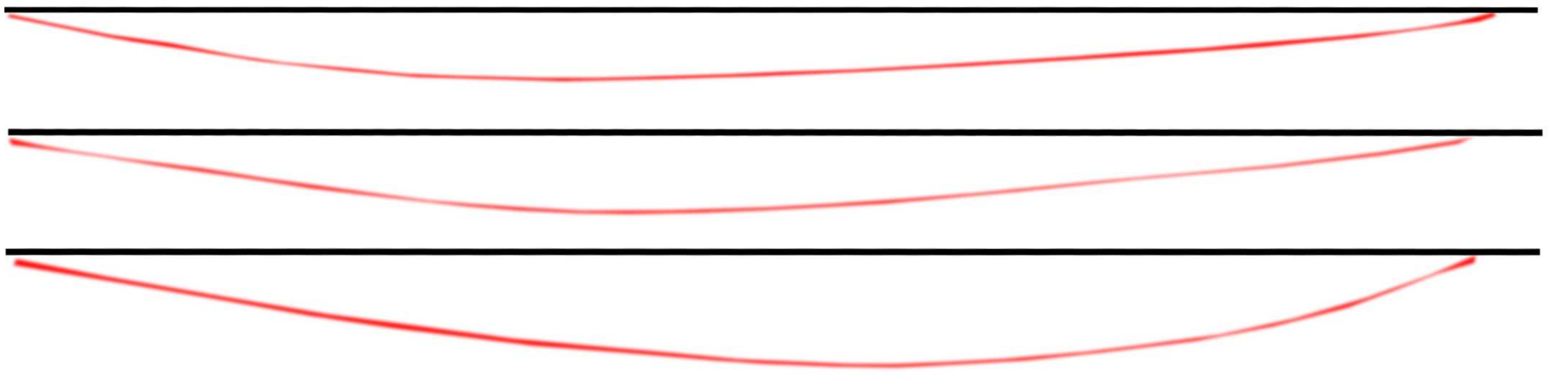
Variable Thread Thickness

- Flexible woven mesh



Variable Thread Thickness

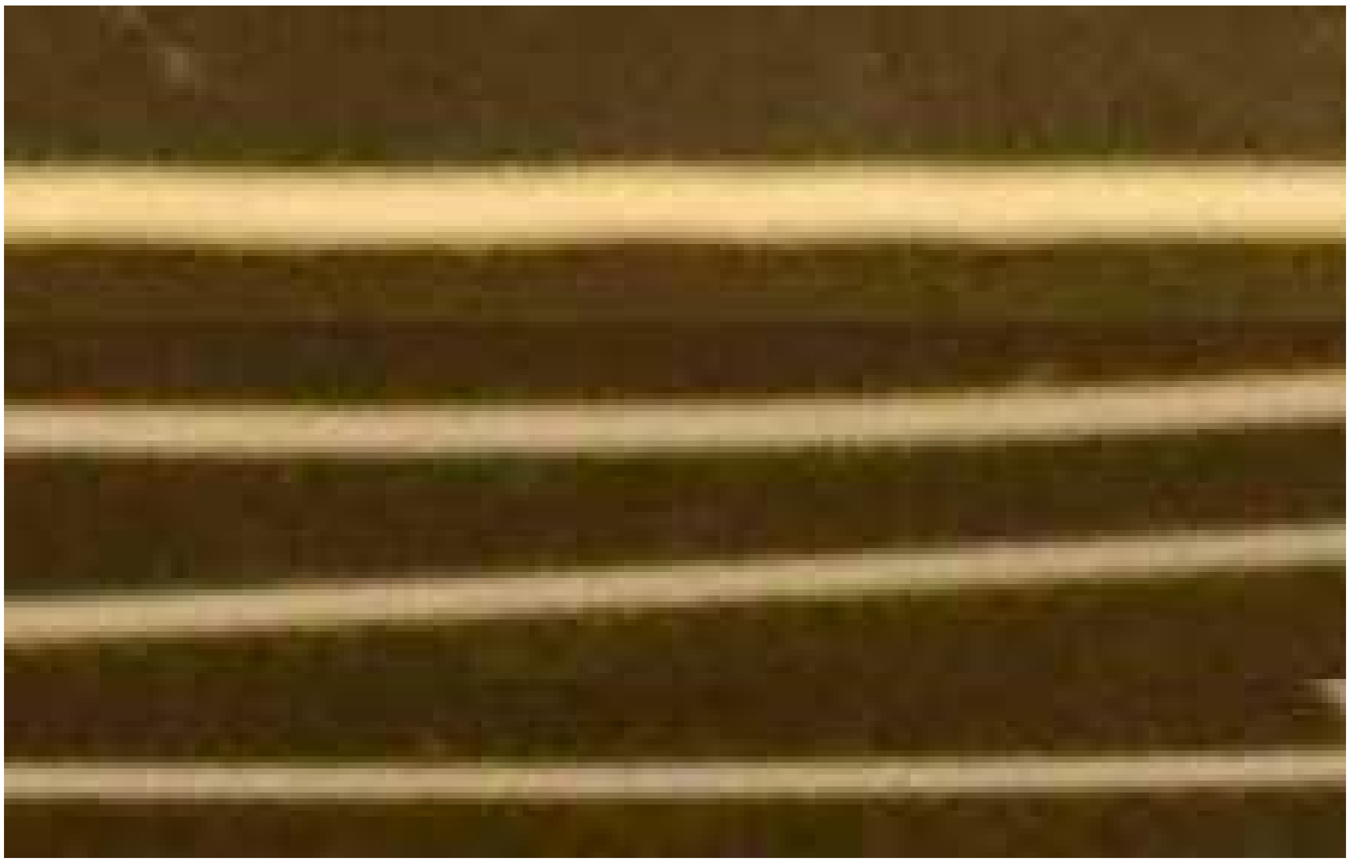
Red: Printed thread
Black: Secant



- Higher temperatures, more deformation (drooping, sticking to other threads)
- Lower temperature prints solidify faster: Less deformation

Variable Thread Thickness

Effects of temperature



Normal thread

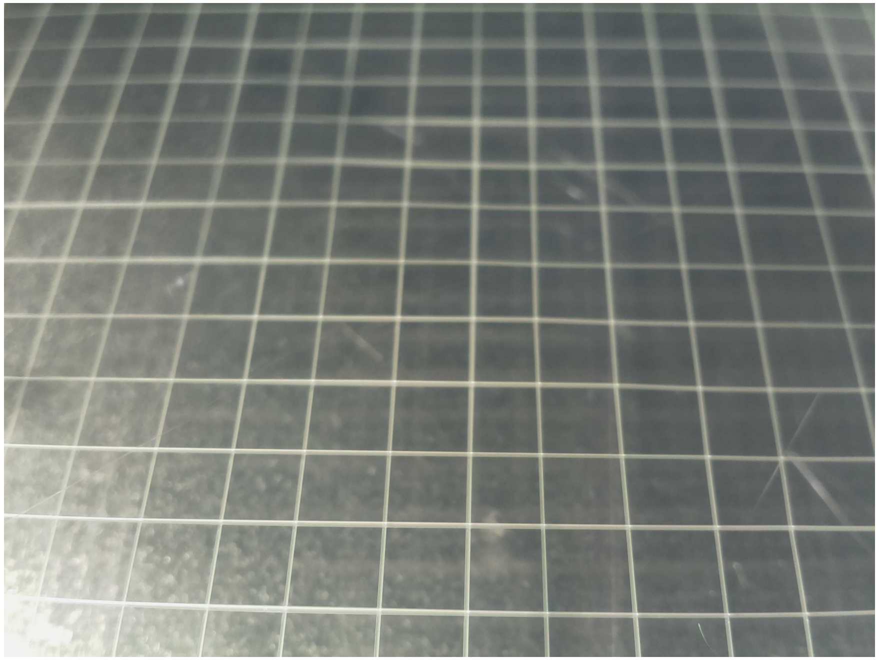
180°C

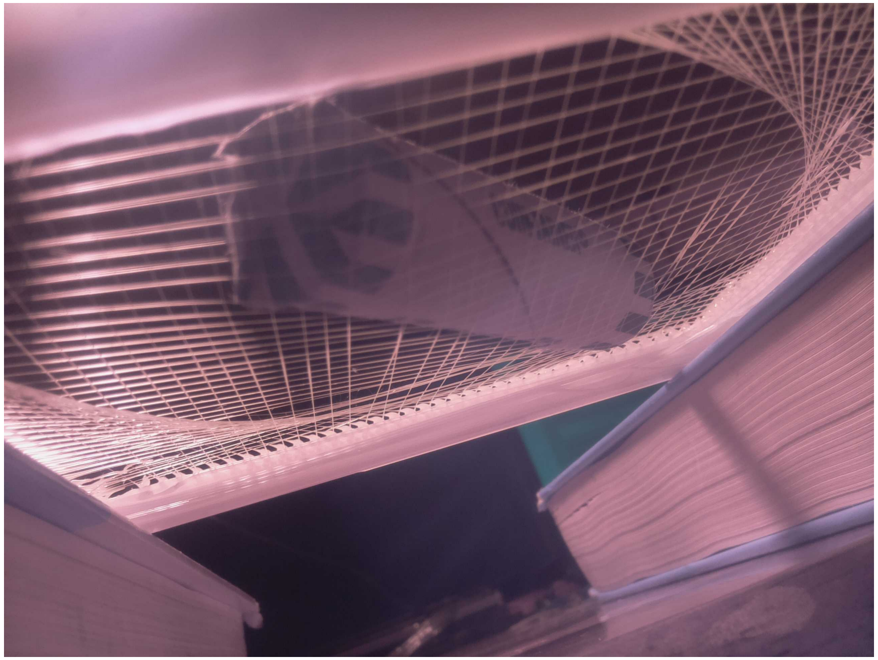
200°C

220°C

Woven Mesh

Woven Mesh





Mapping to a Target Thickness

- Calculate the diameter of the thread after an elongation over a distance
- i.e: If the nozzle extrudes at a length of 3mm at 4mm diameter, what is the diameter after it is stretched across 25mm?
  - At first glance, seems pretty straightforward.
- Not so much...
  - Varies with temperature and the material

Mapping to a Target Thickness: Coefficients

- Poisson's Ratio *v*:
  - Expansion over contraction (The change in diameter after it is stretched by a length)
- Young's (Elasticity) Modulus *E:*
  - Stress/strain $E = \frac{\sigma}{\varepsilon}$
- Shear Modulus *G*:
  - Shear stress / Shear Strain

$$\Delta d = -d \cdot v \frac{\Delta L}{L} \qquad v = \frac{E}{2G} - 1$$

Mapping to a Target Thickness: Coefficients

- Coefficients of shear and elasticity are documented in material science databases.
  - Can calculate Poisson's Ratio from those coefficients
  - Can calculate the reduction in diameter

$$v=\frac{E}{2G}-1 \quad \rightarrow \quad \Delta d=-d\cdot v\frac{\Delta L}{L}$$

Mapping to a Target Thickness: Coefficients

- Coefficients change with temperature
  - Is the relationship linear? (Hooke's Law)
  - A linear relationship is ideal:
    - Have temperature boundaries, Can make relatively accurate approximations
- Polymers are nonlinear elastic materials
- Hooke's Law with Temperature:
  - Possible to model uniaxial stress (stretched in x-direction) and get first order approximation of coefficients.

$$E=\frac{\sigma_{max}}{\varepsilon_{max}-a\Delta T} \qquad a = \text{coefficient of linear thermal expansion}$$

Mapping to a Target Thickness

- Interpolation
  - Print lots of samples at varying states
    - Temperature, extrusion rate, speed
  - Radius is a function of temperature, extrusion and flow rate
  - Much easier

Applications

- Do more with one filament
  - Printing thinner threads for greater elasticity.
- Weaving has yet to be done
  - Printing flexible meshes and netting
  - Possibility for strong cordage
  - Printing fine fabrics
- Adherence changes with temperature
  - Print detachable objects

Conclusions

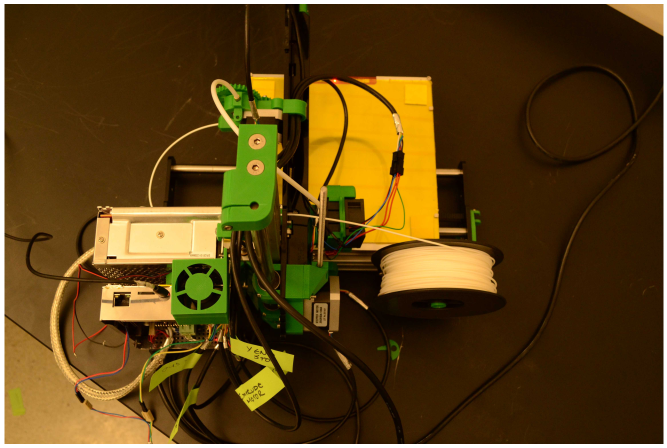
- Proof-of-Concept was achieved
  - Different print patterns can be made
  - Different thread thicknesses
- More to do:
  - Determine best way to map parameters
  - Make universally repeatable
  - Model the materials in a computer
  - Integrate with path planning

Special Thanks

- Dr. Osei
  - Answering my incessant questions
- Joshua Cramer
  - Photographs

Increasing Versatility of 3D Printing

John Harakas
Advisor: Dr. Joel Rosiene
Math and Computer Science Department



Overview

- Following research is part of a proposal to Connecticut Space Grant Consortium: NASA affiliate for a research grant over the summer
- 3D printing has permeated the consumer market
- Bringing the ability to manufacture objects on-the-fly at home is revolutionary concept

Part of a research proposal for the CT Space Grant in relation to NASA's strategic goals
3D printing has become more popular more affordable
Can replicate nearly anything using a computer model at home

What is 3D Printing

- Printing in three dimensions...
  - From 3D computer model
- Consumer 3D printers are becoming increasingly available at lower prices
- Countless different thermoplastics for printing
  - Each have distinct physical characteristics
    - Hard, brittle, elastic
    - Extrusion temperatures,

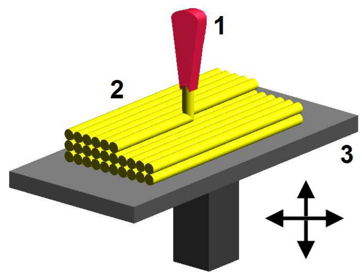
Obvious: Printing in 3 dimensions from a computer model

Lots of different polymers used for printing

some are harder, more flexible, brittle, heat sensitive, conductive

Fused Deposition Modeling (FDM)

- Fused Deposition Modeling
  - Thermoplastic filament heated and extruded across xy-plane
  - Printed in horizontal layers
  - Most common



"FDM by Zureks" by Zureks - Own work. Licensed under GFDL via Wikimedia Commons - http://commons.wikimedia.org/wiki/File:FDM_by_Zureks.png#/media/File:FDM_by_Zureks.png

Focus of this research was on FDM
There are a number of other methods
Photopolymerization
most common method
extrudes heated plastic in horizontal layers
Onto a heated bed

Fused Deposition Modeling (FDM)

- Use Gcode
  - Numerical control programming language
- Input 3D model into slicer program
  - Slices the object into horizontal layers 5mm thick
  - Outputs Gcode that directs the printer
- Print stacks of horizontal layers (xy-plane)
  - Print first layer on xy-plane
  - Increment z-axis to print second layer on top
- Path planning algorithm determines the build order
  - What order to traverse the xy-plane

FDM
- input 3D model into a slicer program
  - slices the model into thin horizontal layers
  - Outputs Gcode
- Gcode is numerical control programming language
- Prints the object as a stack of horizontal layers
- Path planning determines how to traverse all points on the xy-plane

GCode

- Numerical control programing language used for computer-aided manufacturing
  - Normally slicing software generates Gcode for an object
- Controls everything about the print
  - Axis motor movements
  - Speed and temperature
  - Extrusion increments
  - Use absolute or relative coordinate positions

Little more about Gcode
Controls everything about the printing
axis motor movments
the speed and temperature

RepRap Foundation

- **Rep**licating **Rap**id-Prototyper
  - Self-copying machine
  - Open source design and code
  - Firmware follows NIST-compliant Gcode standards
  - Can analyze the source code
  - Modify source code for custom needs
  - Saves time – don't code from scratch

RepRap has open source 3D printer models
Can modify the firmware and software
I don't need to code everything from scratch

Limitations of FDM

- Temperature and speed are manually set and static throughout the print.
- Single thread thickness
  - 1.75mm filament uses .5mm extrusion nozzle
- Printing a single object with multiple properties requires multiple filaments/nozzles
- Gravity: Some objects cannot be printed well
  - Needs a foundation to print on top of

Limitations of FDM printing

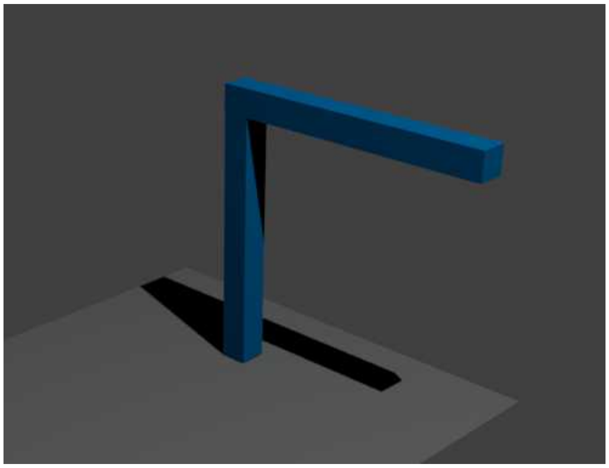
Temperature and speed are static, they do not change throughout the printing

The thread diameter is bound more or less to the nozzle size

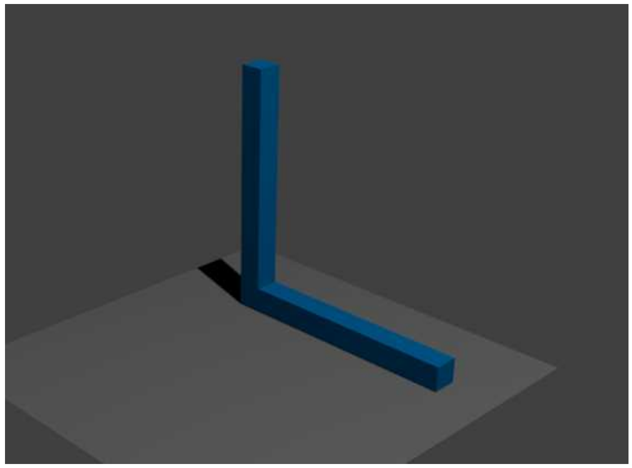
Need multiple nozzles and filaments if an object has multiple propeties

Needs a foundation to print on

Not Printable



Printable



Research Overview

- Overcome Limitations
  - Paramaterize material properties
  - Aggregate database of material properties for common filaments
- Demonstrate proof-of-concept
- Model the polymers to be able to hit a target spec

My Research overview

Figure out how to overcome certain limitations in FDM

Observe material properties and changes with temperature and speed

Get a proof of concept

Try modeling the polymers to hit target specs

Alter Material Properties

- Manipulate material properties with temperature and speed
- Changes in ductility
  - Material's ability to be stretched into a wire
- How a material deforms
  - Warping

Look At Material properties
How can materials be manipulated with temperature and speed
Ductility changes (Ductile-brittle transition)
Deformation of a material, how it warps

Temperature

- Increasing temperature changes material properties
- Changes in ductility
- Look at changes between glass transition range to melting point

Temperaure range

- Looking at the changes in temperature between glass transition and melting temperature
  - Not well defined, are ranges of values
  - Glass transition is where the material starts to be moldable, molecules are more free to move
  - The heated bed of 3D printers are set to a temperature range within glass transition. Otherwise the bases will warp

Speed

- Extrusion at higher temperatures take longer to cool
  - Slower extrusion allows previous layers to cool
- Extruding at varying speed can change rate of deformation

Speed of extrusion affects the material
  Corresponds to temperature
  Higher temperature, faster extrusion
    Cooler temperatures, must extrude more slowly
  The rate of extrusion can change how the material deforms.
  Higher temperatures usually have higher deformation

Deformation

Printed at higher temperature, much greater deformation

Ignore Path Planning and Slicing

- Slicer and path planning determine the Gcode generation for an object
  - Forgo slicing and path planning
- Wrote python program to handle Gcode
  - Handles serial connection and communication
  - Enqueues commands to be sent
  - Simplifies code input
  - i.e. turn off heaters:

```
M104 S0 \n M140 S0 \n  → t off
```

For this project, I need to ignore path planning and slicing
Cannot input 3D models
- All Gcode is generated manually
- Extremely cumbersome

Wrote a python program to handle Gcode, to make things easier
- Used parts of Printrun, the software used by RepRap printers to make things easier

One Filament – More Versatilty

- Achieve variable thread thickness
- Print both flexible and rigid objects
- Uniaxial printing (one dimension)
- Minimize the foundation surface to print on

The goal: Achieve more versatility with one filaments
- Variable thread thickness
  - thinner or thicker threads
  - Thickness affects the flexibility of an object
  - Try printing in one dimension (uniaxial printing)
    - ascending the z-axis, good for vertically symmetric objects
      - like cylinders

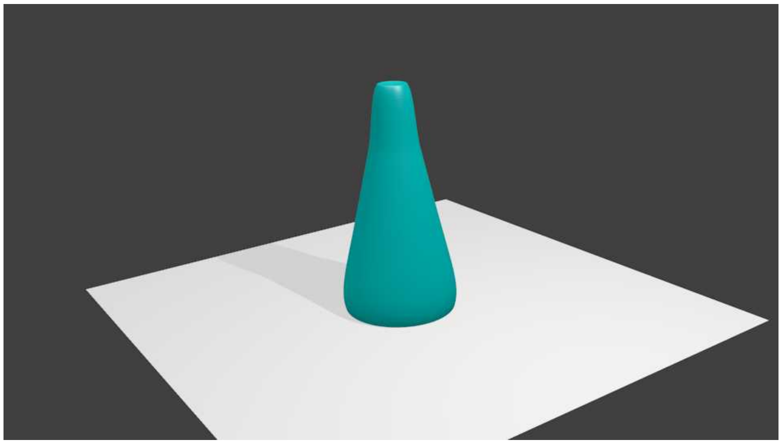
Uniaxial Printing

- Cylinders can be printed much more quickly uniaxially on z-axis
  - As opposed to slicing into horizontal layers

These were printed by only ascending the z-axis
Normal path planning would interpret this as layers.
Much quicker to print them in one dimenson

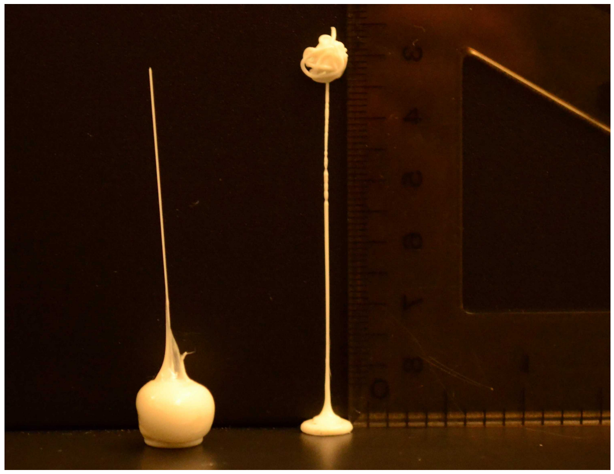
Uniaxial Printing

- Symmetric objects
  - Control the deformation (Like a Hershey's Kiss)



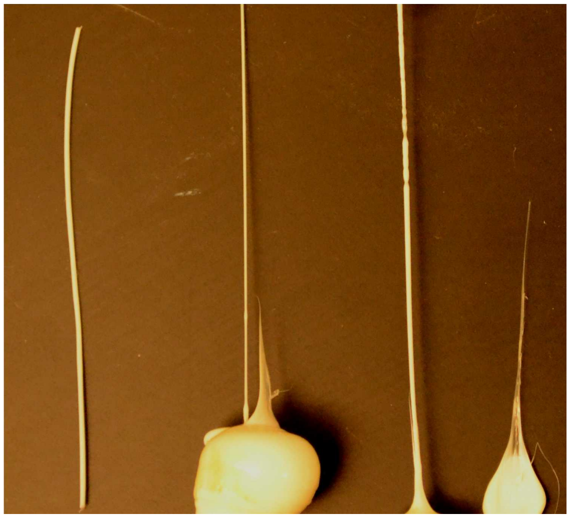
Gravity

- Minimize foundation needed to print
  - Extrude at lower temperature, cools and solidifies faster



Gravity, tried printing objects without supports,

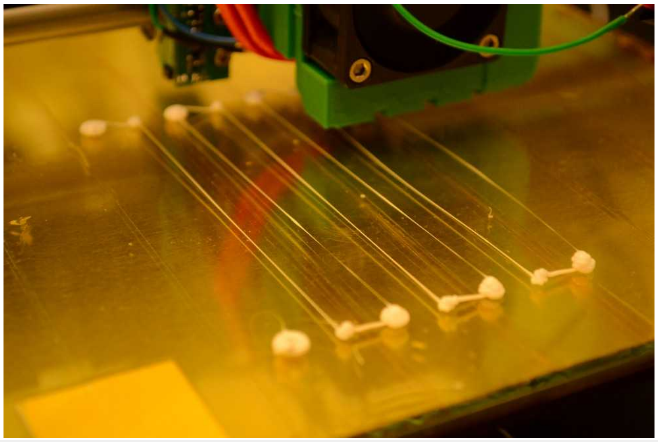
Variable Thread Thickness



Most of my time and effort went into looking at printing with different thread thicknesses

Variable Thread Thickness

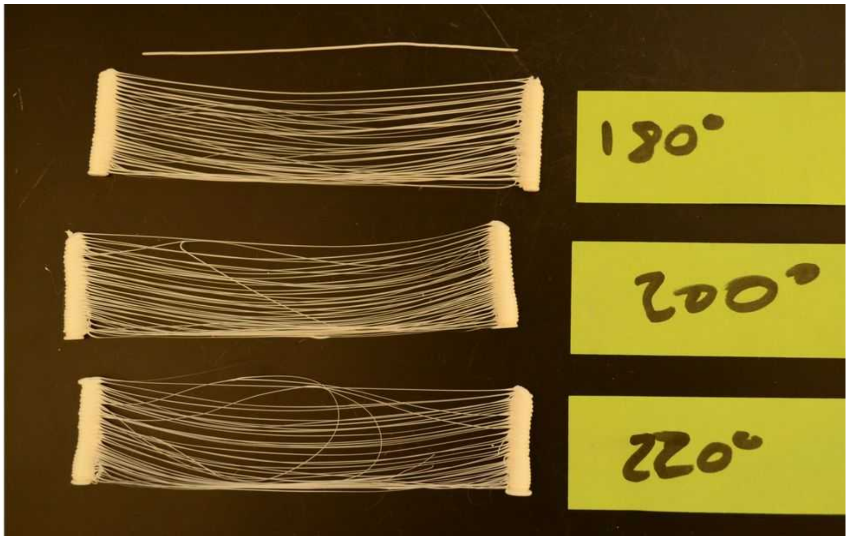
- Using anchor points to print thin meshes.
  - Threads much thinner than nozzle diameter
  - Less rigid, more flexible



Using anchor points, I was able to essentially stretch the end of material over a distance.
The threads were much thinner, and much more flexible

Variable Thread Thickness

- Flexible woven mesh

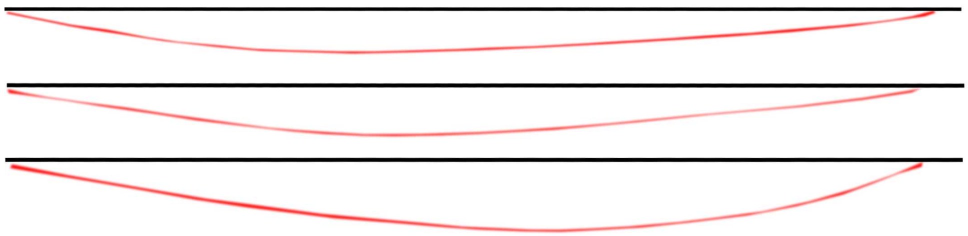


Here are a few samples printed at different temperatures

- These were **printed** going up the z-axis
- The lower temperature is noticeable the cleanest print.
- Can see the bottom is not as clean beacause the bed of the printer is heated
  - Warps the thin threads very quickly
  - Printed going up in this case to get farther away from the heat of the bed
  - The hotter prints also had a tendency to adhere more quickly to other threads

Variable Thread Thickness

Red: Printed thread
Black: Secant

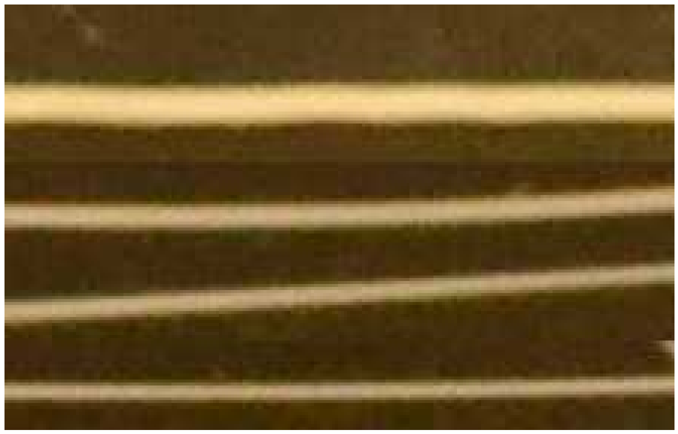


- Higher temperatures, more deformation (drooping, sticking to other threads)
- Lower temperature prints solidify faster: Less deformation

Can see the amount of deformation. Higher temperatures have the most drooping because it takes longer for them to cool back to glass transition
The black secant line provides a good reference

Variable Thread Thickness

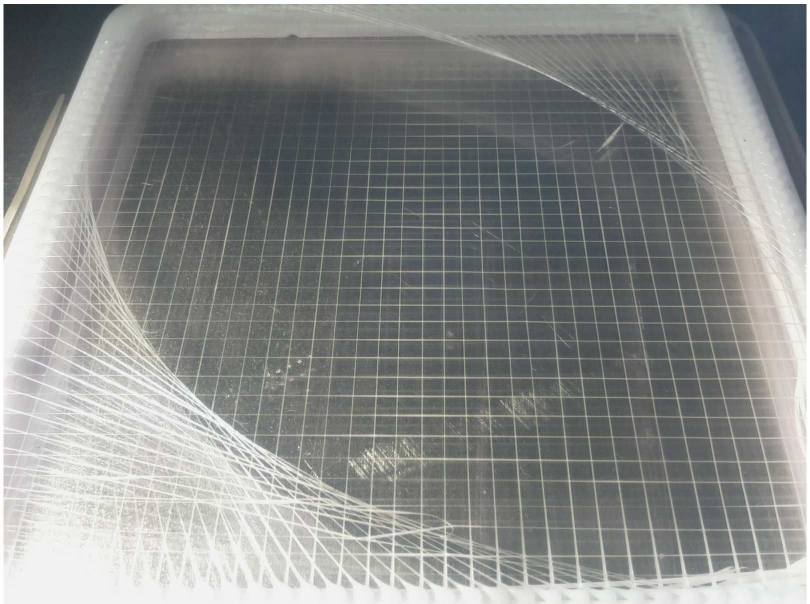
Effects of temperature



Closeup

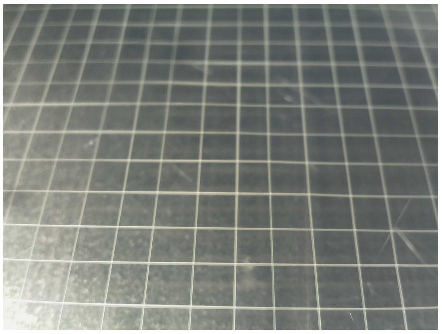
- The threads vary in temperature, the lowest temperature had the thickest thread
  - In due part to drooping, the volume is preserved
  - In part, less material is being pulled because more material adheres to the anchor

Woven Mesh



Worked on printing a woven mesh across the xy-plane
Without a heated bed the foundation warped

Woven Mesh

Mapping to a Target Thickness

- Calculate the diameter of the thread after an elongation over a distance
- i.e: If the nozzle extrudes at a length of 3mm at 4mm diameter, what is the diameter after it is stretched across 25mm?
  - At first glance, seems pretty straightforward.
- Not so much...
  - Varies with temperature and the material

Trying to map to a target thickness
Not nearly as straighforward as would expect
Varies with temperature and material, heat conductivity

Mapping to a Target Thickness: Coefficients

- Poisson's Ratio *v*:
  - Expansion over contraction (The change in diameter after it is stretched by a length)
- Young's (Elasticity) Modulus *E:*
  - Stress/strain $E=\frac{\sigma}{\varepsilon}$
- Shear Modulus *G*:
  - Shear stress / Shear Strain

$$\Delta d=-d\cdot v\frac{\Delta L}{L} \qquad v=\frac{E}{2G}-1$$

Coefficients to calculate target thicknesss
- Poisson's Ratio is generally used in these instances, expansion over contraction
- Young's Modulus is the tangent to the stress/strain curve for a materials. How elastic is a material
  - Materials can be modeled in a stress over strain curve
- Shear modulus, parallel force to an object (similar to friction)
- Knowing those coefficents, can calculate the reduction in diameter over an elongated distance
- All coefficients are documented in material science databases

Mapping to a Target Thickness: Coefficients

- Coefficients of shear and elasticity are documented in material science databases.
  - Can calculate Poisson's Ratio from those coefficients
  - Can calculate the reduction in diameter

$$v = \frac{E}{2G} - 1 \quad \rightarrow \quad \Delta d = -d \cdot v \frac{\Delta L}{L}$$

Mapping to a Target Thickness: Coefficients

- Coefficients change with temperature
  - Is the relationship linear? (Hooke's Law)
  - A linear relationship is ideal:
    - Have temperature boundaries, Can make relatively accurate approximations
- Polymers are nonlinear elastic materials
- Hooke's Law with Temperature:
  - Possible to model uniaxial stress (stretched in x-direction) and get first order approximation of coefficients.

$$E=\frac{\sigma_{max}}{\varepsilon_{max}-a\Delta T} \qquad a = coefficient\ of\ linear\ thermal\ expansion$$

Major problem
- They change with temperature
  - Relationship between them breaks down with changes in temperature.
    - It is a piecewise linear relationship
  - Polymers are nonlinear elastic materials, very difficult to model, they do not go through easily discernable periods of linearity
- Nonlinear elastic materials can be modeled using tensors of degree 9?
- For an ideal elastic solid, can easily apply Hooke's Law with temperatures
  - If model as a uniaxial or planar, (not in 3d), just across x-axis, can get a rough approxomation, reduces tensor problem down to a scalar or vector.
  - Know the material coefficients at glass transition and that Poisson's ratio approaches ½ as it reaches melting point.
    - Can fill in the blanks

Mapping to a Target Thickness

- Interpolation
  - Print lots of samples at varying states
    - Temperature, extrusion rate, speed
  - Radius is a function of temperature, extrusion and flow rate
  - Much easier

Another way to model is with interpolation, much easier, find a function that maps all the data together.
Take samples, record the results

Applications

- Do more with one filament
  - Printing thinner threads for greater elasticity.
- Weaving has yet to be done
  - Printing flexible meshes and netting
  - Possibility for strong cordage
  - Printing fine fabrics
- Adherence changes with temperature
  - Print detachable objects

So the applications of all of this
- The versatility of one filament
  - Printing thinner threads gives greater flexibility in an object
    - The problem normally associated with thinner threads is they generally don't adhere as well to other objects
    - I observed that printing them at much higher tempertures than normal, they have a strong tendency to adhere. Seen in the closeup of thread thickness
    - Looking at the possibility of creating woven fabrics

Conclusions

- Proof-of-Concept was achieved
  - Different print patterns can be made
  - Different thread thicknesses
- More to do:
  - Determine best way to map parameters
  - Make universally repeatable
  - Model the materials in a computer
  - Integrate with path planning

Conclusions and Results

- Made a proof of concept
- Temperature does have a noticeable effect

More to do:

- Determine the approach to model the properties, probably a combination of interpolation and as a planar change
- Make this universally repeatable for other objects
  - There are unused parameters in Gcode, that can be used for this purpose to pass additional parameters
- Integrate this into the path planning.
- The scope was so large, I only scratched the surface here, there are other variables to take into account

Special Thanks

- Dr. Osei
  - Answering my incessant questions
- Joshua Cramer
  - Photographs