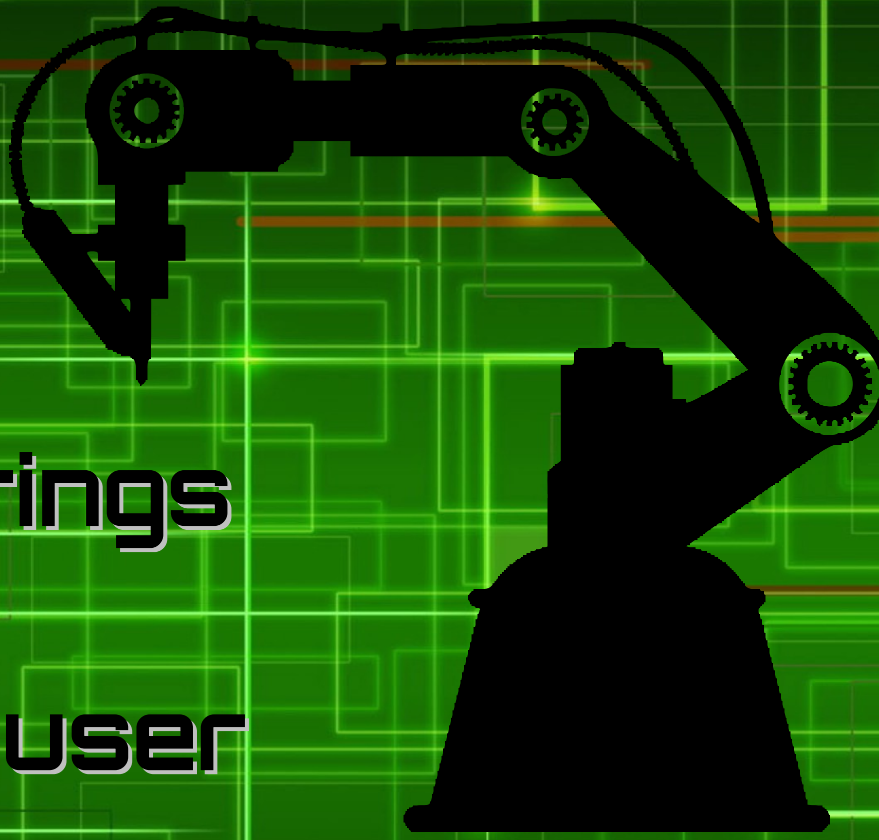
Investigation of Robotic Based Additive Manufacturings



Matt Heuser

Advisor:
Panos Shiakolas, Ph.D

Acknowlegements

- Committee members
  - Pranesh Aswath, Ph.D.
  - Tre Welch, Ph.D.
- MARS research team
  - Christopher Abrego
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  - Sam Williams
- Chris McMurrough, Ph.D
- Hyejin Moon, Ph.D

Introduction

- Conventional 3-D printers
- Solid models → G-code
- Slic3r software
- Workspace size

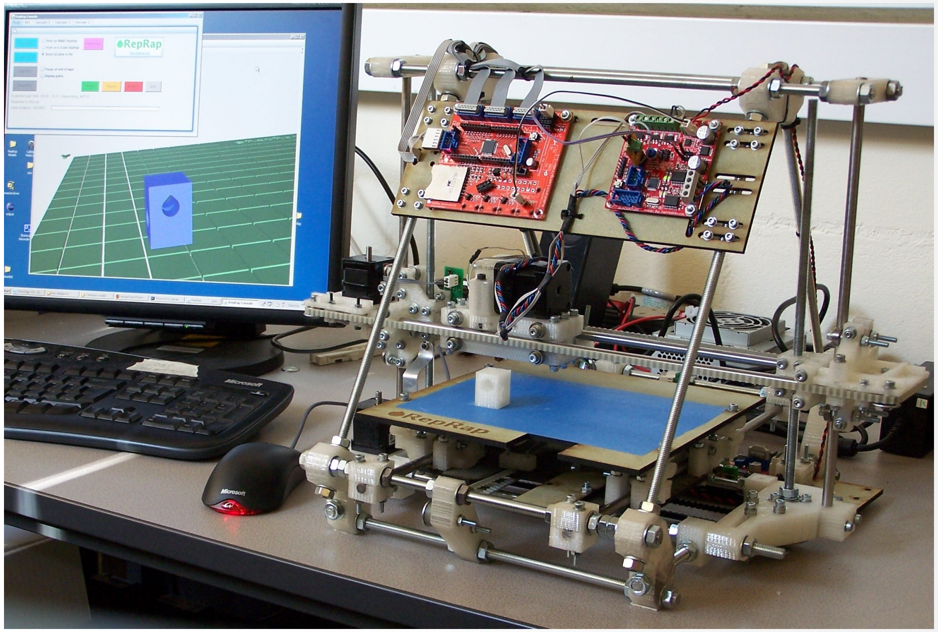


Image courtesy of: www.reprap.org

Introduction

- Research goal
- Viscous extrusion - plunger based
- Manufacturing robots
- G-code → V+
- Eventually transfer to 6 DOF robot

Images courtesy of: www.adept.com

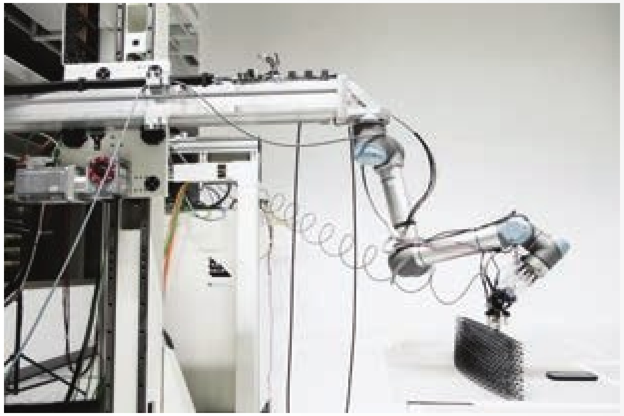
Introduction

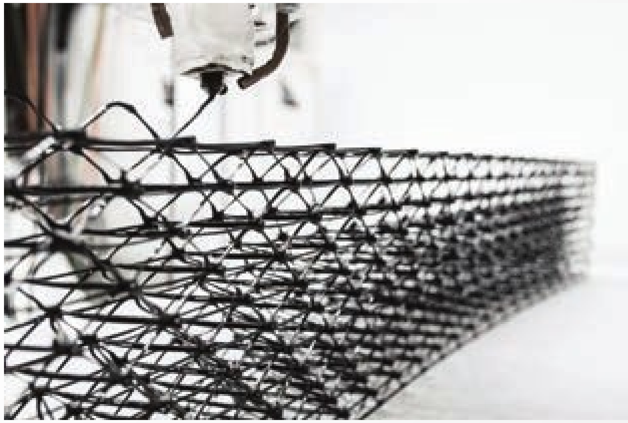
- Stepper motor
- Linear actuator
- Captive nut
- Actuate plunger
- Arduino controlled

Image courtesy of: www.haydonkerk.com

Literature Survey

- ETH Zurich, 2013
  - Robotic construction
  - Articulated robot
  - Large scale: High rise buildings
  - Concrete formwork
  - Polymer reinforcement
  - Reference: [2]





Literature Survey

- Loughborough University, UK, 2012
  - Automated concrete extrudion
  - Cartesian robot
  - 9-20 mm nozzle diameter
  - 6-25 mm layer height
  - Reference: [6]

Literature Survey

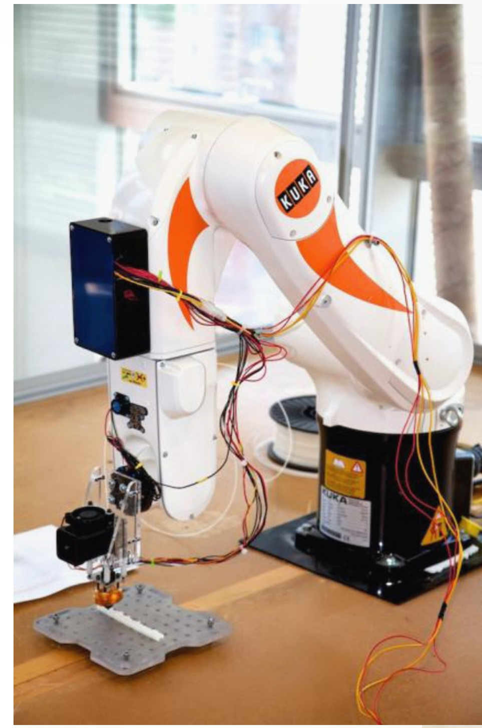
- Robotic assembly
- ABB robot unit
- Mobile platform
- Construction sites
- Pick-and-place is the preliminary step to extrusion
- Reference: [3]

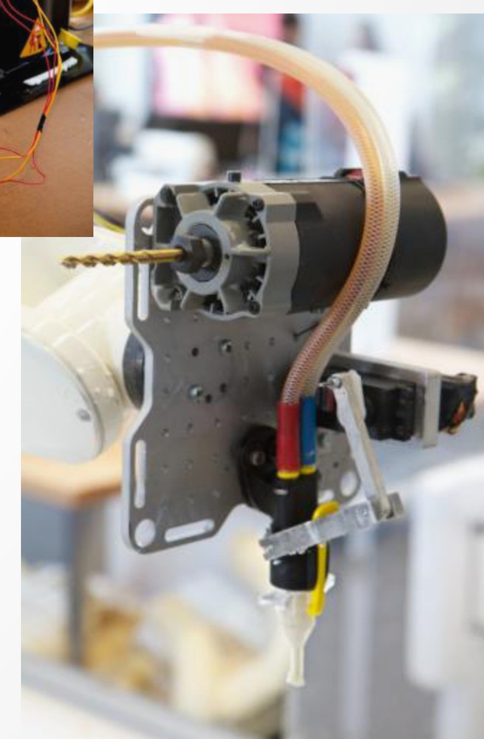
Literature Survey

- Automotive industry
- Adhesive bonding
- Articulated robot
- Aston Martin DB9
- Kawasaki ZX130L
- Reference: [7]

Literature Survey

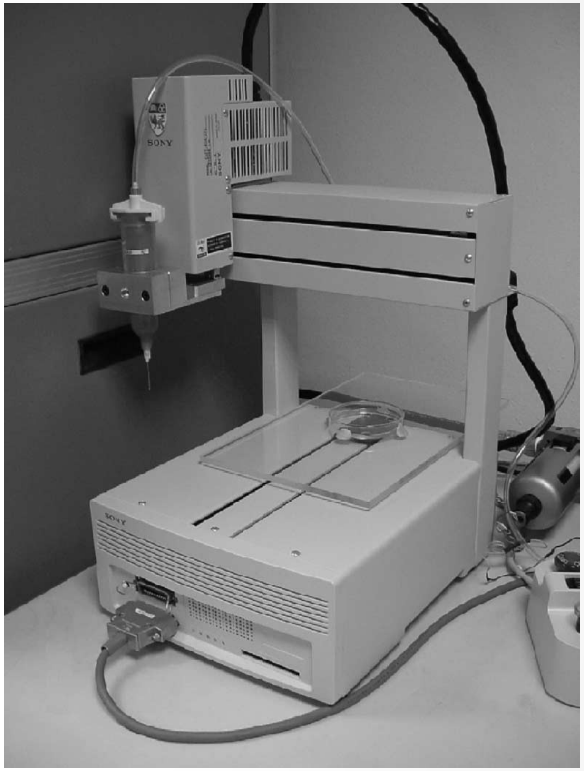
- Massachusetts Institute of Technology, 2013
  - KUKA 6 DOF articulated robot
  - QCD modules for additive, subtractive, and formative methods
  - Integrate 3-D printing, milling and sculpting
  - Reference: [5]

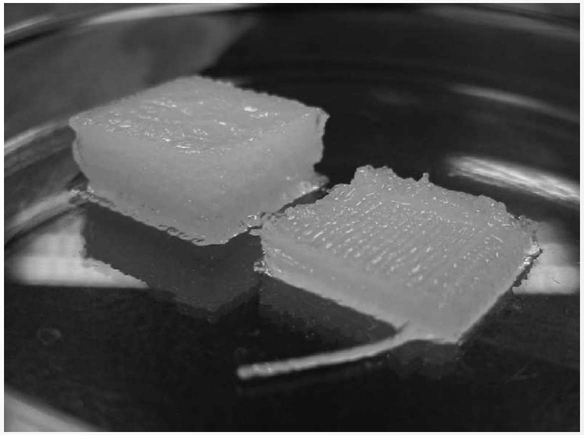




Literature Survey

- National University of Singapore, 2002
  - Hydroxyapatite Scaffolds
  - Pneumatic Dispenser
  - Scaffold Biocompatibility
  - Reference: [1]





Literature Survey

- Dankook University, South Korea, 2009
- Bone Tissue Engineering
- 3-D porous scaffold
- Polycaprolactone (PCL) and hydroxyapatite (HA) solution
- Biocompatible gel
- Cell seeding
- Cartesian robot
- Nozzle diameter: 0.520 mm
- Reference: [4]

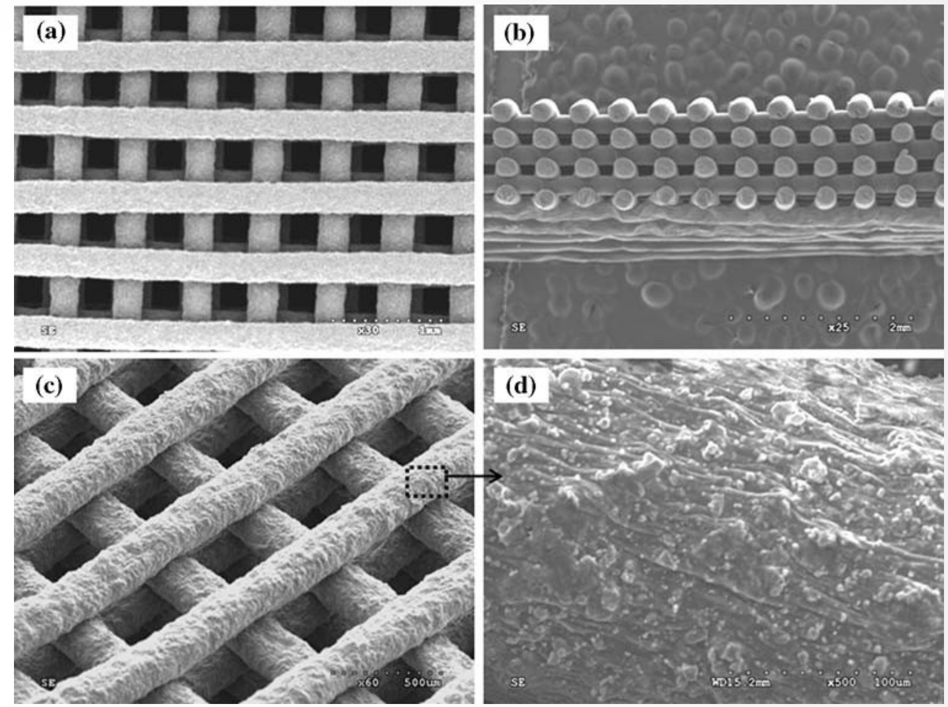
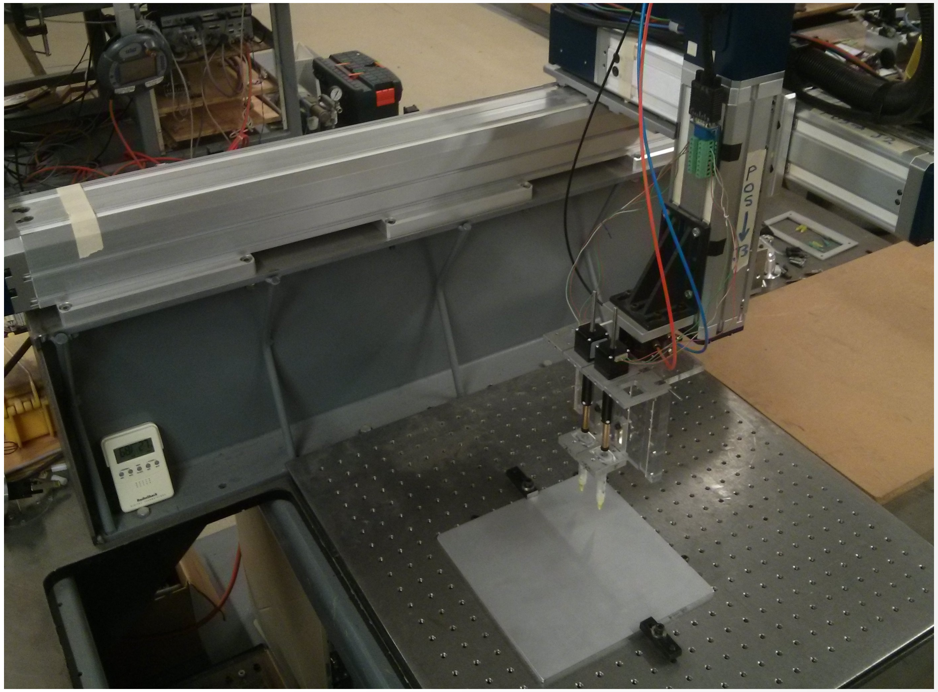


Fig. 2 SEM images of the robotic dispensed HA–PCL bone scaffolds: **a** *xy*-plane horizontal view and **b** *z*-axis vertical view. **c** tilted view of **a**, showing well-developed straight fibers and open-channeled pores. **d** microstructure of the fiber stem in **c**, revealing the hydroxyapatite particles distributed in the PCL matrix

Hardware Tools

- Adept Python
  - Repeatability
  - Large workspace
  - Uses SmartController (unlike iCobra 600)
  - Relatively safe environment
  - Language compatibility with other Adept robots



Hardware Tools

- SmartController CX
  - Digital I/O interface
  - (states!)^(channels)
  - 2!^8 = 256
  - Voltage output
  - Ethernet communication
  - Trivial File Transfer Protocol (TFTP) server

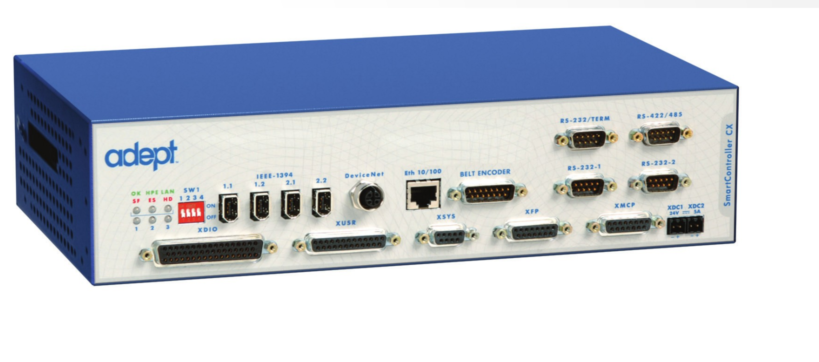
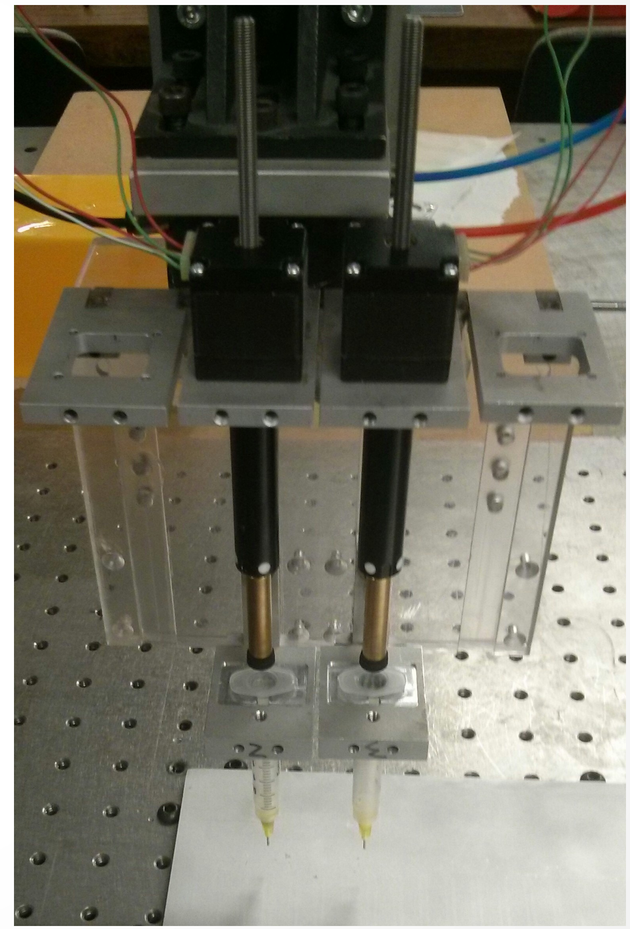


Image courtesy of: www.adept.com

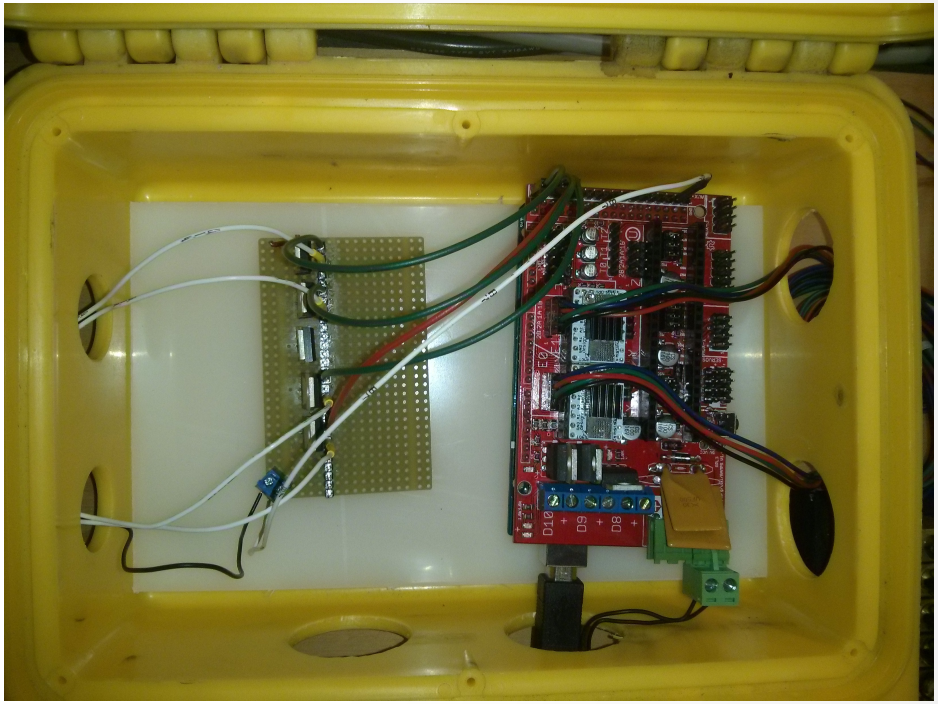
Hardware Tools

- Linear stepper actuators
- Actuate plunger to extrude material
- Resolution: 0.000125 in/step
- Max thrust: 25 lbs



Hardware Tools

- Arduino Mega
- AccelStepper library
- Arduino input pins: 5 V
- SmartController output: 0, 24 V
- Voltage regulator: NTE 960
- RAMPS 1.4
- Cooldrv 8825 stepper driver



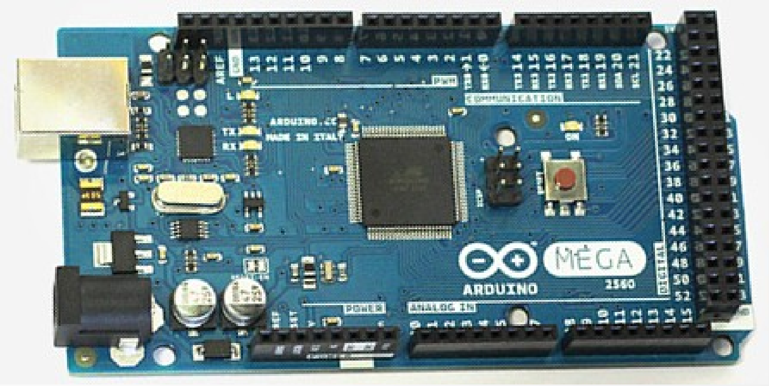
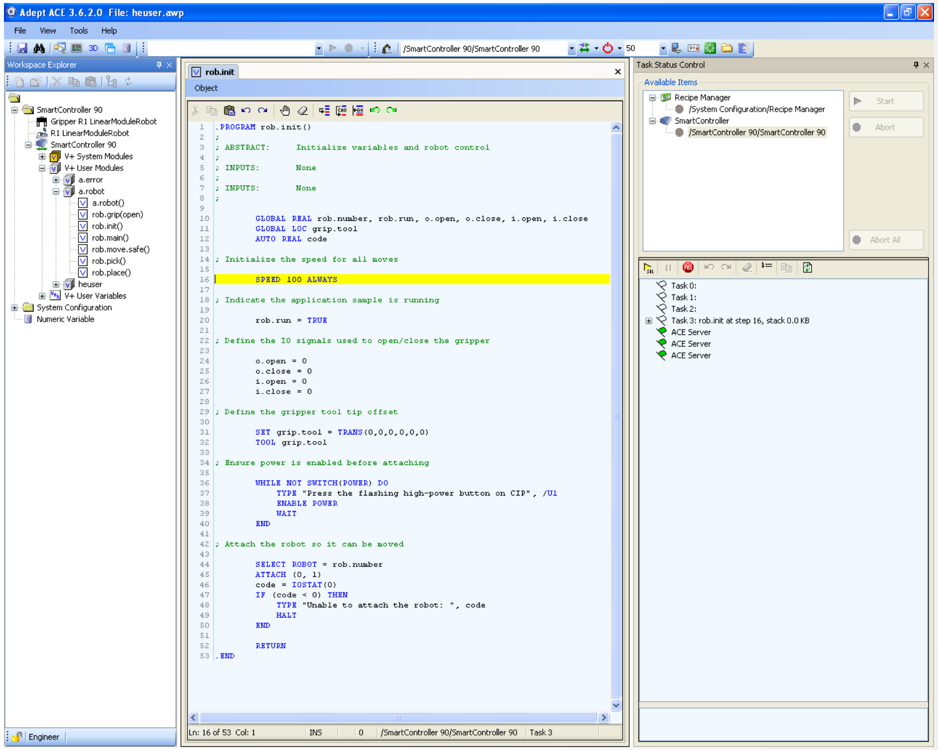


Image courtsey of: www.arduino.cc

Software Tools

- Adept Automated Control Environment (ACE)
  - Left: Workspace explorer
  - Middle: Editor
  - Right: Task status control
- Jog control
- Digital I/O control



Software Tools

- Trivial File Transfer Protocol (TFTP)
  - Client software provided by Adept
  - Large G-code files
  - Even larger V+ files
  - Empire State Building model
    - Slic3r generated G-code: 1562 lines
    - V+ file: 6108 lines
    - Copy-and-paste method: 25min

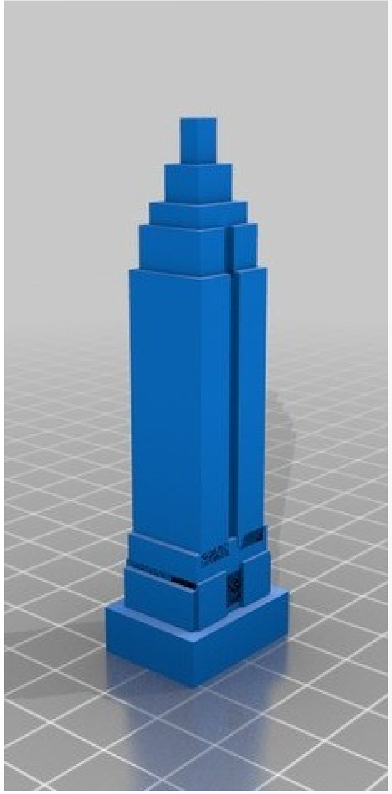
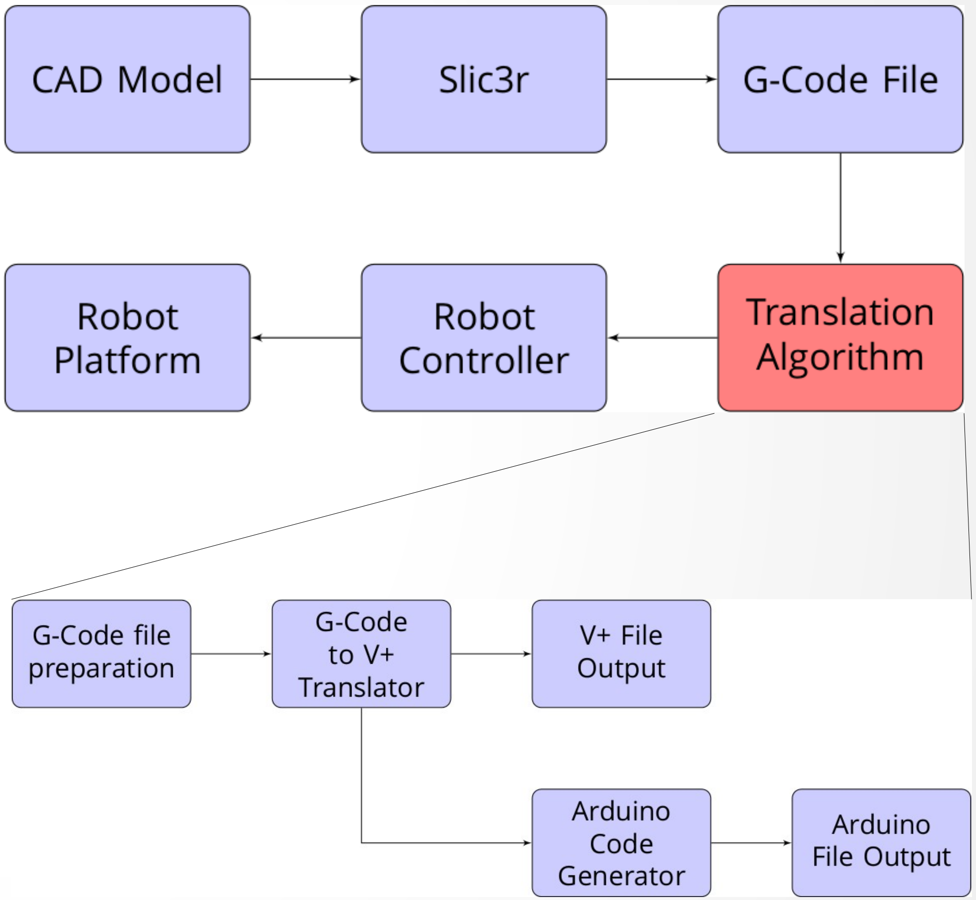


Image courtesy of: www.thingiverse.com

Overall Methodology

- Translation Algorithm
  - Input
    - G-code (with process parameters)
  - Output
    - V+ code for Cartesian motion control
    - Arduino code for extruder control



Algorithm Features

- G-code → V+, Arduino
- Support for multiple extruders
- Position offset
- Workspace limit warning
- Signals limit warning

User defined parameters

- G-code file directory path
- Position offset
- Nozzle diameter
- Syringe diameter
- Home position (G28)
- Workspace limits
- Arduino input pins used
- Arduino pins used for motors
- Maximum number of controller signals
- Maximum stepper speed
- Maximum robot speed (G28)

Algorithm Supported G-code Commands

- G1 Xnnn Ynnn Znnn Ennn Fnnn
- G4 Pnnn Snnn
- G28 X Y Z
- G92 Xnnn Ynnn Znnn Ennn
- Tnnn
- Unknown = error

Volume Extrusion

- Extrusion command
  - Speed
  - Distance
- Digital I/O: time based
  - Unit conversion
  - Volume conservation

$$speed_{plunger} = speed_{nozzle} \times \frac{radius^2_{nozzle}}{radius^2_{syringe}}$$

$$\frac{steps}{second} = \frac{millimeters}{second} \times \frac{inches}{millimeter} \times \frac{steps}{inch}$$

Sample G-code Translation

- G-code → V+, Arduino
- G-code is parsed twice, first to find all speeds

G-code

```
G1 X600 Y150 Z-60 E0.1 F600.000
```

V+

```
.PROGRAM example();
        SPEED 10.0 MMPS ALWAYS
        WAIT STATE(2) == 2
        SIGNAL 1
        MOVE TRANS(600.0,150.0,-60.0,0,180,0)
        WAIT STATE(2) == 2
        SIGNAL -1
.END
```

Arduino

```
#include <AccelStepper.h>

#define D1_SIGNAL_PIN      16

#define E0_STEP_PIN        26
#define E0_DIR_PIN         28
#define E0_ENABLE_PIN      24

AccelStepper E0(AccelStepper::DRIVER, E0_STEP_PIN, E0_DIR_PIN);

void setup()
{
  Serial.begin(9600);

  pinMode(D1_SIGNAL_PIN, INPUT);    // Speed Pin

  pinMode(E0_STEP_PIN, OUTPUT);
  pinMode(E0_DIR_PIN, OUTPUT);
  pinMode(E0_ENABLE_PIN, OUTPUT);

  digitalWrite(E0_ENABLE_PIN, LOW);

  E0.setMaxSpeed(1000);

}

void loop()
{
  int IN0 = digitalRead(D1_SIGNAL_PIN);

  if (IN0 == LOW) {
    // motor does not move
  }
  else if (IN0 == HIGH) {    // Extruder 0, Speed 1
    E0.setSpeed(8.51653543307);
    E0.runSpeed();
  }
}
```

Sample G-code

```
G92 E0
G1 Z0.468 F60000.000
G1 X604.290 Y159.375 F60000.000
G1 X595.710 Y159.375 E0.03587 F600.000
G1 X595.710 Y159.943 E0.03824
G1 X604.290 Y159.943 E0.07411
G1 X604.290 Y160.511 E0.07648
G1 X595.710 Y160.511 E0.11235
G1 X595.710 Y161.079 E0.11473
G1 X604.290 Y161.079 E0.15059
G1 X604.290 Y161.648 E0.15297
G1 X595.710 Y161.648 E0.18883
G1 X595.710 Y162.216 E0.19121
G1 X604.290 Y162.216 E0.22708
G1 X604.290 Y162.784 E0.22945
G1 X595.710 Y162.784 E0.26532
G1 X595.710 Y163.352 E0.26769
G1 X604.290 Y163.352 E0.30356
G1 X604.290 Y163.921 E0.30593
G1 X595.710 Y163.921 E0.34180
G1 X595.710 Y164.489 E0.34418
G1 X604.290 Y164.489 E0.38004
G1 X604.290 Y165.057 E0.38242
```

Sample V+ Output

G-code

```
G1 X600 Y150 Z-60 E0.1 F600.000
```

V+

```
.PROGRAM example();
        SPEED 10.0 MMPS ALWAYS
        WAIT STATE(2) == 2
        SIGNAL 1
        MOVE TRANS(600.0,150.0,-60.0,0,180,0)
        WAIT STATE(2) == 2
        SIGNAL -1
.END
```

Sample Arduino Output

G-code

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G1 X600 Y150 Z-60 E0.1 F600.000
```

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#include <AccelStepper.h>

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  }
}
```
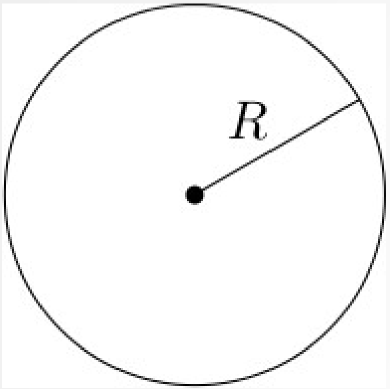
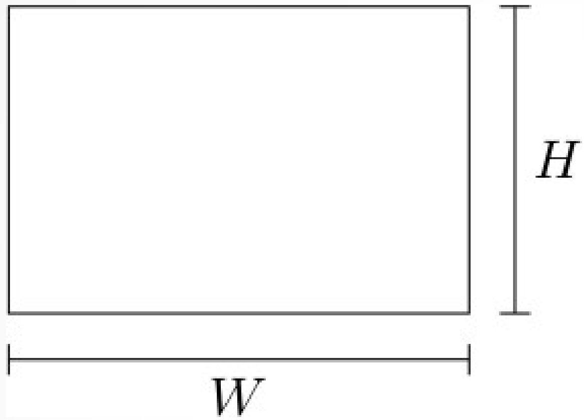
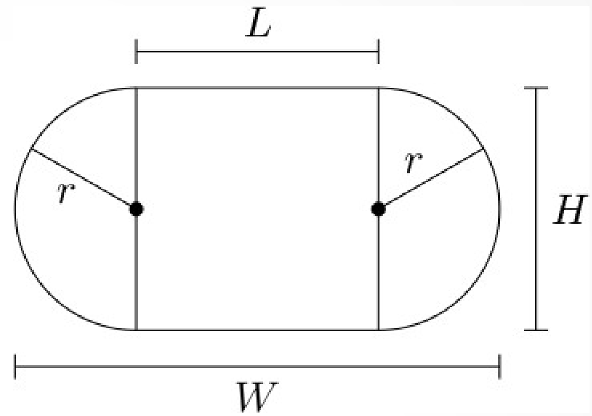

Strand Width Approximation







$$A_0 = \pi R^2$$

h = layer height

$$H = 2Rh$$

$$A_1 = WH$$

$$W = \frac{A_1}{H}$$

$$A_1 = A_0$$

$$W = \frac{A_0}{H} = \frac{\pi}{2h} R$$

$$W = L + 2r$$

$$A_2 = LH + \pi r^2$$

$$L = \frac{A_2 - \pi r^2}{H}$$

$$W = \frac{A_2 - \pi r^2}{H} + H$$

$$r = \frac{H}{2}$$

$$W = \frac{A_2 - \pi (\frac{H}{2})^2}{H} + H = \frac{4A_2 - \pi H^2}{4H} + H$$

$$H = 2Rh$$

$$W = \frac{4A_2 - \pi (2Rh)^2}{4(2Rh)} + 2Rh = \frac{A_2 - \pi R^2 h^2}{2Rh} + 2Rh$$

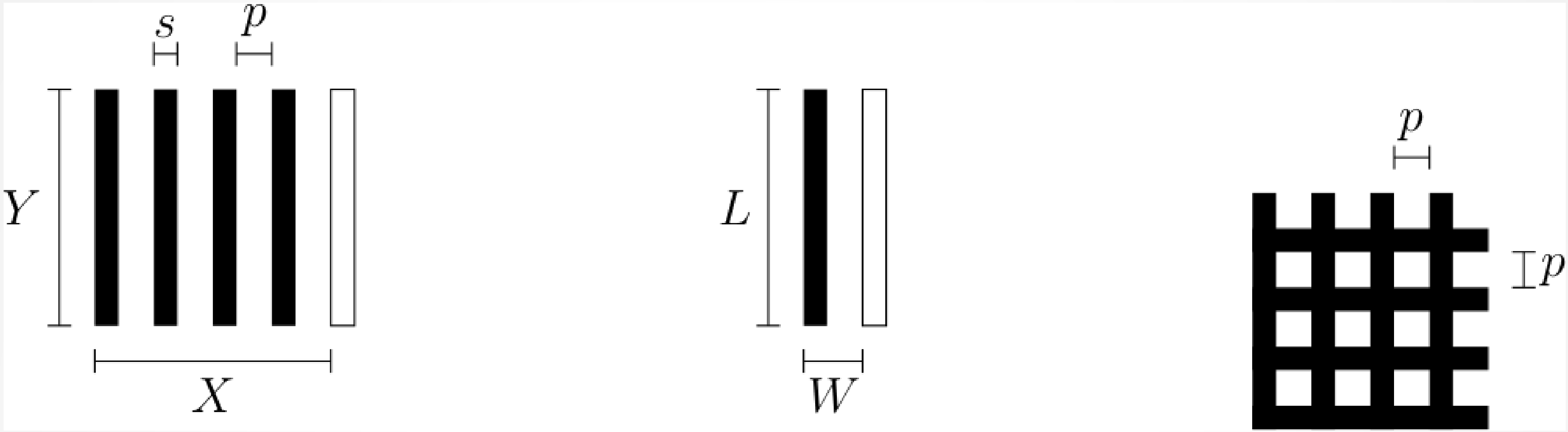
$$A_2 = A_0$$

$$W = \frac{A_0 - \pi R^2 h^2}{2Rh} + 2Rh$$

$$A_0 = \pi R^2$$

$$W = \frac{\pi R^2 - \pi R^2 h^2}{2Rh} + 2Rh = \frac{\pi R - \pi R h^2}{2h} + 2Rh = \left(\frac{\pi - \pi h^2}{2h} + 2h\right) R$$

Scaffold Pore Size Calculation



$$\text{infill density (D)} = \frac{Area_{strands}}{Area_{total}}$$

$$= \frac{sL}{LW}$$

$$= \frac{s}{W}$$

$$W = s + p$$

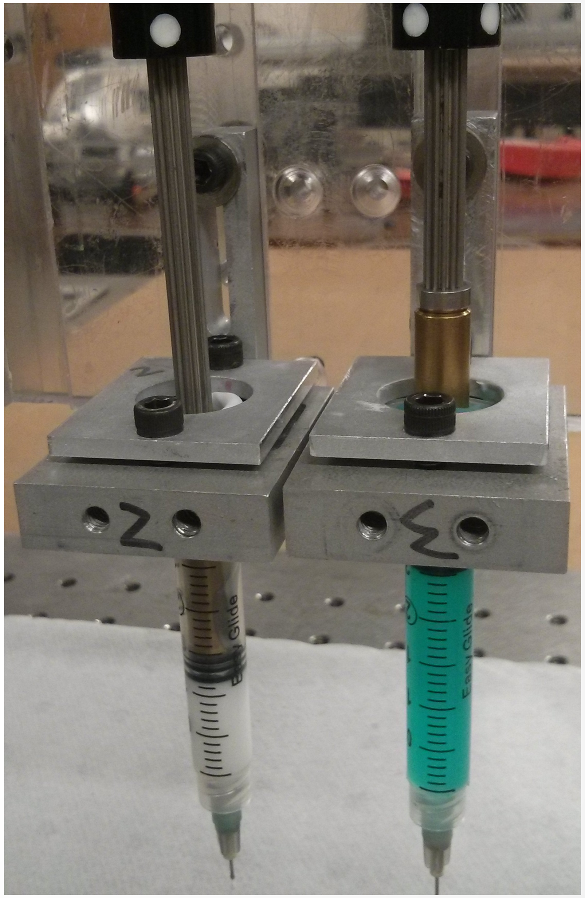
$$s = W - p$$

$$D = \frac{W - p}{W}$$

$$= \frac{s}{s + p}$$

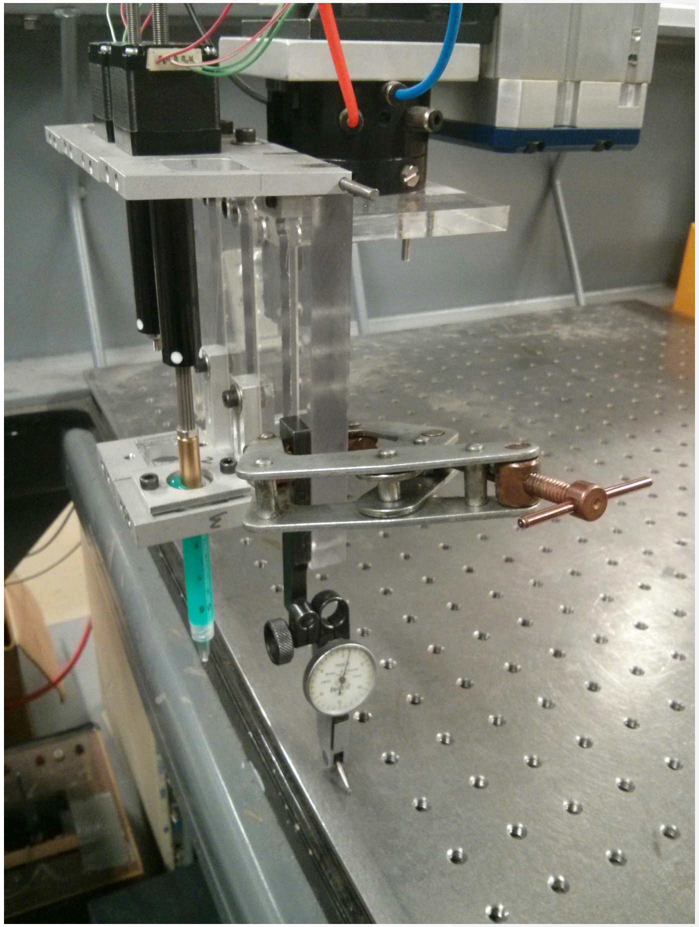
Preparation

- Remove syringe
- Manually fill material
- Replace syringe
- Advance plunger past syringe lip
- Identify Z-0 position



Challenges

- Bed Leveling
  - Machinists level
  - Dial gauge
  - 0.003 in

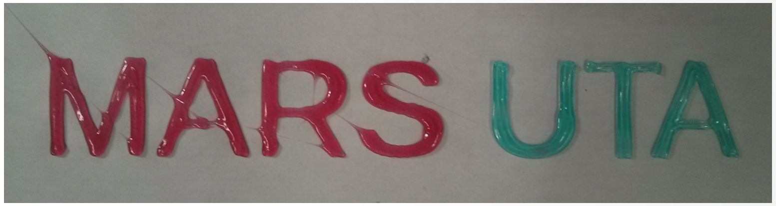


Challenges

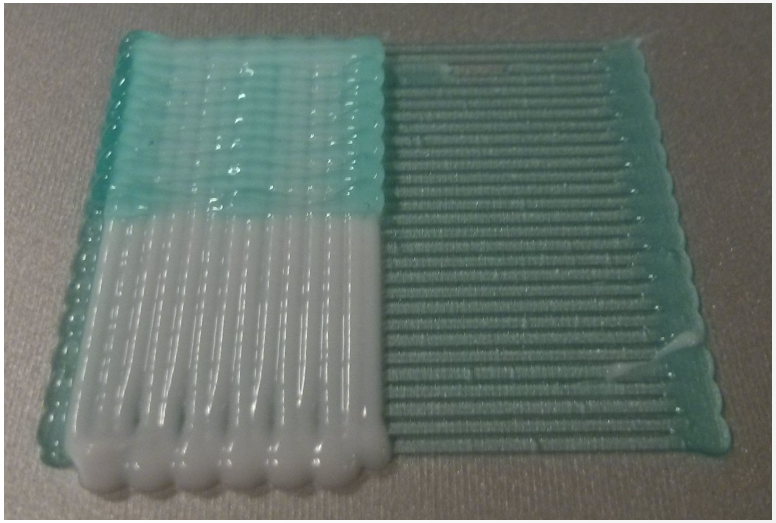
- Adhesion to bed
- Surface material
  - Paper
  - Polymer
  - Teflon
  - Brushed aluminum
  - Sandblasted Aluminum

Challenges

- Toothpaste Variety
  - Aim (green)
  - Pepsodent (white)
  - Close-Up (red)
    - Air pockets



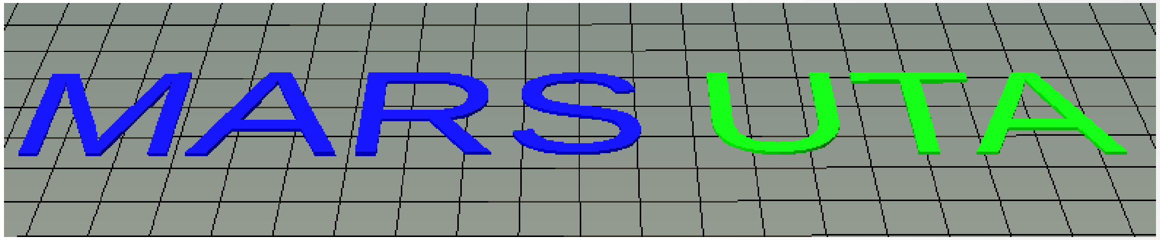
Scale: Letter height = 3 cm

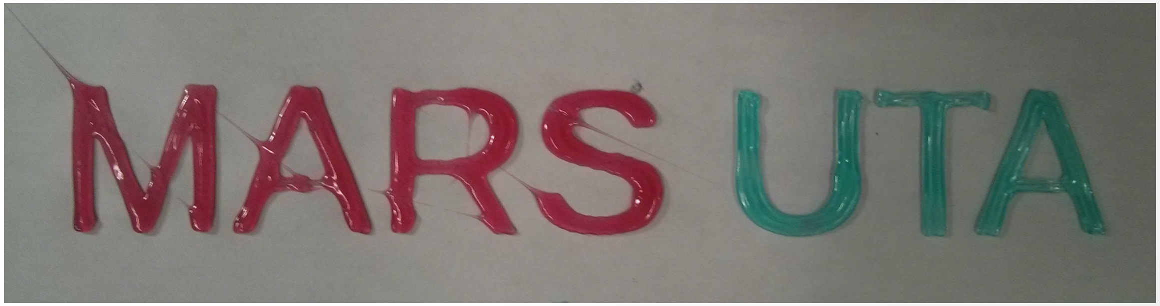


Scale: length and width = 3 cm

Methodology Verification

- Multiple extruder demonstration
  - CAD model
  - 100% infill density
  - Streaking





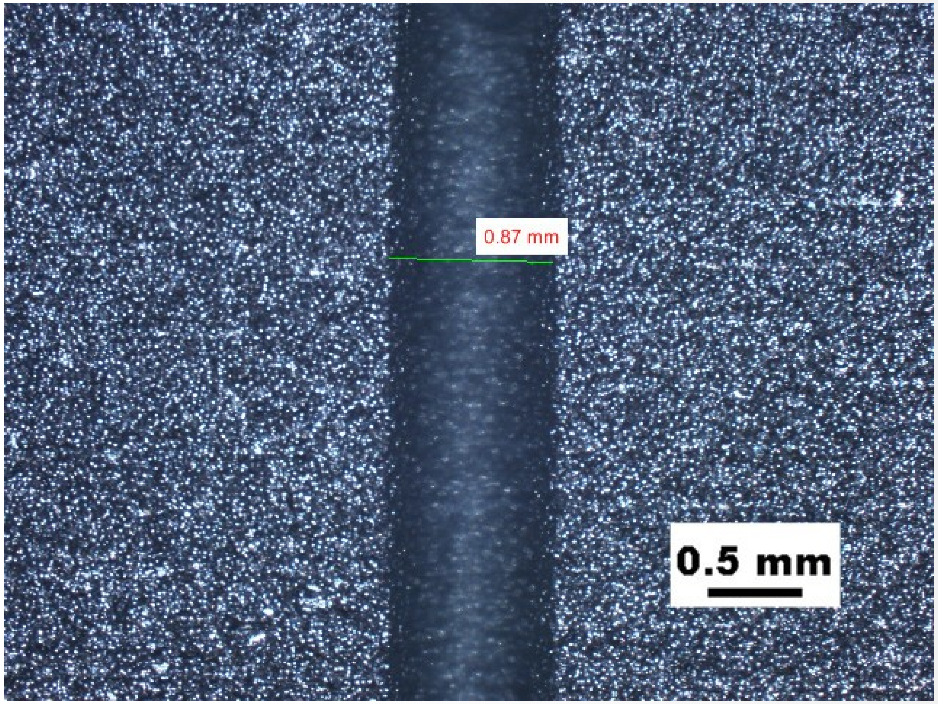
Scale: Letter height = 3 cm

Strand Width Experiments

- Factors:
  - Nozzle Diameter
    - 0.468 mm
    - 0.566 mm
    - 0.650 mm
  - Speed
    - 8 mmps
    - 10 mmps
    - 12 mmps
- 3^2 = 9 (full factorial)
- 9x3 = 27 (3 replications)
- Surface material: sandblasted aluminum plate

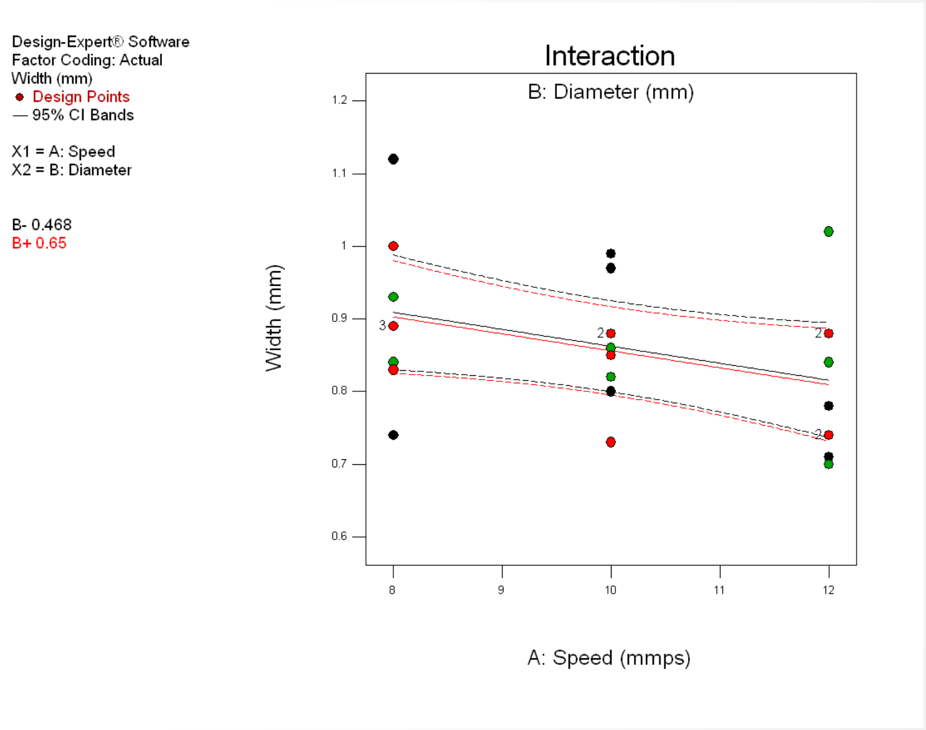
Strand Width Experiments

- Microscope image measurement
- 2.5x magnification lens



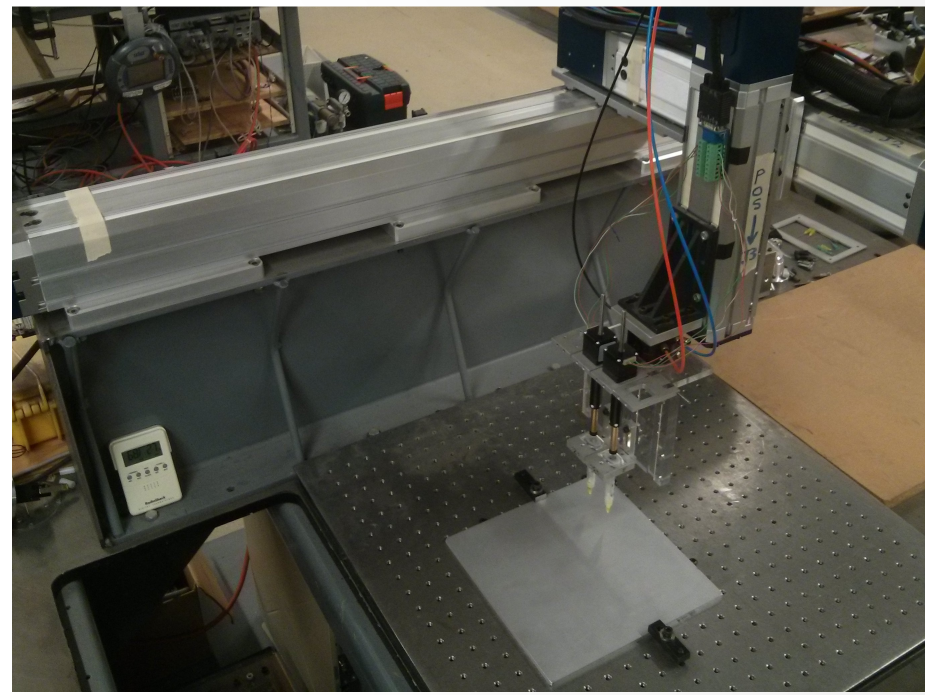
Strand Width Experiments

- Design Expert software
- Interaction plot
- Parallel lines = similar behavior
- Analysis of variance (ANOVA) indicates data not significant



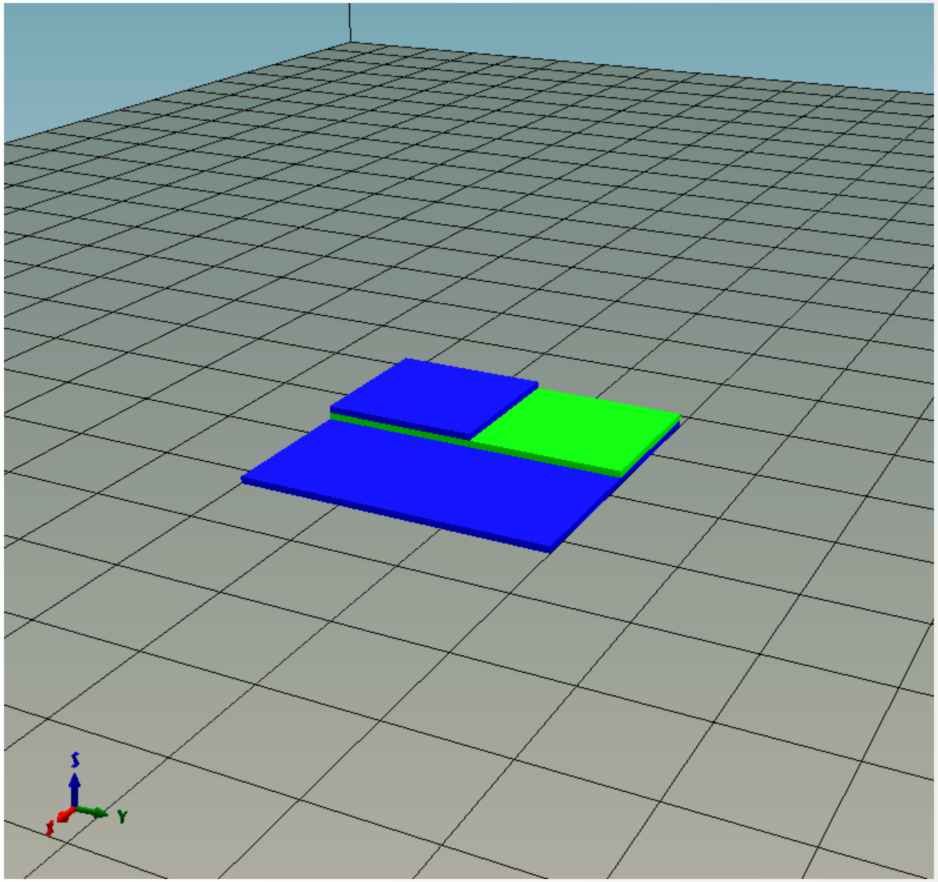
Strand Width Experiments

- Possible sources of error
  - Bed leveling
    - 3 thousandths ~ 75 μm
  - Surface flatness
    - Removable clamps



Scaffold Model

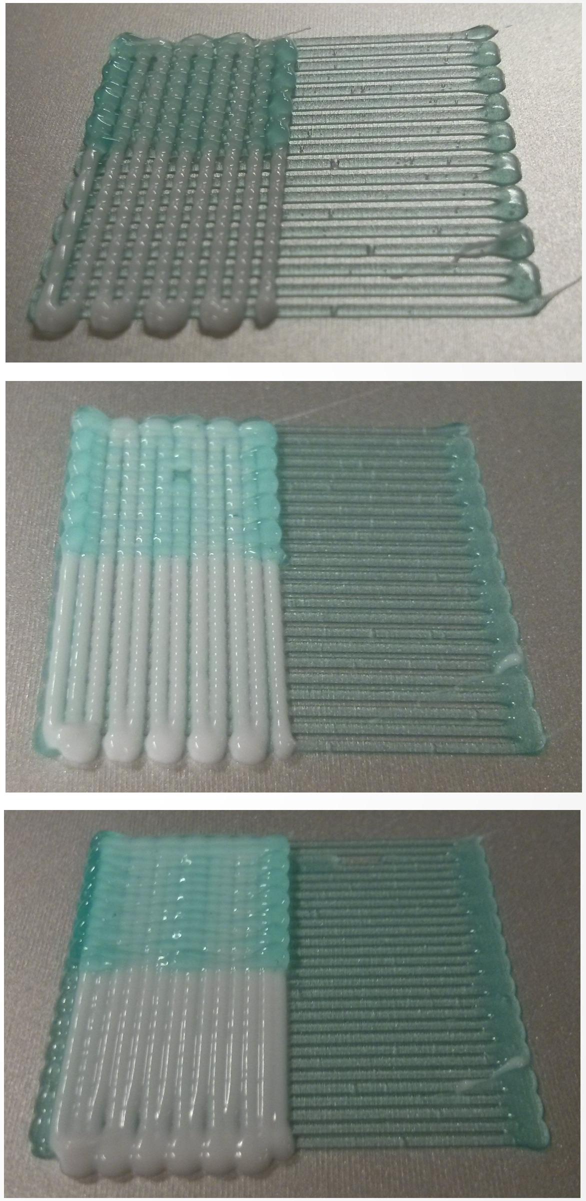
- CAD model
- G-code generated by slic3r
- V+ generated by algorithm
- Varied Parameters:
  - Nozzle diameter
  - Infill density
  - Layer height



Scale: length and width = 3 cm

Infill Density Demonstration

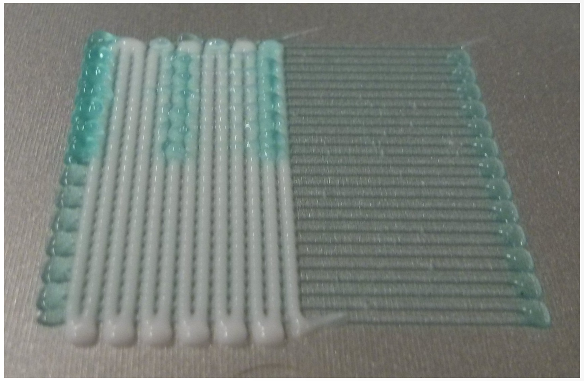
- Nozzle diameter: 0.650mm
- Infill densities
  - 30%
  - 40%
  - 50%

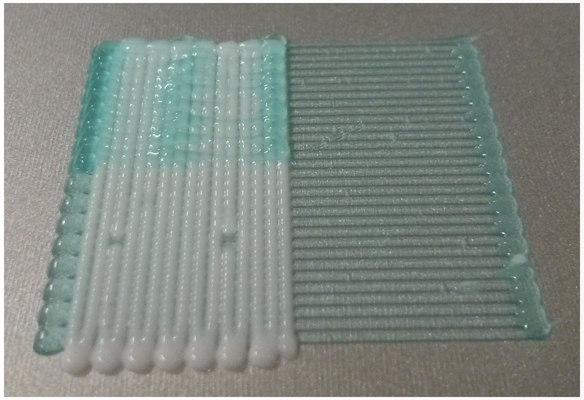


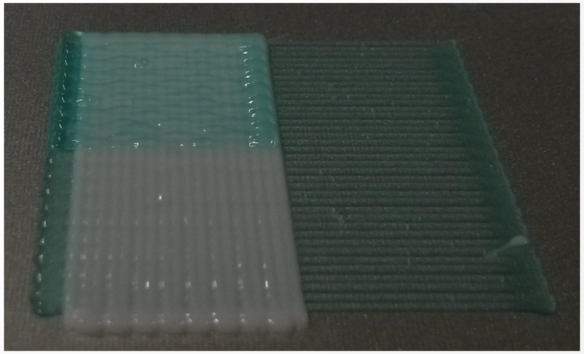
Scale: length and width = 3 cm

Infill Density Demonstration

- Nozzle diameter: 0.468mm
- Infill densities:
  - 50%
  - 60%
  - 70%
- Over-extrusion at corners
  - Syringe pressure
  - Robot acceleration and deceleration



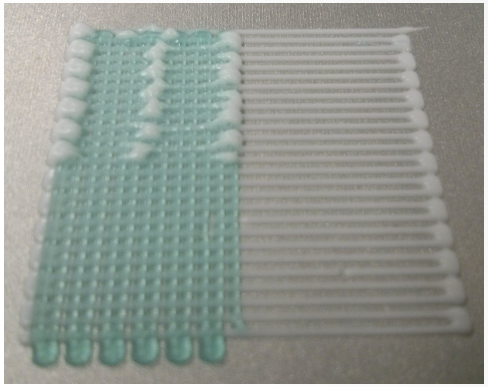


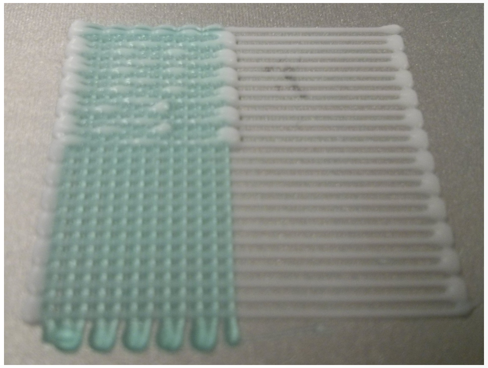


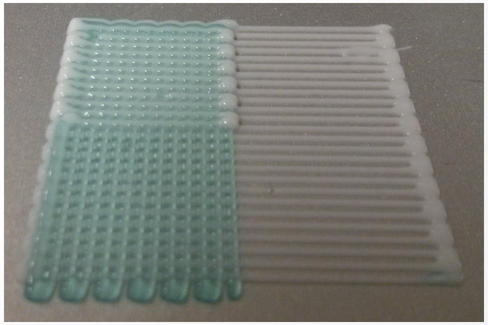
Scale: length and width = 3 cm

Layer Height Demonstration

- Nozzle diameter: 0.468 mm
- Infill density: 50%
- Layer heights:
  - 100%
  - 90%
  - 80%







Scale: length and width = 3 cm

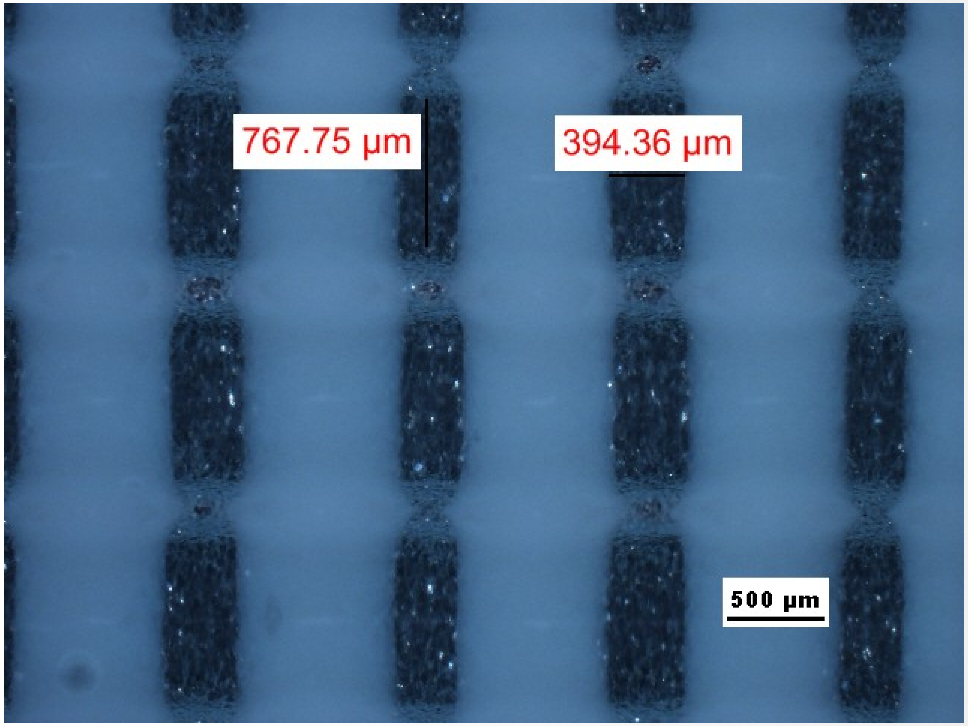
Scaffold

Video

Pore Size Measurements

- Nozzle diameter: 0.468 mm
- Infill density: 50%
- Layer height: 80%

- Rectangular shape
- Different toothpaste brands
- 1st layer on surface
- 2nd layer on toothpaste



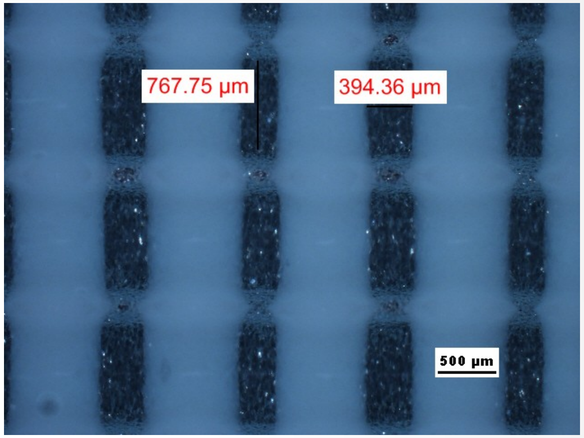
Comparison with Approximation

Rectangular Approximation

$$W = \frac{\pi}{2h}R$$
$$= \frac{\pi}{2 \times 0.8}\frac{0.468mm}{2}$$
$$= 0.459mm$$

Shape Composite Approximation

$$W = \left(\frac{\pi - \pi h^2}{2h} + 2h\right)R$$
$$= \left(\frac{\pi - \pi(0.8)^2}{2 \times 0.8} + 2 \times 0.8\right)\frac{0.468mm}{2}$$
$$= 0.539mm$$



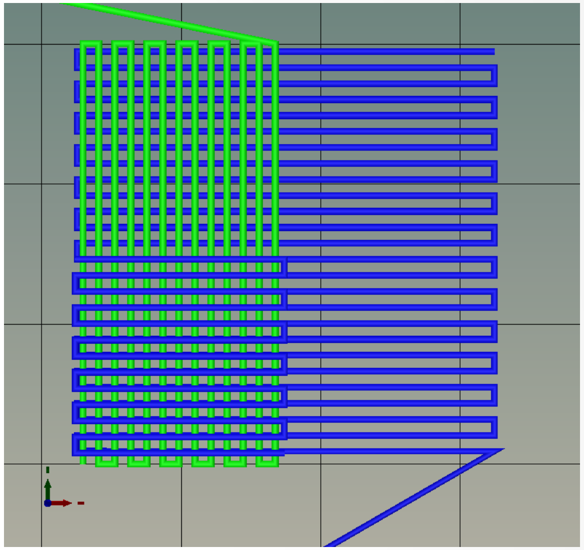
$$D = \frac{s}{s+p}$$
$$p = \frac{s(1-D)}{D}$$
$$p_1 = \frac{(0.459mm)(1-0.5)}{0.5}$$
$$= 0.459$$
$$p_2 = \frac{(0.540mm)(1-0.5)}{0.5}$$
$$= 0.540$$

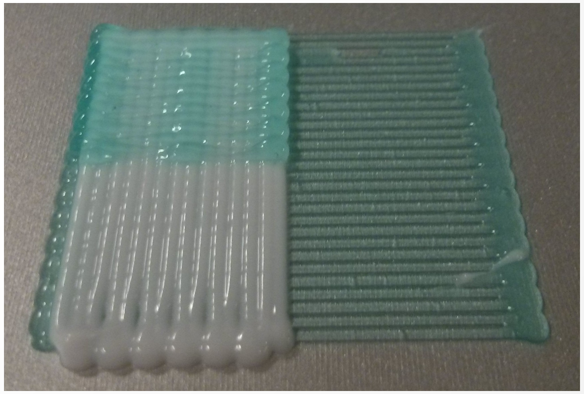
Conclusion

- Translation algorithm
  - Learned G-code, V+, and Arduino languages
  - Coordinate robot motion platform with stepper motor actuation
- Developed voltage regulation circuit
- TFTP – large files
- Demonstrated multiple extruder capabilities
- Process characterization
  - strand width experiment
  - scaffold pore size experiment

Future Work

- Expand functionality to include other 3-D printing modalities
  - Heated extrusion
  - Photopolymerization
- Include support for multiple simultaneous nozzle diameters
- Examine cross section with profilometer
- Investigate plunger retraction to reduce accumulation
  - Anticipate robot acceleration and deceleration
- Investigate additional materials
  - Scaffolds for cell seeding





Scale: length and width = 3 cm

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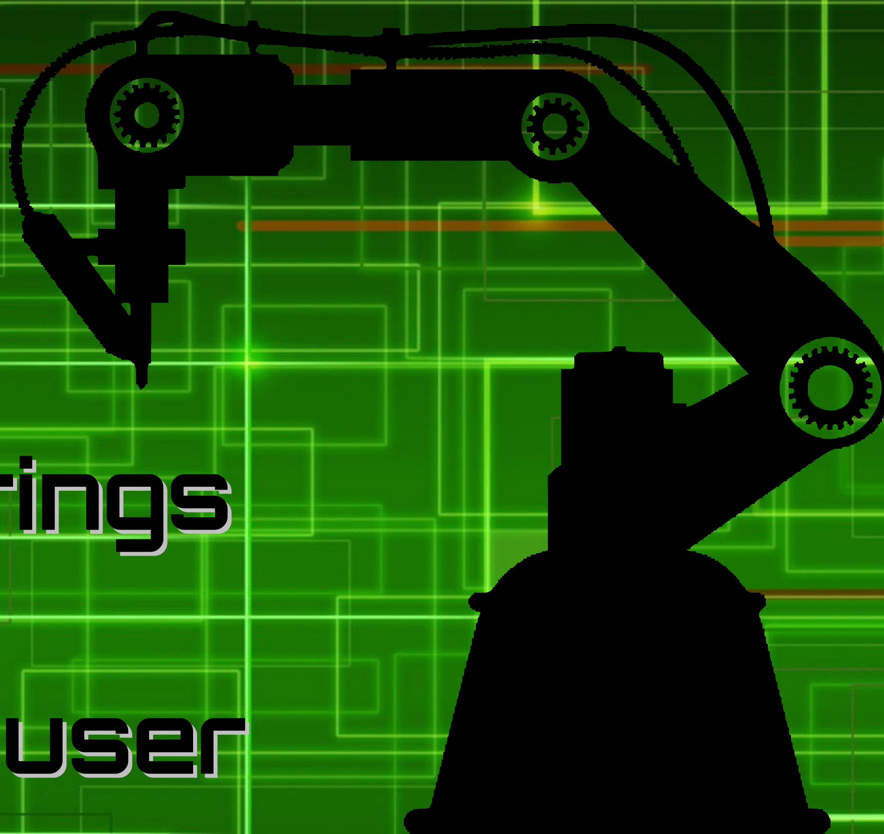

Matt Heuser

Advisor:
Panos Shiakolas, Ph.D