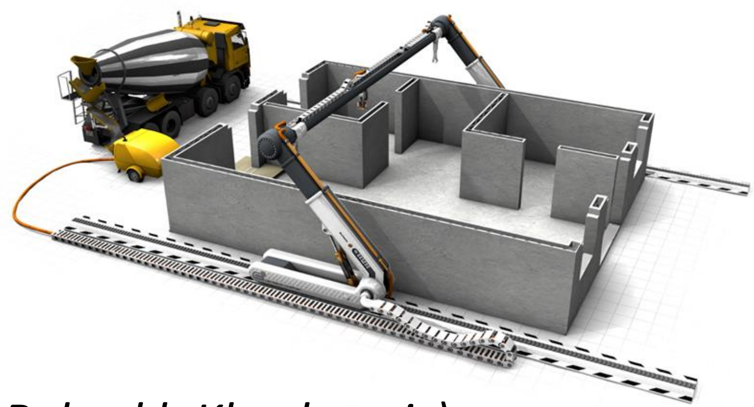
# Performance-based Laboratory Testing of Cementitious Materials for Construction-scale 3D Printing



*Presentation by:*

*Ali Kazemian*

*PhD Candidate at USC (PhD adviser: Dr. Behrokh Khoshnevis)*

*R&D Engineering Intern at Contour Crafting Corporation*

*ACI Concrete Convention and Exposition*

*Concrete and Digital Fabrication*

*October 2017*

# 1. Introduction

# Automation

- Manufacturing
- Aerospace
- Military
- Retail

*Mercedes Benz factory*


*Amazon Robotic Warehouse*

# Automation

- Manufacturing
- Aerospace
- Military
- Retail

**What about "Construction"?**

*Amazon Robotic Warehouse*

# Automation in Construction: Earlier Efforts

- Early efforts were made mostly in Japan (1980s)


*The Obayashi Big-Canopy system*

# Automation in Construction: Recent Advances

- Use of additive manufacturing techniques (layer by layer)

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- Smart dynamic casting (a robotic slip-forming process)


*Smart dynamic casting and mesh mold (ETH Zurich)*

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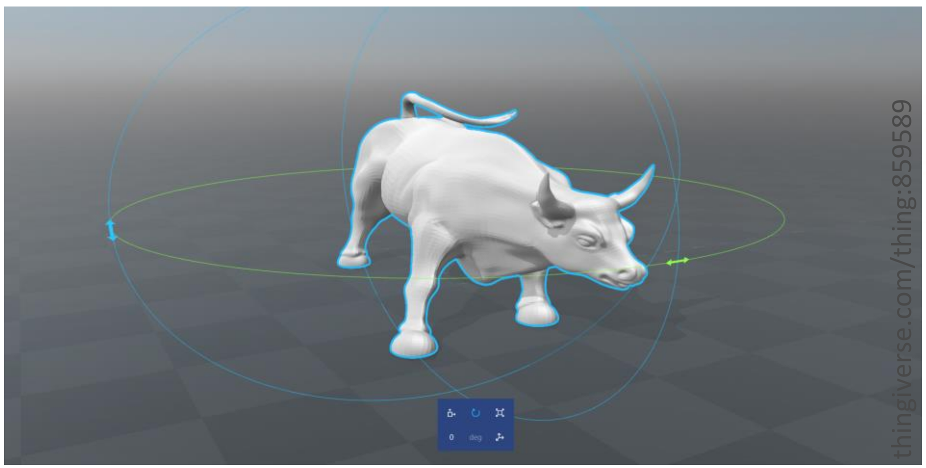
- Use of **additive manufacturing** techniques (layer by layer)
- Smart dynamic casting (a robotic slip-forming process)

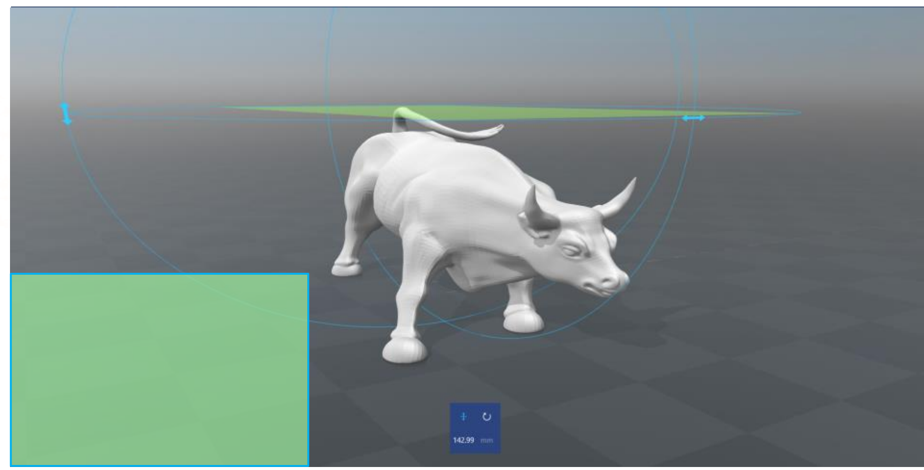



*Smart dynamic casting and mesh mold (ETH Zurich)*

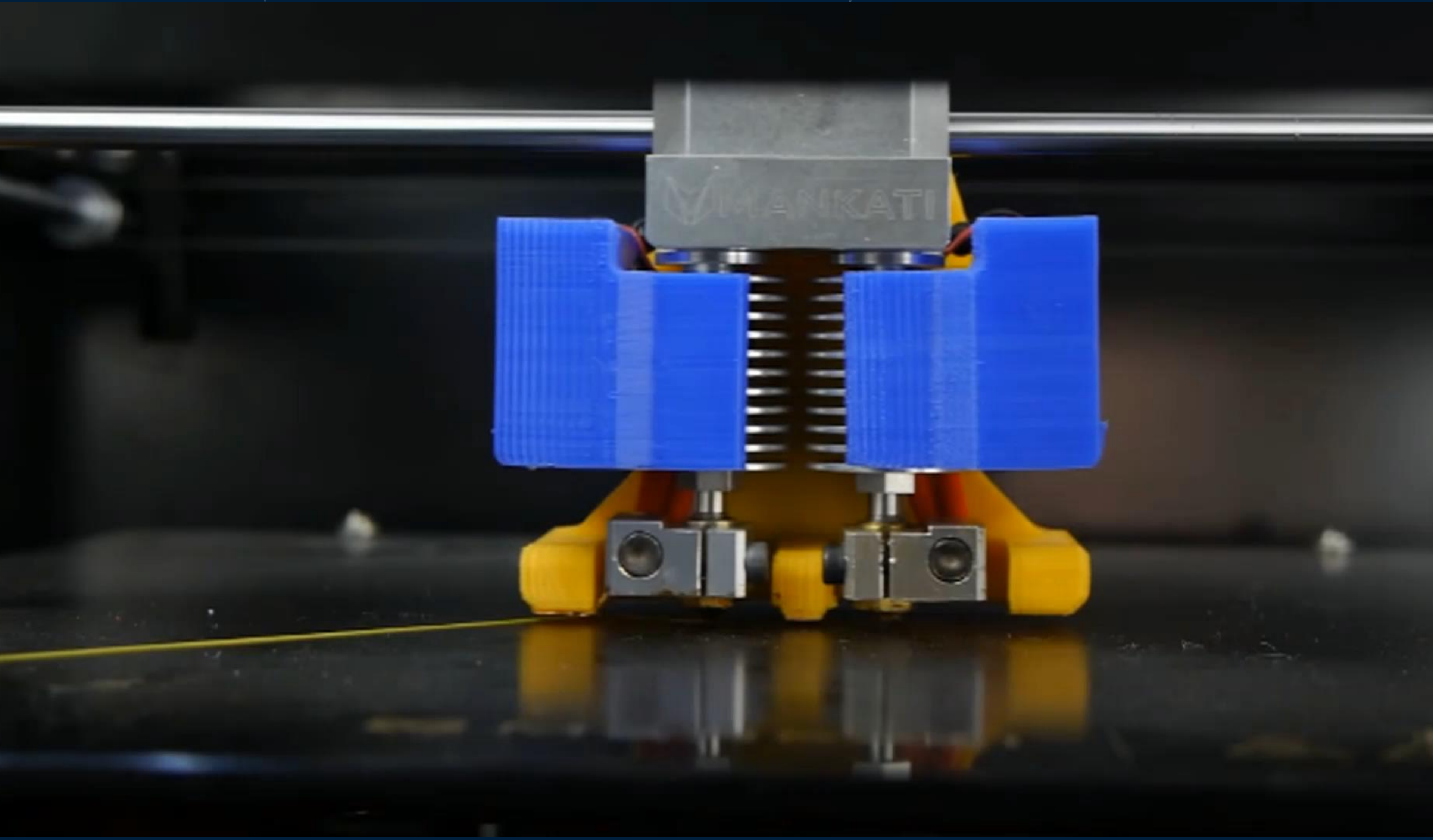
# Additive Manufacturing (3D Printing)

- Principle: Adding 2D layers of material one at a time to build the solid 3D part



Complex 3D Geometry ➔ Simple 2D Shapes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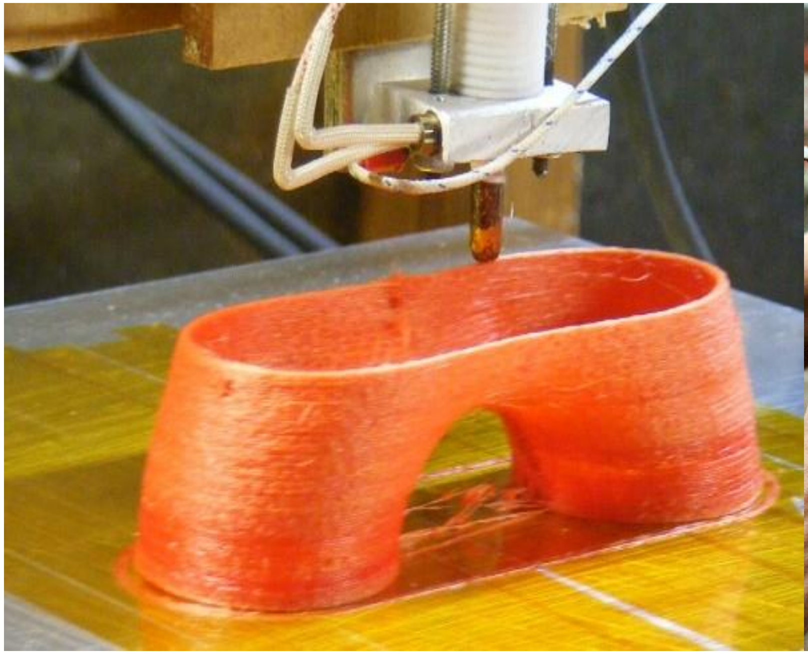
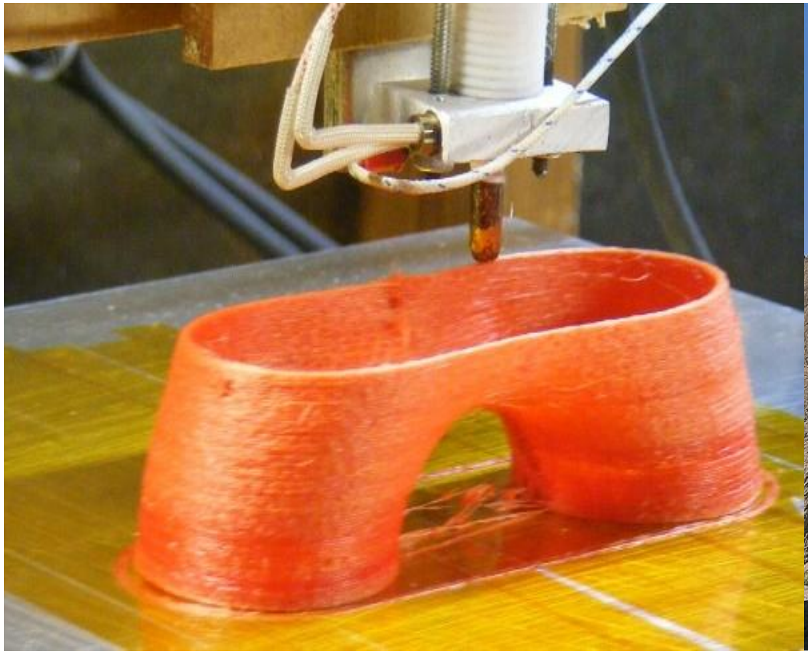
# Additive Manufacturing (3D Printing)

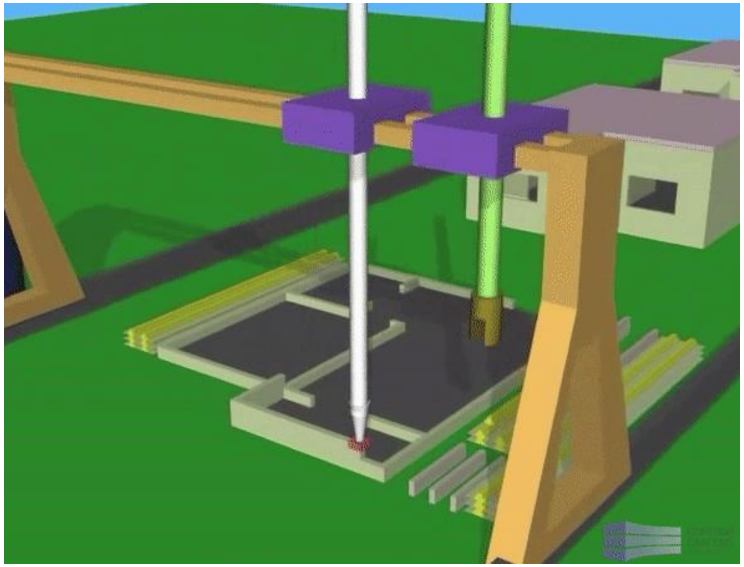


# Additive Manufacturing (3D Printing)



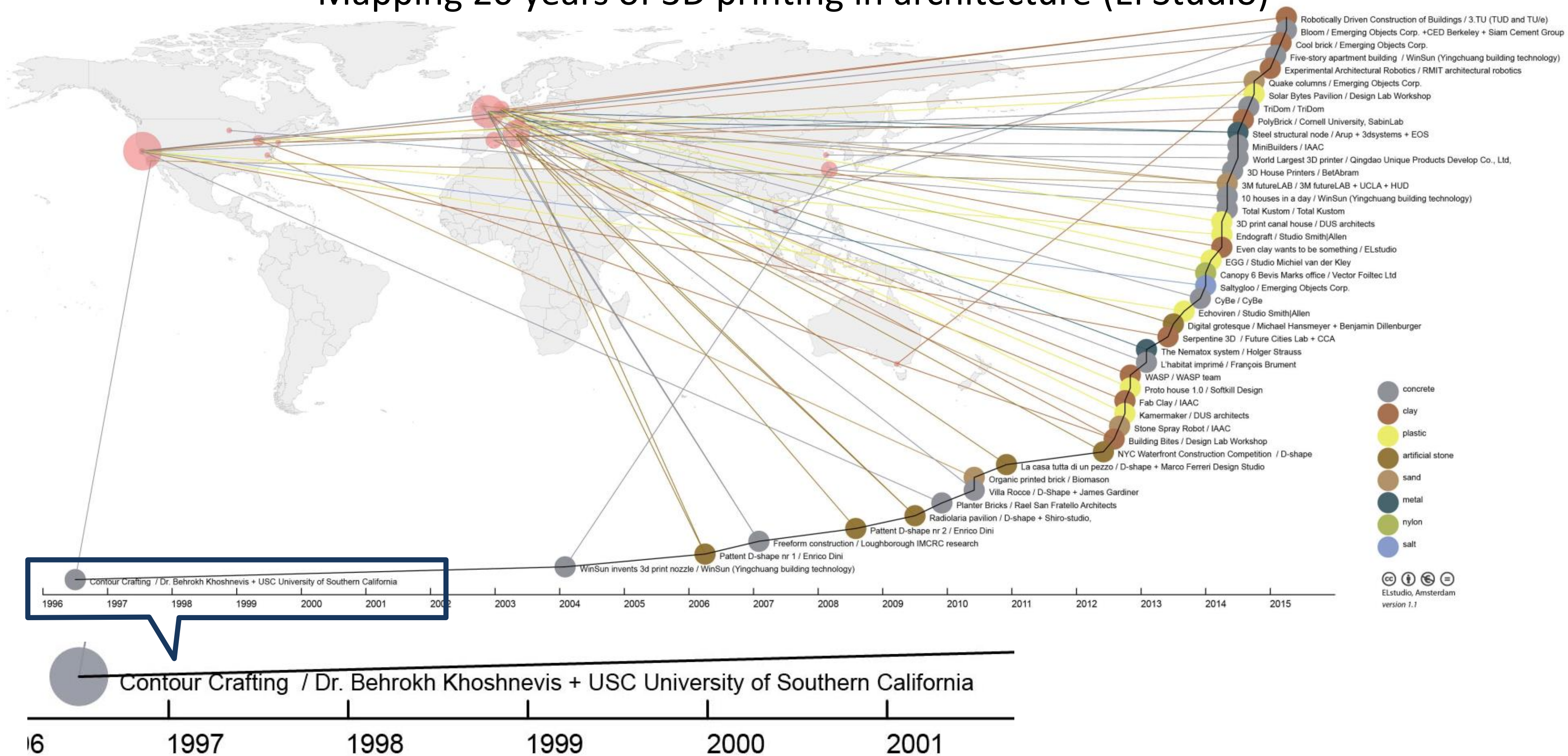
## Automation in Construction

- Realizing an old idea using modern tools
- Layer-based automated building construction
- Contour Crafting, freeform construction, additive construction, construction-scale 3D printing, etc.



# Automation in Construction

Mapping 20 years of 3D printing in architecture (El Studio)



# Automation in Construction

- Advantages:
  - *The possibility to build concrete structures without formwork*

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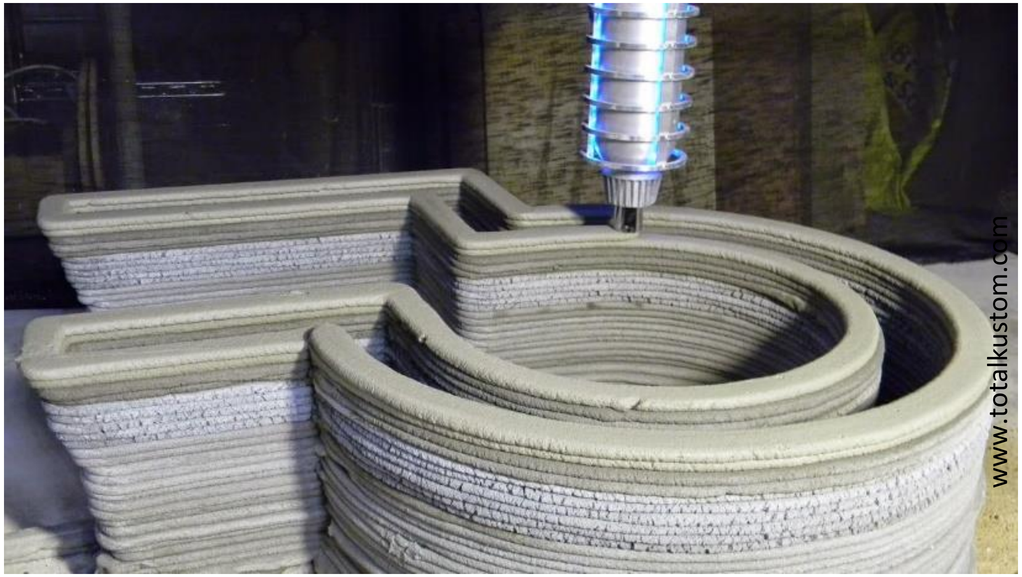


# Automation in Construction

- Advantages:
  - *The possibility to build concrete structures without formwork*
  - *Customization at no additional cost*
  - *High construction speed*
  - *Design freedom*
  - *Minimum waste of materials*

# Contour Crafting (CC)

- CC is an extrusion based layer-wise fabrication technology that builds objects with successive “thick” layers of concrete as it smoothens out external surfaces

# 2. Cementitious Materials for Contour Crafting

# Knowledge Gaps

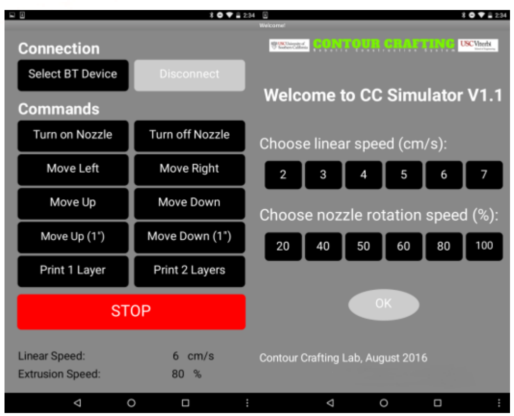
- No procedure has been suggested for mixture design and laboratory testing of printing concrete
- Performance requirements of fresh and hardened printing concrete are not well-defined
- Acceptance criteria for fresh and hardened printing concrete are missing

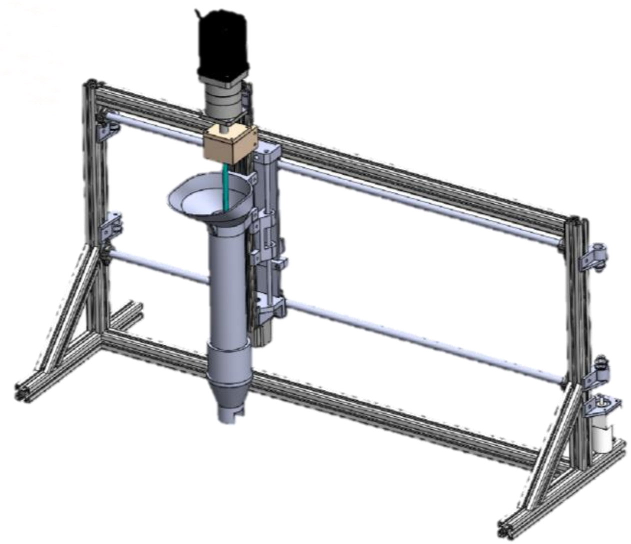
# Research Objectives

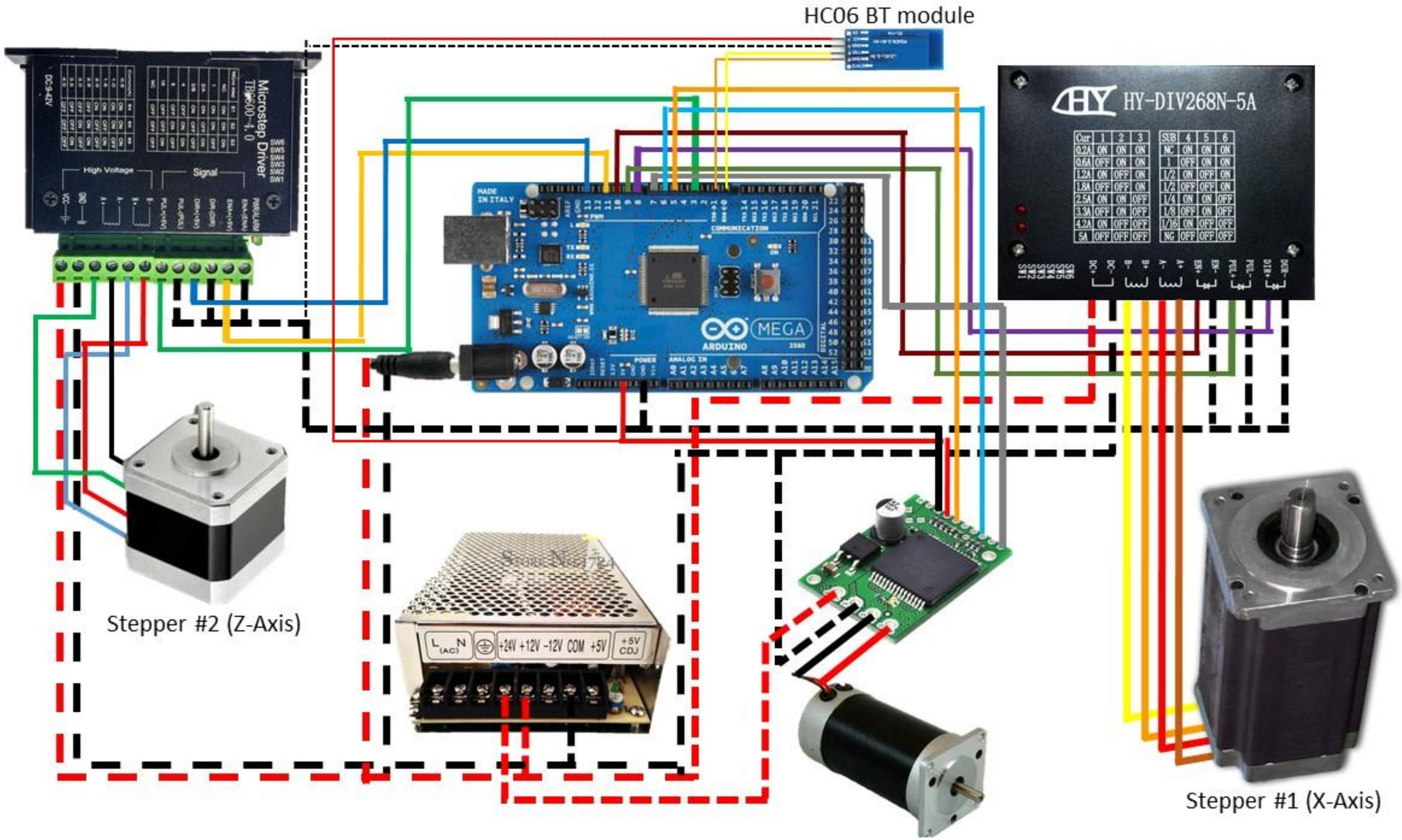
- Describing performance requirements of fresh printing concrete
- Developing a framework for performance-based laboratory testing of printing mixtures in fresh state
  - *An experimental program for demonstration*
  - *Suggesting new test methods*
  - *A basis for future specifications and guidelines*
- Developing real-time quality monitoring measures for concrete printing process- Ongoing

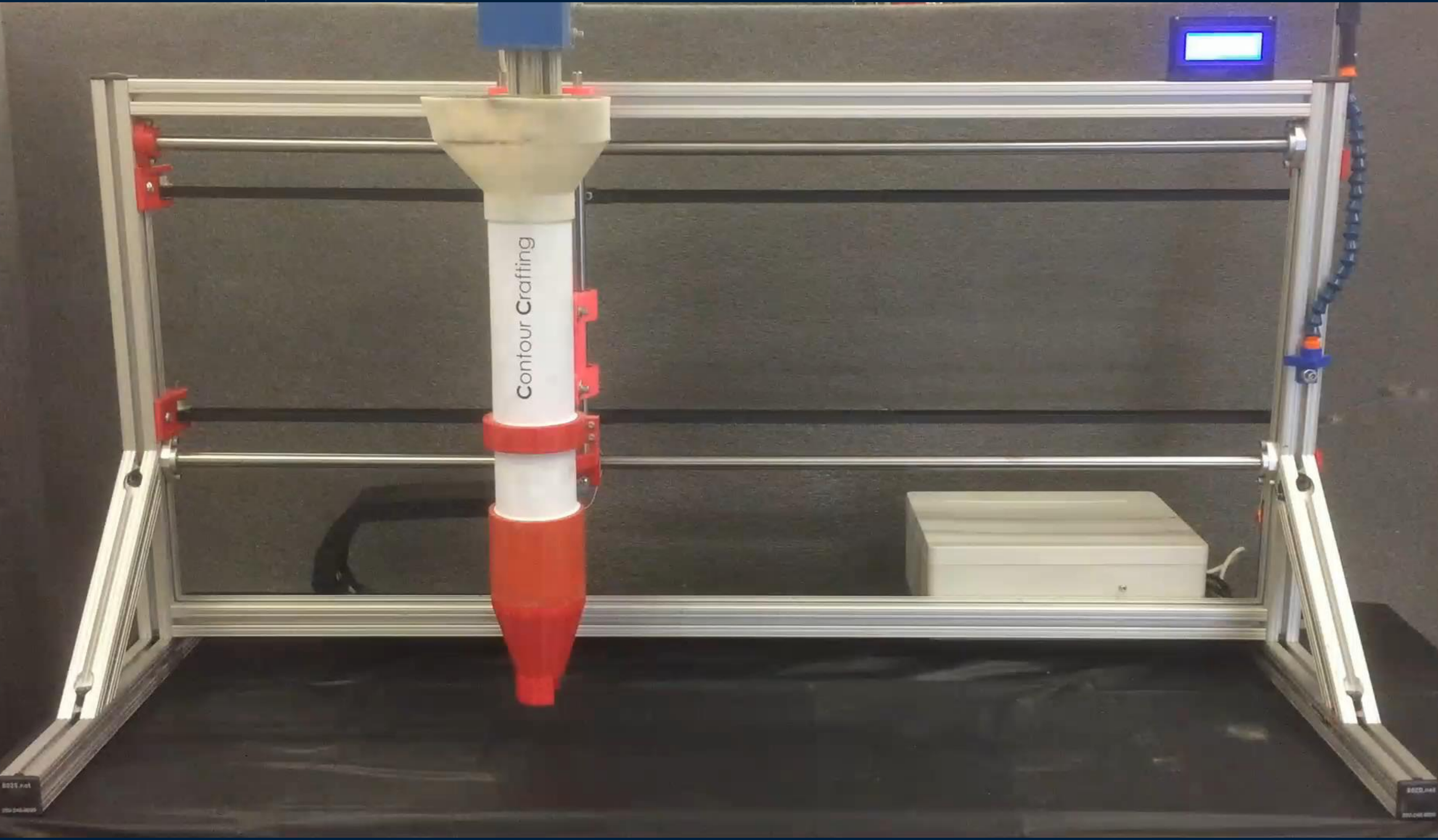
# Construction of a Linear Concrete Printer

- To facilitate carrying out large number of experiments
- Capable of printing up to 10 layers of 1.2m long concrete layers
- An Android application was also developed to facilitate the remote control of the setup




HC06 BT module
Microstep Driver
HY-DIV268N-5A
Stepper #2 (Z-Axis)
Stepper #1 (X-Axis)


Contour Crafting

## Development of Printing Mixtures (Materials)

- Type II/V Portland cement (CalPortland)

- A commercially available manufactured sand:
  - *Nominal maximum aggregate size of 2.36mm*
  - *Fineness modulus of 2.9*
  - *Specific gravity of 2.6*
  - *Absorption capacity of 1.3%*

# Development of Printing Mixtures (Materials)

- Polycarboxylate-based superplasticizer (ASTM C494 Type A)
  - *Specific gravity of 1.1*
  - *pH value of 5.6*
  - *Recommended addition rate: 130-650 mL/100 kg of cement*

- Viscosity modifying admixture (VMA)
  - *Commonly used for anti-washout concrete*
  - *Specific gravity of 1.02*
  - *pH value of 6*

# Development of Printing Mixtures (Materials)

- Polypropylene fiber
  - *6mm long*
  - *Aspect ratio of 29*
  - *Specific gravity of 0.91*
  - *Commonly used as shrinkage and temperature reinforcement*
- Densified silica fume
  - *Supplementary cementitious material*
  - *Specific gravity of 2.2*
  - *Enhancing viscosity of fresh concrete*
  - *Enhancing durability and mechanical strength of concrete*

# Development of Printing Mixtures (Materials)

- Highly-purified attapulgite clay
  - *Average particles length of 1.75µm*
  - *Average particle diameter of 3nm diameter*
  - *Specific gravity of 2.29*
  - *Average aspect ratio of 583*

# Development of Printing Mixtures (Proportions)

| Mixture ID | Fine aggregate (SSD) | Portland cement | Free Water | Silica fume | Fiber | Nano-clay | HRWRA | VMA |
|---|---|---|---|---|---|---|---|---|
| | $Kg/m^3$ | $Kg/m^3$ | $Kg/m^3$ | $Kg/m^3$ | $Kg/m^3$ | % | % | % |
| **PPM** | 1379 | 600 | 259 | 0 | 0 | 0 | 0.05 | 0.11 |
| **SFPM** | 1357 | 540 | 259 | 60 | 0 | 0 | 0.16 | 0 |
| **FRPM** | 1379 | 600 | 259 | 0 | 1.18 | 0 | 0.06 | 0.10 |
| **NCPM** | 1379 | 600 | 259 | 0 | 0 | 0.30 | 0.15 | 0 |

# Laboratory Testing of Mixtures

**Printing Mixture Characterization**

Conventional Testing

# Conventional Mixture Characterization

- Flowability determined using flow table (ASTM C1437)

- 7- and 28-day compressive strength (ASTM C109)
  - *2-inch cubes*
  - *1200N/s loading rate*

# Conventional Mixture Characterization

| Mixture ID | Unit weight | Flow | 7-day Compressive Strength | 28-day Compressive Strength |
|---|---|---|---|---|
| | $kg/m^3$ | % | MPa | MPa |
| PPM | 2250 | 119 | 32.9 [0.7] | 44.7 [1.3] |
| SFPM | 2210 | 116 | 35.2 [1.6] | 48.5 [1.3] |
| FRPM | 2265 | 118 | 31.0 [1.9] | 45.1 [1.1] |
| NCPM | 2250 | 113 | 31.8 [1.2] | 45.9 [1.5] |

- Similar compressive strength and strength gain for PPM, FRPM, and NCPM
- Positive effect of silica fume on 7- and 28-day strength

# Print Quality

- Refers to the properties of printed layers when using a mixture
- Three criteria were defined:

  **C1:** The printed layers should be free of surface defects, including any discontinuity due to excessive stiffness and inadequate cohesion

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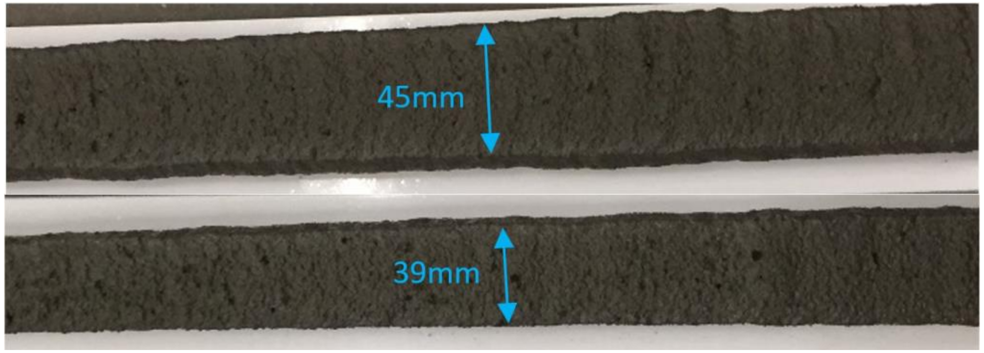
  **C2:** The layer edges should be visible and squared (versus round edges)

  **C3:** Dimension conformity and dimension consistency




Dimension conformity

▼

Target layer width (38.1mm)

# Print Quality

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**C2:** The layer edges should be visible and squared (versus round edges)

**C3:** Dimension conformity and dimension consistency


Dimension consistency

▼

Variations in a single layer

(max acceptable: 10%)

# Shape Stability

- The ability to resist deformations as a result of following layers being printed
- Three sources of deformation:
  - *Self-weight*
  - *Weight of following layer(s)*

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- Three sources of deformation:
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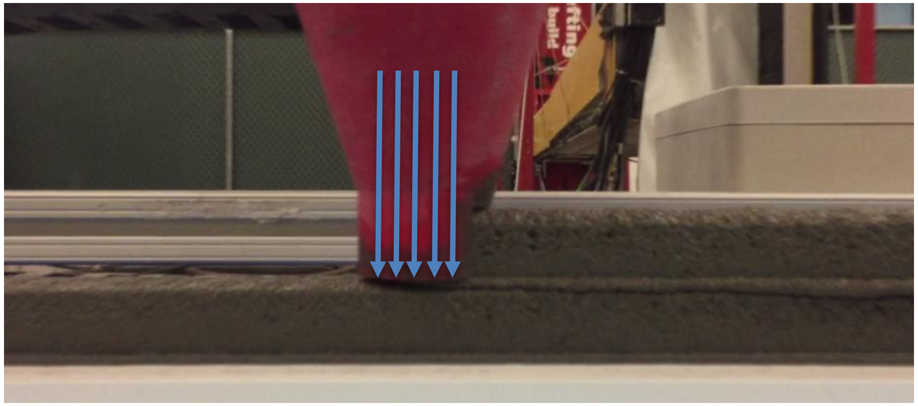
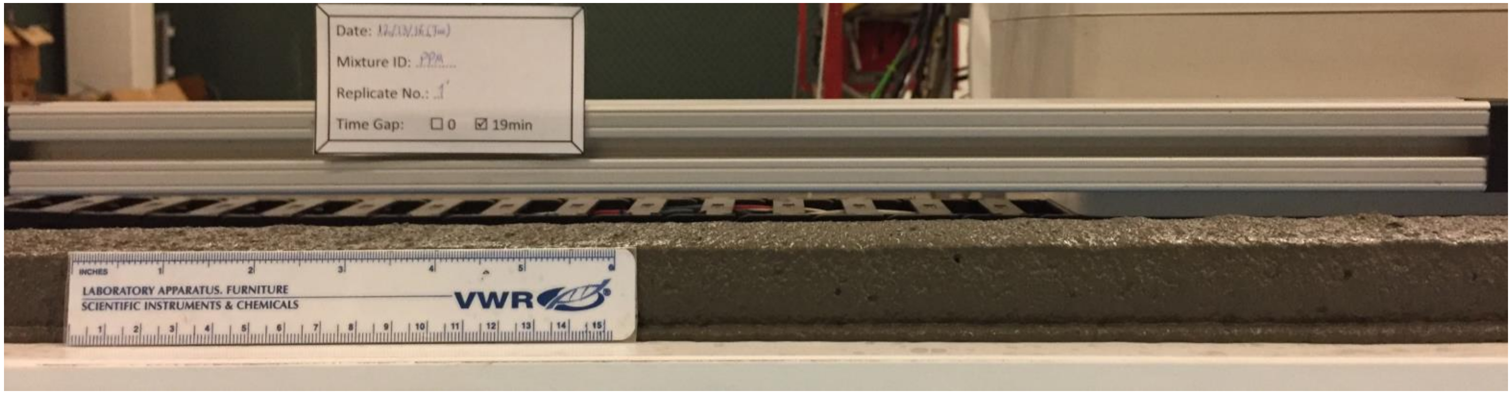
  - *Weight of following layer(s)*
  - *Extrusion pressure*



## Shape Stability

- Layer settlement test:
  - *Printing double layer specimens with specific time gaps*
  - *Placing a camera in front of layers and taking photos before and after the top layer is printed*



## Shape Stability

- Layer settlement test:
  - *Printing double layer specimens with specific time gaps*
  - *Placing a camera in front of layers and taking photos before and after the top layer is printed*
  - *Measuring layer settlements using ImageJ (average of five readings was recorded for each layer, and three layers were printed per mixture)*

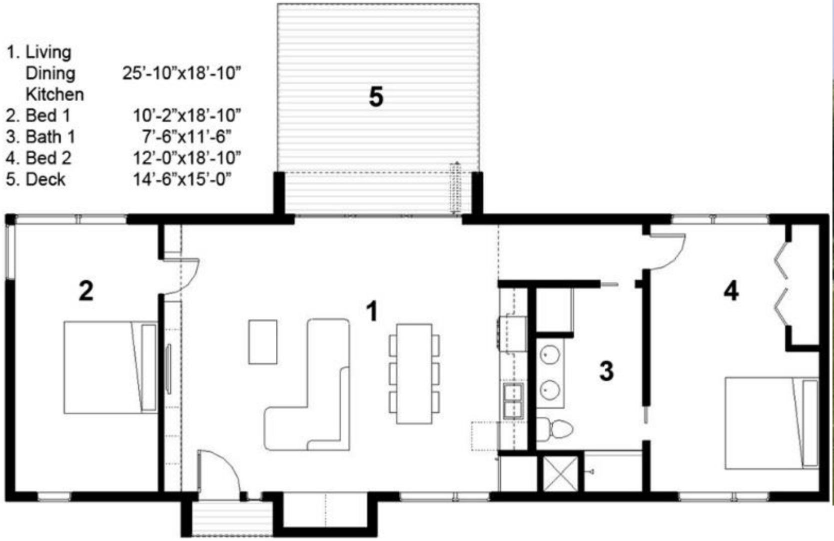
ImageJ

Image Processing and Analysis in Java

*Available at: https://imagej.nih.gov*

# Shape Stability (Time Gap)

- A realistic measure of time gap
- Layer-by-layer construction of a 110 $m^2$ house
- Designed by FreeGreen architectural and design company




*Available at : https://www.houseplans.com/plan/1160-square-feet-2-bedroom-1-bathroom-0-garage-modern-39050*

# Shape Stability (Time Gap)

- Nozzle travelling distance per layer: 67 meters
- Linear printing speed: 6 cm/s ► ~ 19-min time gap

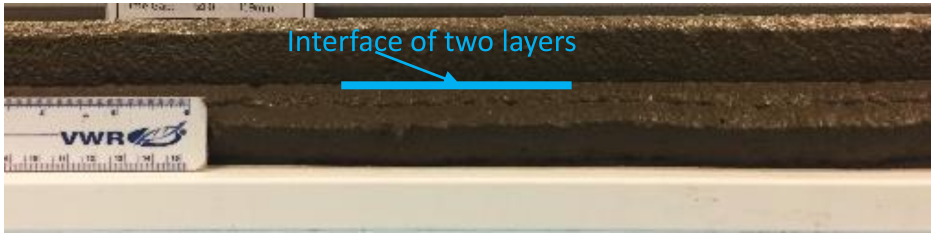
# Shape Stability (Time Gap)

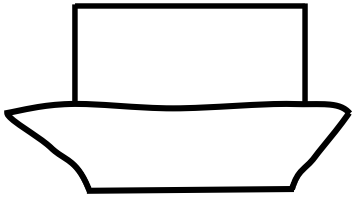
- Nozzle travelling distance per layer: 67 meters
- Linear printing speed: 6 cm/s ▶ ~ 19-min time gap
- For experiments, two scenarios were considered:
  - *Realistic: 19-min time gap*
  - *Worst-case: Zero time gap*

# Shape Stability (Results)

- Zero time gap

| Mixture ID | Test 1 | Test 2 | Test 3 | Average Reading [Std. Dev.] |
|---|---|---|---|---|
| | mm | mm | mm | mm |
| PPM | Collapse | Collapse | Collapse | - |
| SFPM | 2.2 | 1.8 | 1.5 | 1.8 [0.3] |
| FRPM | 2.8 | 3.3 | 2.5 | 2.9 [0.3] |
| NCPM | 2.0 | 1.1 | 1.6 | 1.6 [0.4] |



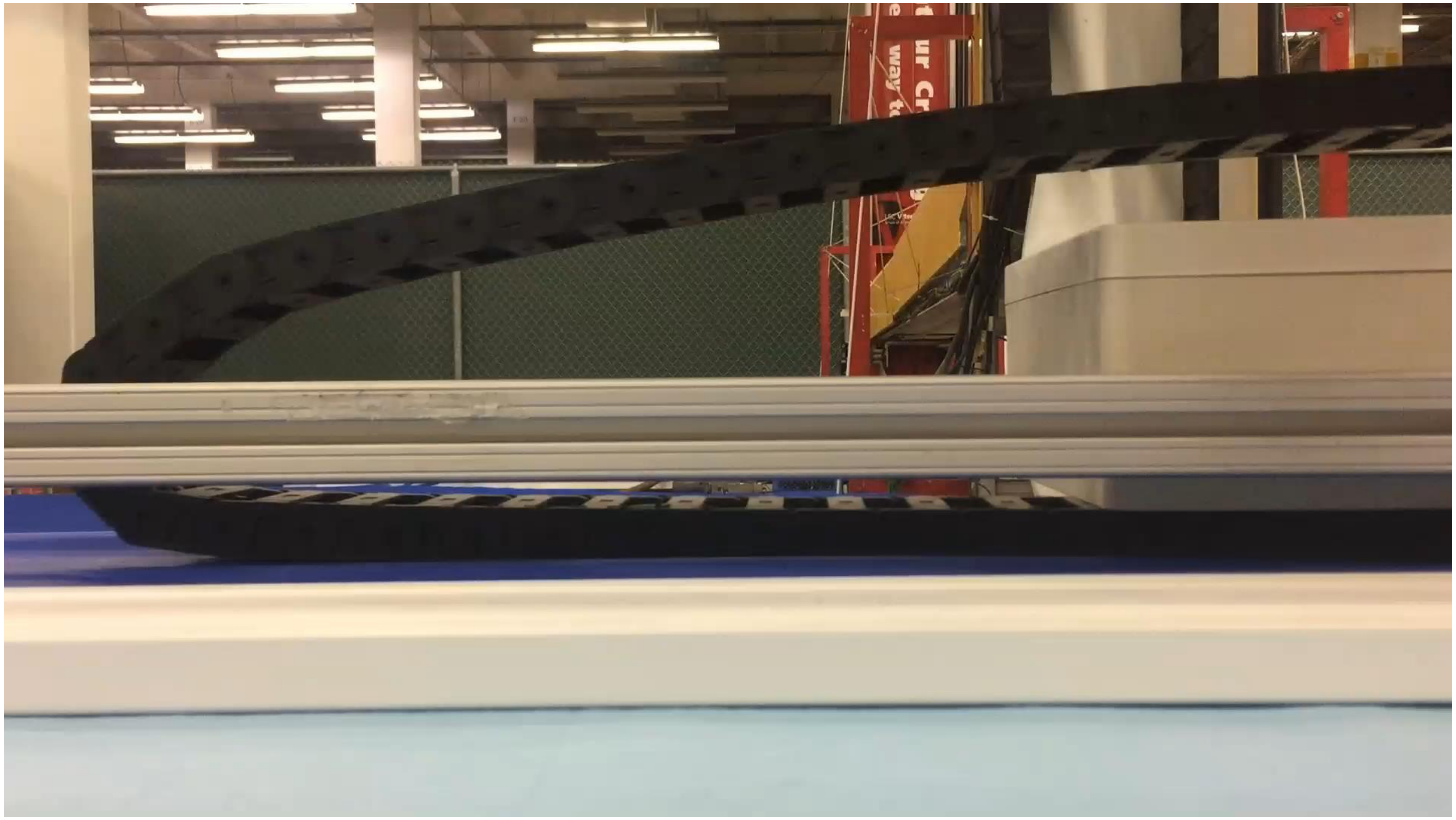
# Shape Stability (Results)

- 19-minute time gap

| Mixture ID | Test 1 | Test 2 | Test 3 | Average Reading [Std. Dev.] |
|---|---|---|---|---|
| | mm | mm | mm | mm |
| PPM | 1.9 | 1.1 | 1.6 | 1.5 [0.3] |
| SFPM | 0 | 0 | 0 | 0 |
| FRPM | 0 | 0 | 0 | 0 |
| NCPM | 0 | 0 | 0 | 0 |

# Shape Stability (Results)

- Scalability Testing (NCPM)

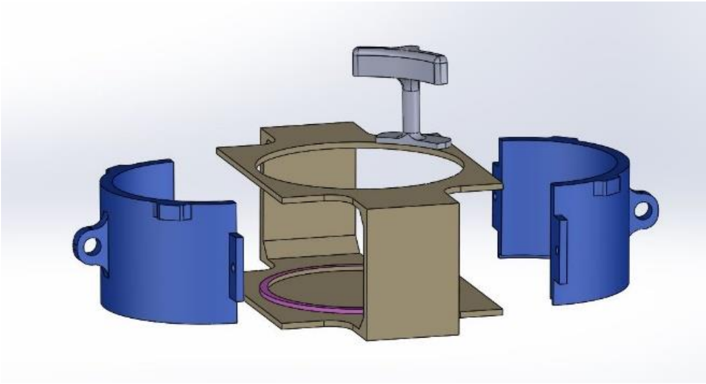


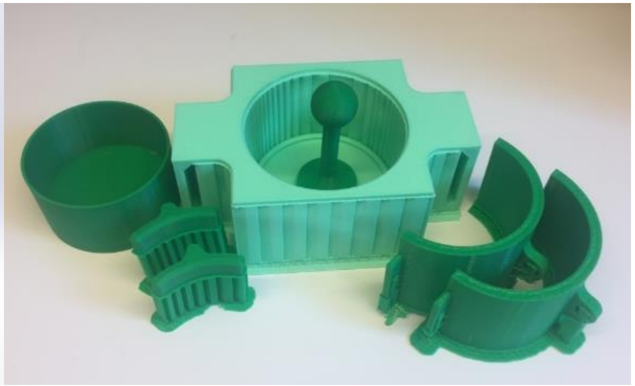
## Shape Stability (Cylinder Stability Test)

- Developed for quick assessment and comparison of different mixtures. Test procedure:

  *(1) The semi-cylinders are fixed in place and locked, and a concrete layer of 40mm is placed*

  *(2) The layer is consolidated by rodding 15 times evenly distributed around the layer*





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  *(2) The layer is consolidated by rodding 15 times evenly distributed around the layer*

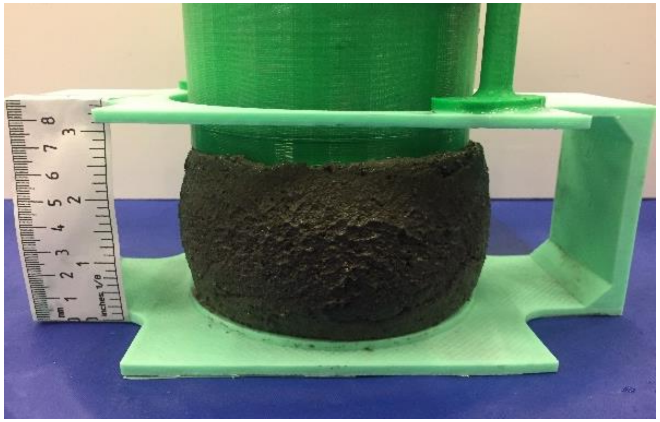
  *(3) The same procedure is repeated for second layer*

  *(4) The two semi-cylinders are unlocked and gently removed*

  *(5) A load of 5.5kg is applied and the resulting deformation in the fresh concrete cylinder is measured in terms of change in height*

# Shape Stability (Cylinder Stability Test)

| Mixture ID | Test 1 | Test 2 | Test 3 | Average Reading (mm) |
|---|---|---|---|---|
| PPM | 41 | 37 | 38 | 38.7 |
| SFPM | 15 | 15 | 14 | 14.7 |
| FRPM | 34 | 29 | 31 | 31.3 |
| NCPM | 12 | 15 | 11 | 12.7 |



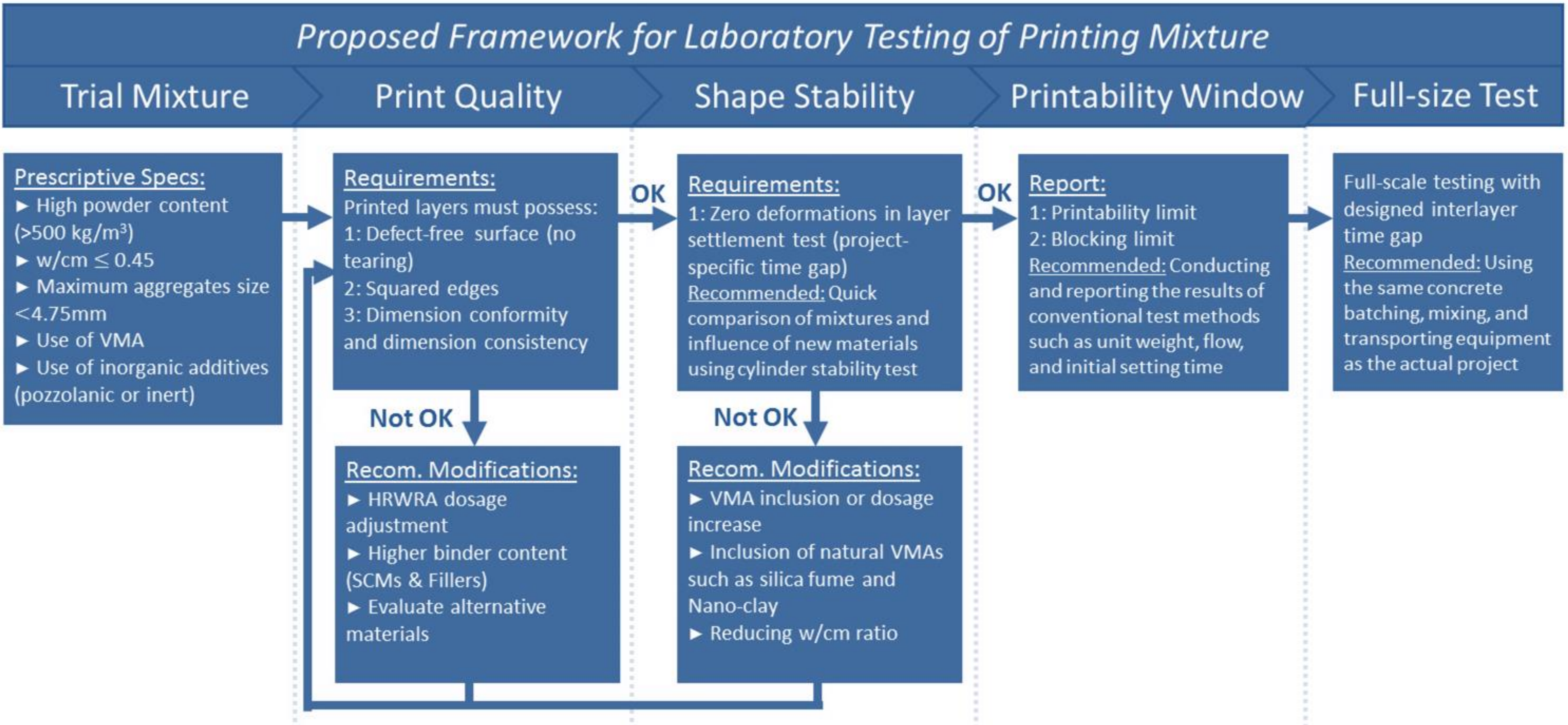
## Printability Timespan

- Refers to the time period during which the printing mixture could be extruded by the nozzle (considering the workability loss that happens over time)

- Highly important in terms of the timing of material delivery to the nozzle and operation of a building printer such as Contour Crafting machine

# Printability Timespan

- Described in terms of:
  - Printability Limit: The time when the quality of printed layer is affected as a result of workability loss, recognized by triple “print quality” requirement
  - Blocking Limit: The time when the concrete cannot be guided out of printing nozzle at all, and further delay would result in mixture hardening and damage to the nozzle


Proposed Framework for Laboratory Testing of Printing Mixture
Trial Mixture
Print Quality
Shape Stability
Printability Window
Full-size Test
Prescriptive Specs:
► High powder content (>500 kg/m³)
► w/cm ≤ 0.45
► Maximum aggregates size <4.75mm
► Use of VMA
► Use of inorganic additives (pozzolanic or inert)
Requirements:
Printed layers must possess:
1: Defect-free surface (no tearing)
2: Squared edges
3: Dimension conformity and dimension consistency
OK
Requirements:
1: Zero deformations in layer settlement test (project-specific time gap)
Recommended: Quick comparison of mixtures and influence of new materials using cylinder stability test
OK
Report:
1: Printability limit
2: Blocking limit
Recommended: Conducting and reporting the results of conventional test methods such as unit weight, flow, and initial setting time
Full-scale testing with designed interlayer time gap
Recommended: Using the same concrete batching, mixing, and transporting equipment as the actual project
Not OK
Recom. Modifications:
► HRWRA dosage adjustment
► Higher binder content (SCMs & Fillers)
► Evaluate alternative materials
Not OK
Recom. Modifications:
► VMA inclusion or dosage increase
► Inclusion of natural VMAs such as silica fume and Nano-clay
► Reducing w/cm ratio

## Ongoing Research

- Real-time quality monitoring of fresh concrete (electrical resistivity and nozzle power consumption)
- Monitoring early age compressive strength of concrete (Maturity and electrical resistivity)

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- Real-time quality monitoring of fresh concrete (electrical resistivity and nozzle power consumption)
- Monitoring early age compressive strength of concrete (Maturity and electrical resistivity)
- **Unexplored areas:**
    - Shrinkage
    - Material/Process Robustness
    - Structural Performance
    - Durability Concerns, etc.

# Publications

Contents lists available at ScienceDirect

Construction and Building Materials

journal homepage: www.elsevier.com/locate/conbuildmat

## Cementitious materials for construction-scale 3D printing: Laboratory testing of fresh printing mixture

Ali Kazemian [a,b,*], Xiao Yuan [c], Evan Cochran [a], Behrokh Khoshnevis [a,c]

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[b] *Department of Computer Science, University of Southern California, Los Angeles, CA, USA*
[c] *Department of Industrial and Systems Engineering, University of Southern California, Los Angeles, CA, USA*

**Proceedings of the ASME 2017 12th International Manufacturing Science and Engineering Conference**
**MSEC2017**
**June 4-8, 2017, Los Angeles, CA, USA**

**MSEC2017-2823**

## CONSTRUCTION-SCALE 3D PRINTING: SHAPE STABILITY OF FRESH PRINTING CONCRETE

**Ali Kazemian*[1,2], Xiao Yuan[3], Ryan Meier[1], Evan Cochran[1], Behrokh Khoshnevis[1,3]**

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[3] Department of Industrial and Systems Engineering, University of Southern California, Los Angeles, CA, USA
* Contact author

# Publications

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Construction and Building

## Perspectives on BIM for Automated Construction through Contour Crafting

**Omid Davtalab*[1,2], Ali Kazemian[1,2], and Behrokh Khoshnevis [1,3]**

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### Abstract

Automated building construction through concrete 3D printing is an in-progress revolution in construction industry. A reliable automated building construction system presents numerous advantages including design freedom, superior construction speed, lower material waste, and higher degree of customization. While there has been significant progress with respect to construction robots and material preparation and delivery equipment, software and information related issues of such innovative construction system have been less discussed. In this paper, initially the essential components of a well-developed automated building construction system are discussed. Then a framework is proposed to integrate Building Information Modelling (BIM) into automated construction through concrete 3D printing. A Planning and Operations Control Software for Automated Construction (POCSAC) is developed within the framework as a major enabler for a seamless integration of BIM and Contour Crafting. The details of interoperation between different components of an automated construction system and BIM platform are proposed such that maximum benefit is realized through synergy of the two technologies.

**Keywords:** Contour Crafting; Automated Construction; BIM; 3D Printing; POCSAC software; Concrete

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# Technology Commercialization: CC Corporation


Contour Crafting Corporation gets Investment from Doka Ventures, leases 33000+ sq-ft space in El Segundo to start production of construction 3D printers.

Read more:
http://contourcrafting.com/


Questions/Comments?

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