

Brick Geometries: 5-Axis Additive Manufacturing for Architecture

A Thesis Submitted to the Department of Architecture
Harvard University Graduate School of Design, by

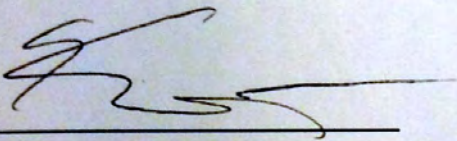
Kevin Hinz

In Partial Fulfillment of the Requirements for the Degree of
[Master of Architecture]


January 2016

(Month and Year Thesis Submitted)

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Kevin Hinz



Leire Asensio Villoria



BRICK GEOMETRIES: 5-AXIS ADDITIVE MANUFACTURING FOR ARCHITECTURE

Building Technologies profoundly affect architectural design. Digital Technologies offer computational models to analyze structure, articulate design intention and develop creative production techniques. The means, methods and exchange of building construction knowledge is advancing on many fronts. However, traditional material systems still dominate the architectural pallet. Glass, steel, concrete, clay and wood are cut, shaped, bent and assembled in increasingly complex ways. It is the architect's job to compose and orchestrate these systems. With this knowledge of production, materials and structure, the architect can integrate the skill and intelligence at the core of architecture.

Brick Geometries interrogates how digital technology can contribute to 6000 years of knowledge in architectural ceramics. Historically associated with craft-based manufacturing or high-volume industrial production, novel ceramic forms and innovative brick structures are typically developed from a ready-made, already existing selection of building components. This research proposes a new approach to the fabrication process of ceramic materials, constructing the tools and developing the material technology to explore 5-Axis Additive Manufacturing as a function to rethink construction methods and geometric form. The project exploits material effect of the clay body, design computation and software manipulation to innovate on what is becoming a 21st century craft.

SPONSORS AND THANKS-TO

OPEN-SOURCE CREDITS

CONTRIBUTORS

SPONSORS AND THANKS-TO

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OPEN-SOURCE CREDITS

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http://www.keep-art.co.uk/Self_build.html

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http://www.marlinfirmware.org/index.php/Main_Page
<https://github.com/MarlinFirmware/Marlin>

World's Advanced Saving Project (WASP):
<http://www.wasproject.it/w/en/>
<http://www.personalfab.it/en/downloads-2/download-info/lm-wasp-extruder/>

CONTRIBUTORS

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<https://www.facebook.com/CodeWithoutFrontiers>

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<http://www.rukamathsmith.com/rukamathu-smith>



FORMAT SUMMARY



1 PAGE SPREAD

Format Summary

This area includes notes written by the author to describe each slide for the 30 minute presentation, highlighting critical moments in the research, raising items for discussion.

This area shows the original images, diagrams and text as displayed during the slide presentation beginning at 10:00, Jan. 19, 2016.

Image Sources (books, websites, photographers and authors) cited in this area.

Placement of citations correspond to the placement of images above.

If no citation is listed, the drawing or photograph belongs to the author.

2 PAGE SPREAD

Material Technologies

Theories guiding the goals of research investigated in this thesis.



MATERIAL TECHNOLOGIES



Architectural Technologies

In general, we know that technology effects the state of architecture, the designer and the idea of craft in the 21st century:

- System Design
- Material Technology
- Manufacturing Technology

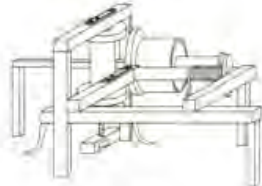
Material & technology are directly connected to design potential. All have an impact on Architectural Form



+



+



+



=



source: Andreani

Andreani, S. (2013). Stefano Andreani, "[R]evolving Brick: Informed Design and Robotic Fabrication Workflow for Strategic and Sustainable Mass Customization of Complex Ceramic Building Systems" Master in Design Studies Technology Concentration, Harvard University Graduate School of Design, 2013.

SYSTEM DESIGN + STRUCTURAL FORM



Barcelona, Spain, 1904

MATERIAL SYSTEM + FABRICATION TECHNOLOGY



Stuttgart 2014

MANUFACTURING + EXPRESSIVE FORM



Paris c.1900

"Mannheim Multihalle." WAM. Accessed September 10, 2015. <http://www.worldarchitecturemap.org/buildings/mannheim-multihalle>.

"ICD/ITKE Research Pavilion 2013-14." Achim Menges. Accessed September 10, 2015. <http://www.achimmenges.net/?p=5713>.

Boake, Terri Meyer. "Innovative Connections." SSEF. Accessed December 2, 2015. <http://www.tboake.com/SSEF1/cast.shtml>.

INDUSTRIAL PRODUCTION + CRAFT

Ceramic Medium

Ceramics are the medium used to explore this agenda --as inspiration for material-based research:
---looking at system design
---developing expressive form
----for structure, light & experiential effect

This Thesis investigates the design of ceramic structures in the light of industrial production.



Barcelona, Spain, 1904



Terrassa, Catalunya, 1909

“The Best of Barcelona - Barcelona Blonde.” Barcelona Blonde. Accessed September 5, 2015. <http://barcelonablond.com/the-best-of-barcelona/>.

“Technology: The Catalan Vault – A Historical Structural Principle with a Bright Future | DETAIL Inspiration.” Technology: The Catalan Vault – A Historical Structural Principle with a Bright Future | DETAIL Inspiration. Accessed July 20, 2015. <http://www.detail-online.com/inspiration/technology-the-catalan-vault-%E2%80%93-a-historical-%C2%ADstructural-principle-with-a-bright-future-106565.html>

2 PAGE SPREAD

Ceramics in Architecture

A brief history of a centuries
old building element.



CERAMICS IN ARCHITECTURE



Ceramic History
(in architecture)

Formal architectural ceramic elements appear as early as 2600 BC. Custom 3D reliefs appeared sometime around 600 BC.

However, Ceramic production today is as it was for almost 5000 years. However, the digital revolution is changing how we approach and look at the medium in the 21st century.



Glazed Brick 2600 B.C

+4000 YR OF REFINEMENT



Italy, 21st c.



Danube Delta, 21st c.



Babylon, Mesopotamia, 604-562 B.C.



Babylon, Mesopotamia, 604-562 B.C.



Luxor, Egypt, 20th c.

Mira, Javier. "Ceramics for Architecture. FUNDAMENTALS." Lecture, September 3, 2015. <https://performativeceramicscreens.files.wordpress.com/2013/07/javier-mira-ceramic-for-architecture-ok.pdf>.

"Visiting the Ancient City of Babylon - Ancient History Et Cetera." Ancient History Et Cetera. 2014. Accessed January 26, 2016. <http://etc.ancient.eu/2014/11/17/visiting-ancient-city-babylon/>.

"Panel: striding lion [Excavated at Wall of Processional Way, Babylon, Mesopotamia]" (31.13.2) In Heilbrunn Timeline of Art History. New York: The Metropolitan Museum of Art, 2000-. <http://www.metmuseum.org/toah/works-of-art/31.13.2>. (October 2006)

"IBL: Naturalmente Casa." IBL Spa. Accessed September 3, 2015. <http://www.iblspa.it/>.

Soare, RomaniaDanubeDelta. digital, 2,272 x 1,712 pixels. Available from: Wikimedia Commons, https://commons.wikimedia.org/wiki/File:RomaniaDanubeDelta_MakingMaterialForCONstructing0002jpg.JPG (accessed September 3, 2015).

"THaWS Project – Start of the week survey at Kom el Hetan." Kristian Strutt. Accessed September 2, 2015. <https://kdstrutt.wordpress.com/page/6/>.

Ceramic History (in modern architecture)

Ceramics Production has an effect on the architectural result.

-Where craft production is often tied to a particular place and set of local knowledge, location is not as important in a global economy (as is the case today); knowledge is easily transferred across continents.

-Industrial economy (today) inspires uniform, mass-produced design elements; as Corbu alluded to in the 1930s

-In all cases, architectural ceramics prove to be a very versatile medium for the architect's design pallet



Zurich, Switzerland, 2012



Poissy, France, 1931



Buffalo, NY, United States, 1896

DIGITAL DESIGN + STRUCTURAL FORM



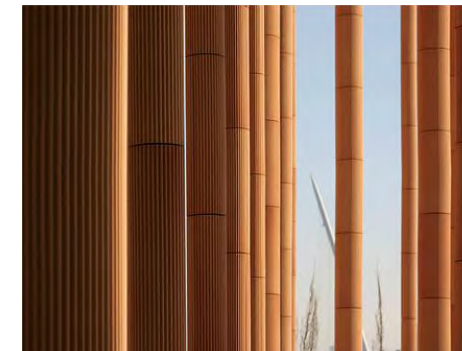
Barcelona, Spain, 2005



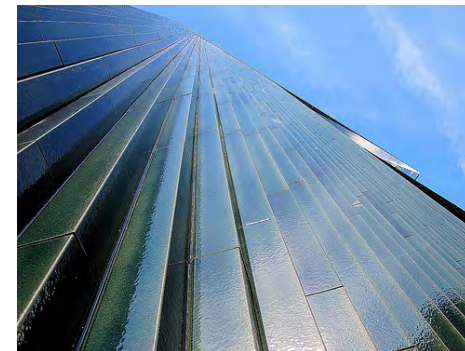
Aichi, Japan, 2005

MACHINE AESTHETIC

EXPRESSIVE FORM



Zaragoza, Spain, 2008



Mainz, Germany, 2010

Breitfuss, Klemen. "Free-form Catalan Thin-tile Vault, Zurich, Switzerland." BLOCK Research Group. Accessed January 26, 2016. <http://www.block.arch.ethz.ch/brg/project/free-form-catalan-thin-tile-vault>.
 Sullivan, Mary Ann. "Images of Villa Savoye by Le Corbusier." Images of Villa Savoye by Le Corbusier. 2006. Accessed September 3, 2015. <https://www.bluffton.edu/~sullivanm/france/poissy/savoye/corbu9.html>.
 Sullivan, Mary Ann. "Images of the Guaranty/Prudential Building by Louis Sullivan." Accessed January 26, 2016. <https://www.bluffton.edu/~sullivanm/newyork/buffalo/sullivan/guaranty.html>.

"Cerámica Cumella." Cerámica Cumella. Accessed October 26, 2015. <http://www.cumella.cat/quefem.htm>.
 "Cerámica Cumella." Cerámica Cumella. Accessed October 26, 2015. <http://www.cumella.cat/quefem.htm>.
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Ceramic Technologies

The most advanced
architectural ceramic
technologies available today.



CERAMIC TECHNOLOGIES



Contemporary Direction + Method

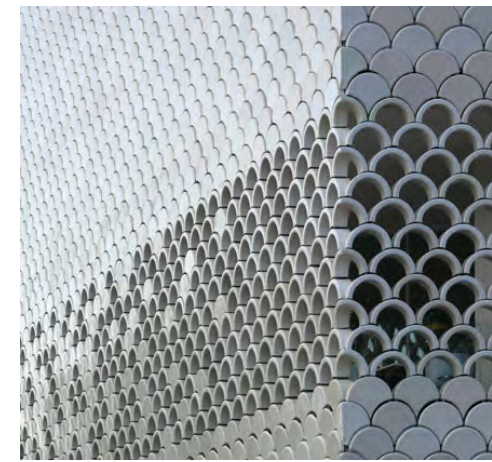
Innovative architecture using ceramic components seems to use two basic component assemblies:

-Method

-Pattern



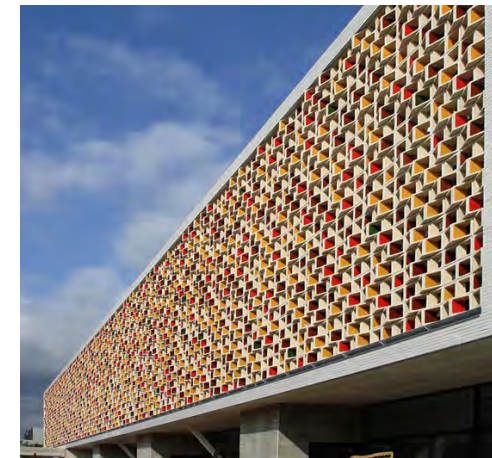
France / Netherlands, 2013



Lisbon, Portugal, 2011



Amsterdam, 2013



Barcelona, Spain, 2010

ARRANGE BY METHOD

Oswald, Samantha. "Techne and Poiesis: 2013-06-09." *Techne and Poiesis: 2013-06-09*. Accessed July 7, 2015. http://techneandpoiesis.blogspot.ca/2013_06_09_archive.html.

Rietveld, Gerrit. "Bricking Pattern." *Bricking Pattern*. Accessed July 8, 2015. <http://www.the-interiordesign.com/en/design-data/bricking-pattern/326>.

ARRANGE BY PATTERN

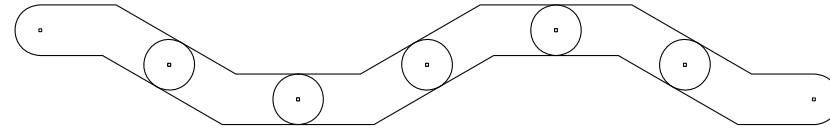
Lutyens, Dominic. "Out on the Tiles: Ceramic Architectural Facades." *Articles We Keep You Informed with Our News*. 2013. Accessed July 7, 2016. <http://www.architonic.com/ntsht/out-on-the-tiles-ceramic-architectural-facades/7000794>.

Lutyens, Dominic. "Out on the Tiles: Ceramic Architectural Facades." *Articles We Keep You Informed with Our News*. 2013. Accessed July 7, 2016. <http://www.architonic.com/ntsht/out-on-the-tiles-ceramic-architectural-facades/7000794>.

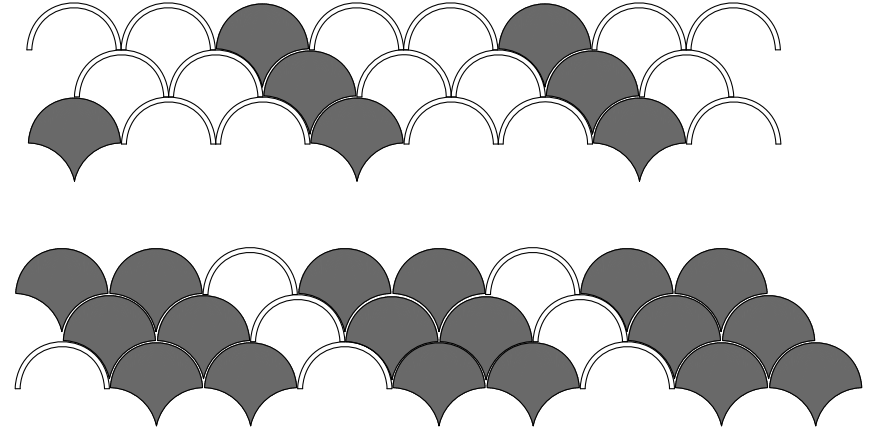
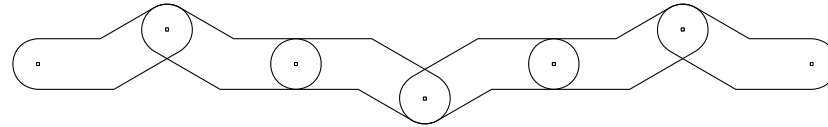
Contemporary
Direction + Method

To clarify:

-Arrange by Method
--where identical components
are designed with a smart
geometry supporting an
articulated assembly



-Arrange by Pattern
--where 2 or more components
have a geometrical relationship
with changes in color, opacity,
similar points of relationship
and are interchanged
according to the will of the
designer



Digital technology can have a
profound effect on industrial
production to contribute
more design options for our
architectural pallet.

ARRANGE BY METHOD

ARRANGE BY PATTERN

Manufacturing Technology

I've been fortunate to have contributed on two projects that combine digital design and industrial production technologies.

-In each case, machines and digital fabrication technology had a significant influence on the final design.

However, the manufacturing technologies employed to produce the final products haven't changed. In the case studies I encountered, traditional machines were more often than not used to manufacture digitally designed architectural components.



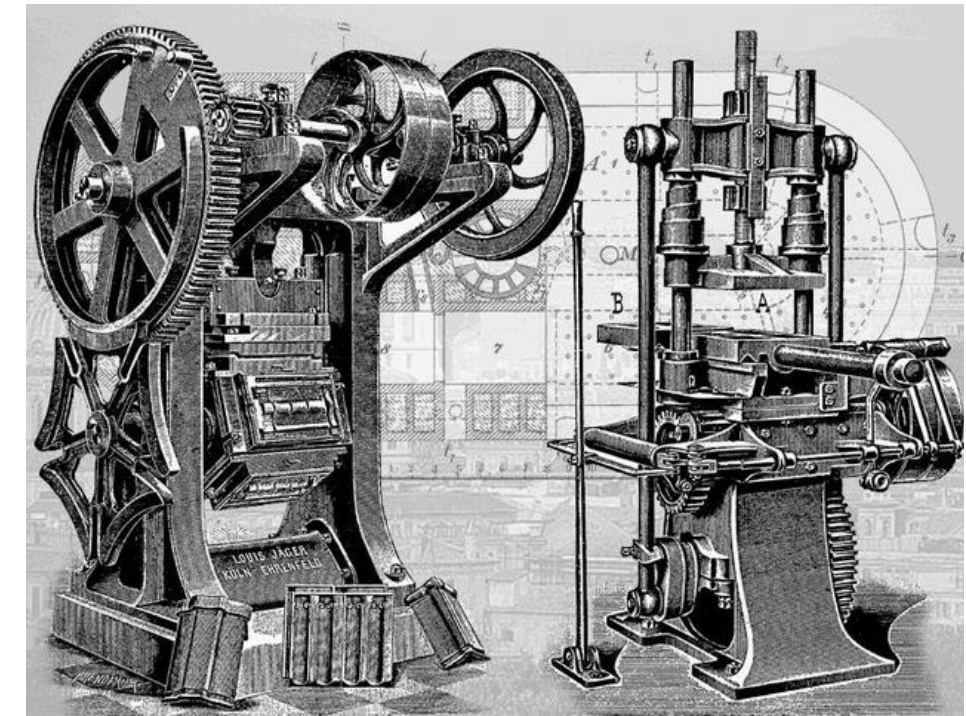
Valencia, Spain, 2014



Cambridge, MA, United States, 2014

"Ceramic Shell @ Cevisama 2014." MaP S. 2014. Accessed July 7, 2015. <http://research.gsd.harvard.edu/maps/portfolio/4936/>.
copyright: Harvard University

Maggie Janik [Harvard GSD]. *Chromosomes*. Dec. 2014. Source: photographer.



United States c.19th c.

FORWARD DESIGN + TRADITIONAL MANUFACTURING

"History." Team Fritz Clay Roof Tiles. Accessed July 30, 2015. <http://www.clayrooftiles.org/history.htm>.

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Industrial Technology

A short description about the state of industrial ceramic production.



INDUSTRIAL TECHNOLOGY



Forming Methods		SLIP CASTING	EXTRUDING	DRY PRESSING
<p>Nearly all manufactured Ceramics are produced by a few primary forming methods:</p> <ul style="list-style-type: none"> -Slip Casting -Extruding -Dry Pressing <p>----each type facilitates a mixed assement of geometric complexity, permeability and productivity, among others.</p> <p>I have highlighted the attributes that most greatly effect the research I am presenting today such as:</p> <ul style="list-style-type: none"> --production cost --avg moisture --shrinkage <p>Most of my work focused on extrusion technologies (as will be later defined).</p>	Specific production costs	high	low	medium
	Plant complexity	high	low	medium
	Automation level	low	high	high
	Productivity	low	high	very high
	Article thickness	highly varilable	variable	constant
	Article size	large	medium	small
	Geometry of shaped article	complex	quite complex	simple
	Firing ability	low	medium	high
	Glazing ability	low	low	high
	Surface permeability	low	low	high
	Drying energy consumption	high	low	high
	Drying ability	low	low	high
	Shrinkage after firing	high	medium	low
	Mould/die porosity	yes	no	no
	Mould/die material	rigid	rigid	rigid or elastic
Green deformability	high	medium	low	
Green density	low	medium-high	high	
Shaping energy consumption	low	medium	high	
Duration of shaping process	high	medium	low	
Avg. moisture after shaping	18% by wt.	17% by wt.	5% by wt.	
Avg. moisture before Shaping	28% by wt.	17% by wt.	5% by wt.	

source: Händle

SLIP CASTING

EXTRUDING

DRY PRESSING

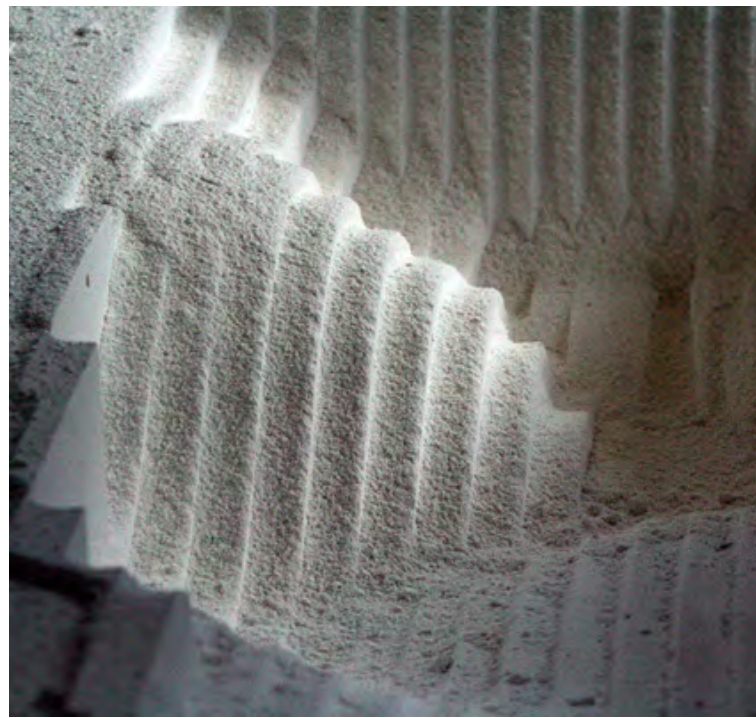
Existing Digital-Ceramic Research

Existing research combining ceramic manufacturing and digital technologies with building-scale applications deploy the three methods listed above:

- Slip Casting
- Extrusion
- and Pressing (moist & dry)

As reference, I am deploying extrusion in my research presented today: a piston extruder supplying a smaller, more nimble auger extruder.

In any case, 3D printing ceramics is relatively new to the craft.



Oisterwijk Netherlands, circa 2012



Girona, Spain, 2009

Stein, Joshua G. "Projects :: Tectonic Horizons." Data Clay. Accessed January 26, 2016. <http://www.data-clay.org/projects/Tectonic Horizons/index.html>.

"Cerámica Cumella." Cerámica Cumella. Accessed October 26, 2015. <http://www.cumella.cat/quefem.htm>.

ADVANCED DESIGN + PRODUCTION



Cambridge, MA, 2012

Andreani, S. (2013). Stefano Andreani, "[R]evolving Brick: Informed Design and Robotic Fabrication Workflow for Strategic and Sustainable Mass Customization of Complex Ceramic Building Systems" Master in Design Studies Technology Concentration, Harvard University Graduate School of Design, 2013.

Digital Manufacturing Methods

Some of the more advanced precedents make extensive use of digital technologies, combining:

- Material Science
- Computational Science
- and established Craft and Industrial Process

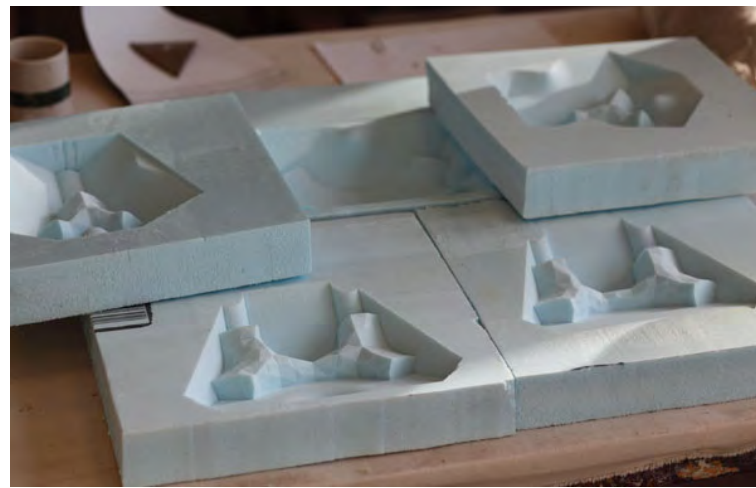
****Ceramic Craft is migrating into the hands of the digital designer; especially as the next generations become more fluid with machine technologies.**

This thesis research investigates how digital technologies can help architects:

-Create elegant architectural solutions with advanced technology.

-Contribute to manufacturing Technology, with the knowledge about what is possible with the means of the craftsmen employed.

-*Reiterate the definition of a 21st century craftsmen by uncovering ways to exploit material as a digital craft.



DIGITAL FABRICATION



COMPLEX GEOMETRIES



Harrow, Del. "Projects :: Bone Scaffolding." Data Clay. Accessed January 26, 2016. <http://www.data-clay.org/projects/Bone Scaffolding/index.html>.

Russo, Rhett, and Katrin Mueller-Russo. "Projects :: Flabella." Data Clay. Accessed January 26, 2016. <http://www.data-clay.org/projects/Flabella/index.html>.

Harrow, Del. "Projects :: Bone Scaffolding." Data Clay. Accessed January 26, 2016. <http://www.data-clay.org/projects/Bone Scaffolding/index.html>.

Russo, Rhett, and Katrin Mueller-Russo. "Projects :: Flabella." Data Clay. Accessed January 26, 2016. <http://www.data-clay.org/projects/Flabella/index.html>.

Manufacturing Methods

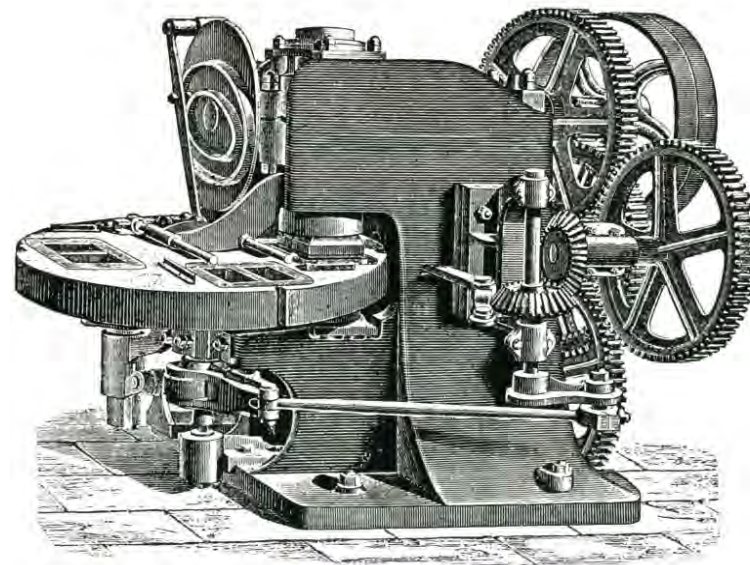
Typically, ceramic manufacturing involves a series of combined methods:

- Craft based manufacturing
- Digital technologies (primarily for die, mold and prototype making)
- Often deploying Product-Specific machines



CRAFT-BASED MANUFACTURING

MANUFACTURING METHOD



PRODUCT-SPECIFIC MACHINES

Kaltenbach, Frank. "Thousand-Year Sheen." Detail, Vol. 2011. 466-76.

Andreani, S. (2013). Stefano Andreani, "[R]evolving Brick: Informed Design and Robotic Fabrication Workflow for Strategic and Sustainable Mass Customization of Complex Ceramic Building Systems" Master in Design Studies Technology Concentration, Harvard University Graduate School of Design, 2013.

"CNC Router and Machining Centers BMG 500/600 - Staircase Production ." HOMAG Group. Accessed January 26, 2016. http://www.homag.com/en-en/products/productdatabase/homag/Pages/bmg500_stairs.aspx.

Existing 3D Printing Ceramic Technology

Fortunately, ceramic material properties (grain, adhesion properties, mailability, reaction to moisture, etc) lends itself to 3D printing technologies.

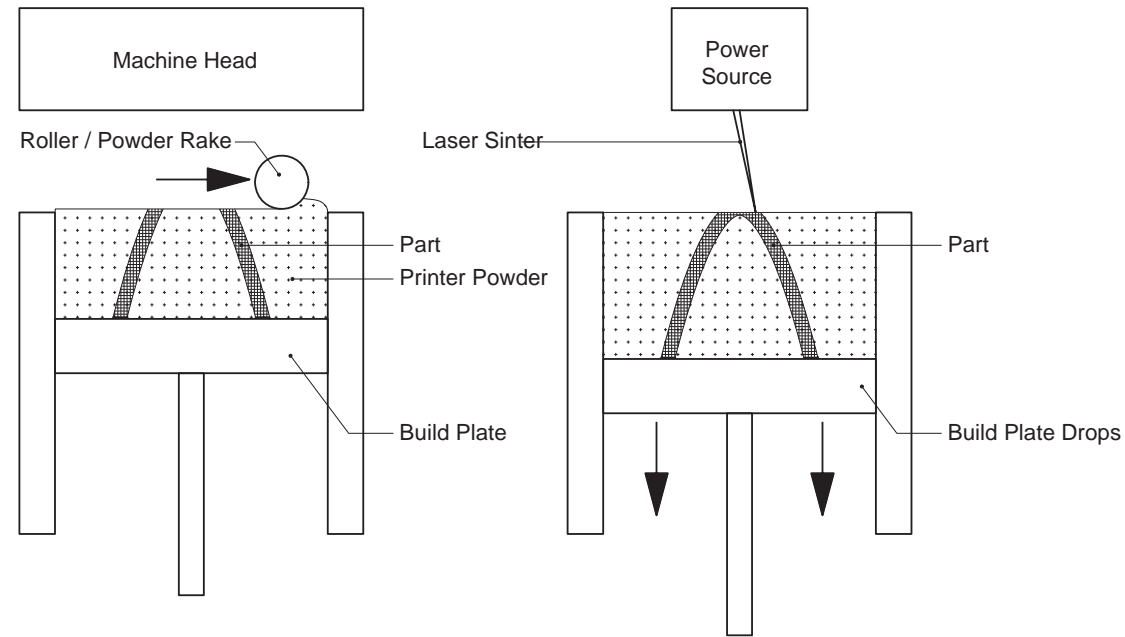
Existing methods deploy the powder-bed method to either bind or sinter a fine ceramic dust.

There is a small group of people experimenting with ceramic extrusion technology but not much is published (outside of blogs and misc websites). Knowledge of the subject is still limited but information exists on the technology.

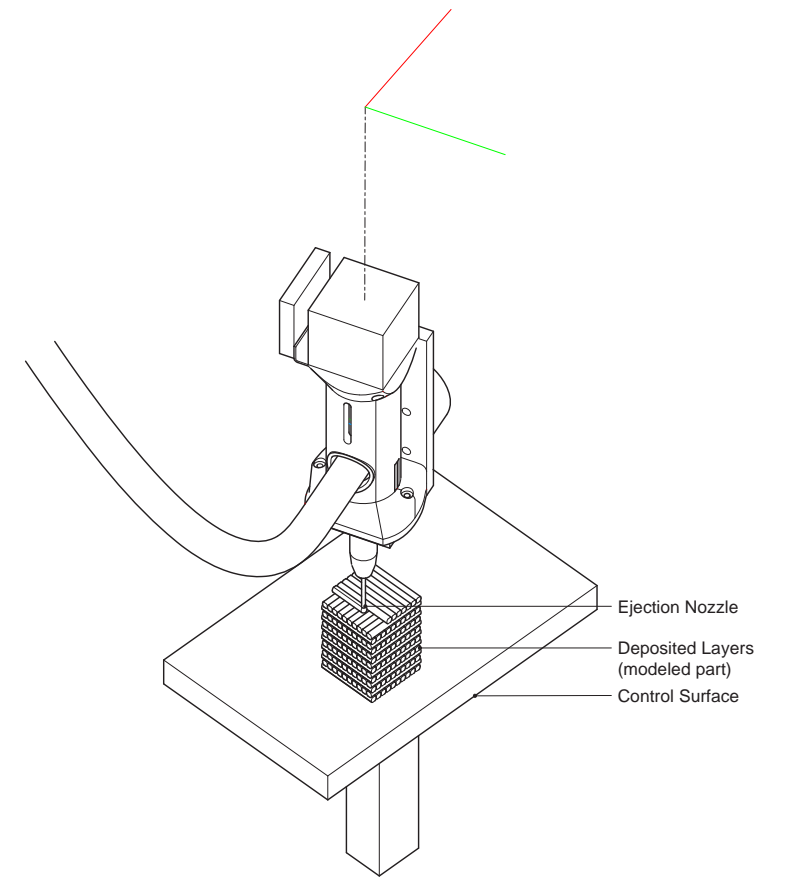
Most importantly:
*ceramic material properties fit within frameworks of these existing technologies.

NOTE:
LSL (laser selective sinter)
--production at Shapeways.
FDM (fused deposition modeling)
--most applicable for industrial production
(speed, scale, accuracy & cost)

DIGITAL PRODUCTION / 3D PRINTING



POWDER BED



X,Y,Z EXTRUSION

Machine-Material Manufacturing Design

To advance ceramic extrusion 3D printing technologies, it was important to gather a small but more informed understanding of larger scale extrusion manufacturing.

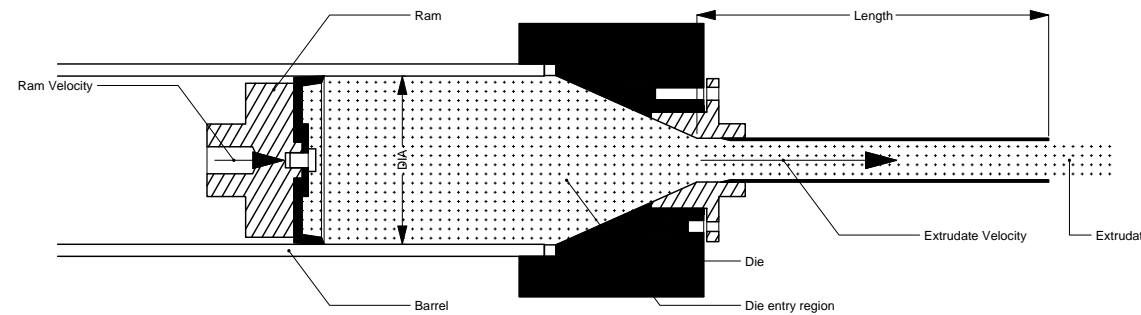
Machine science and material science have a profound effect on the production of architectural components.



Basic Column Extrusion Machinery



source: Andreani



Basic Piston Extrusion



Händle, F. *Extrusion in Ceramics*

MACHINE SCIENCE

"Ceramic Roller Extruder." Xiangtan Weida Electrical and Machinery Manufacture Co.,LTD. Accessed January 26, 2016. <http://www.tilemachinery.com/product/ceramic-roller-extruder-2/>.

Diagram by Author

MATERIAL SCIENCE

Andreani, S. (2013). Stefano Andreani, "[R]evolving Brick: Informed Design and Robotic Fabrication Workflow for Strategic and Sustainable Mass Customization of Complex Ceramic Building Systems" Master in Design Studies Technology Concentration, Harvard University Graduate School of Design, 2013.

Händle, Frank. *Extrusion in Ceramics*. Berlin: Springer, 2007.

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Design Argument

Why 3D printed ceramic
extrusion.

Why the research is valuable.

What the research can
contribute to architectural
construction technology.



ARGUMENT



Argument

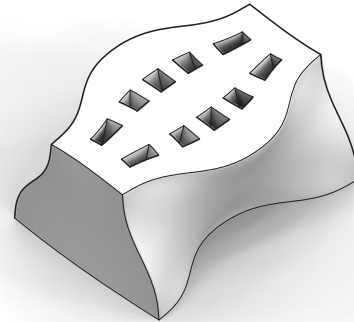
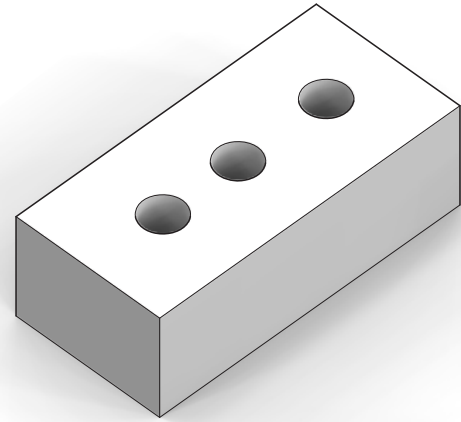
I had to ask:

- Why does the brick need to be manufactured with 3D printing technology?
- Why wouldn't this item be produced with other proven manufacturing methods?

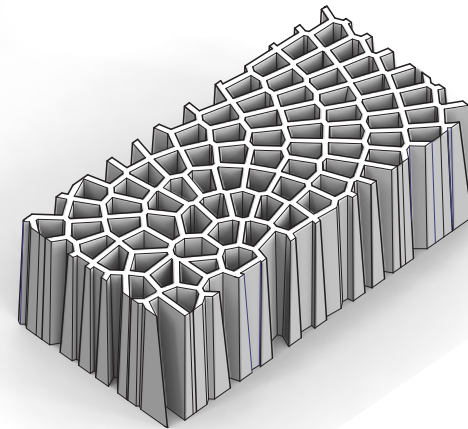
Essentially, the brick has a performative aspect embedded into its geometry.

- mass customization (most obvious argument)
- environmental performance
 - heat transfer
 - light
- connection detail / interface
- or simply visual articulation for experiential effect

I used this thesis to exercise my ideas for structural performance and visual / experiential effect.



NOVEL GEOMETRY



Manufacturing Typology

Screen shows on left a brick I printed but had quoted by the GSD FabLab. At right is an image of a block I used to investigate the fabrication parameters of a system I would later design to test toolpaths for a 6-Axis robotic arm.

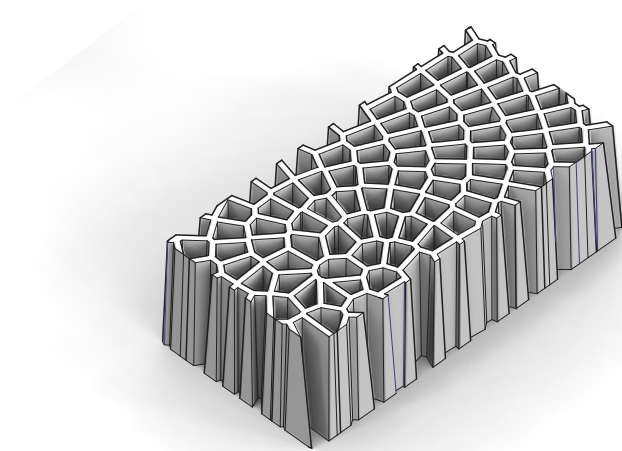
In any case, no matter which method is used: 3D printing affords the designer an architectural advantage with -limited bespoke manufacturing

But it's expensive...

Powder printing is an option with machines similar to those at the GSD; only a slight modification is required. However, it is not currently a viable manufacturing process for architectural components. Material costs are high and from what I understand, due to its low density, powder-printed components are not capable of carrying the structural loads expected in architectural design. Market dynamics might change cost and access to these materials.

+3.5 hr print time
subsidized at \$160 USD

low-density



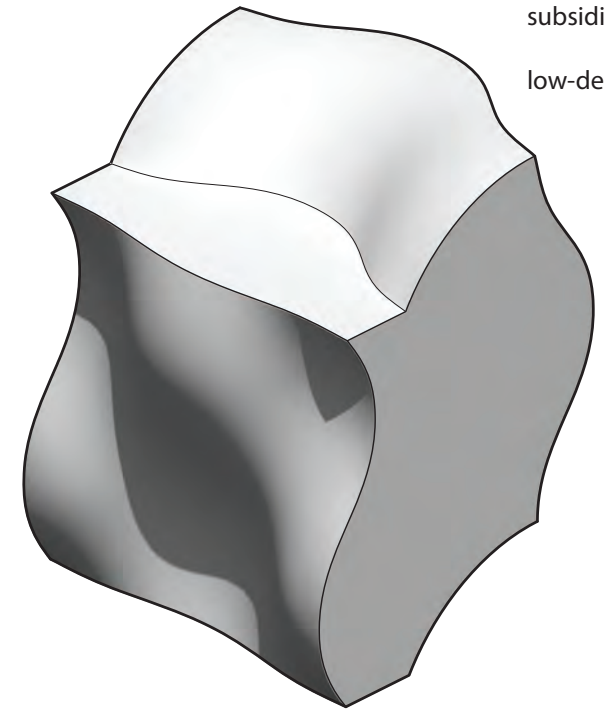
+34 hr print time
subsidized at \$155 USD

high resolution
tensile strength

POWDER BED PRINTER

subsidized at \$900 USD

low-density



ABS EXTRUSION PRINTER

Manufacturing Innovation

--Structural Loads Cont.--

I believe that the field of 3D printed ceramics can contribute more to architectural design than the examples I've encountered to date..

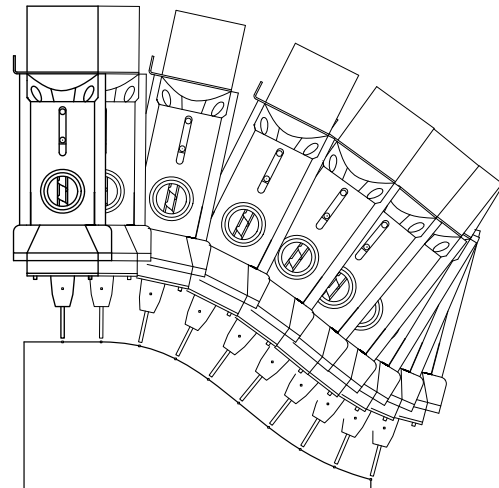
Powder printing has its structural limits and the printing machines keep getting bigger and bigger. Extruding custom building components seems to have a greater range of promise.

I believe that multi-axis printing further increases this range of potentially printed architectural components.

I will explain 3,5 and 6-Axis printing in a minute.



LAUFEN ceramic factory



5-Axis Clay Extruder

"LAUFEN Factory Visit: Ceramic Casting." Designboom Architecture Design Magazine. 2012. Accessed January 18, 2016. <http://www.designboom.com/design/laufen-factory-visit-ceramic-casting/>.

Diagram by Author

TECHNOLOGICAL VALUE



3D Printed "Sand" Masonry, V. San Frantello & R. Rael

Flaherty, Joseph. "Architects Create a 3-D Printed Column That Survives Earthquakes." Wired.com. Accessed June 7, 2015. <http://www.wired.com/2014/10/architects-create-3-d-printed-column-survives-earthquakes/>.

Construction Technology -design driver

As a personal interest, I used this opportunity to consider structural innovation with a contribution to construction technology.

I recognized that an arch is stable only when entirely complete but the form work used to construct the arch must be stable during the entire construction project; then carry the weight of the arch before it is removed.

-As much design goes into the construction of the formwork as does the finished project. I wanted a masonry building design that could be constructed using minimal formwork.

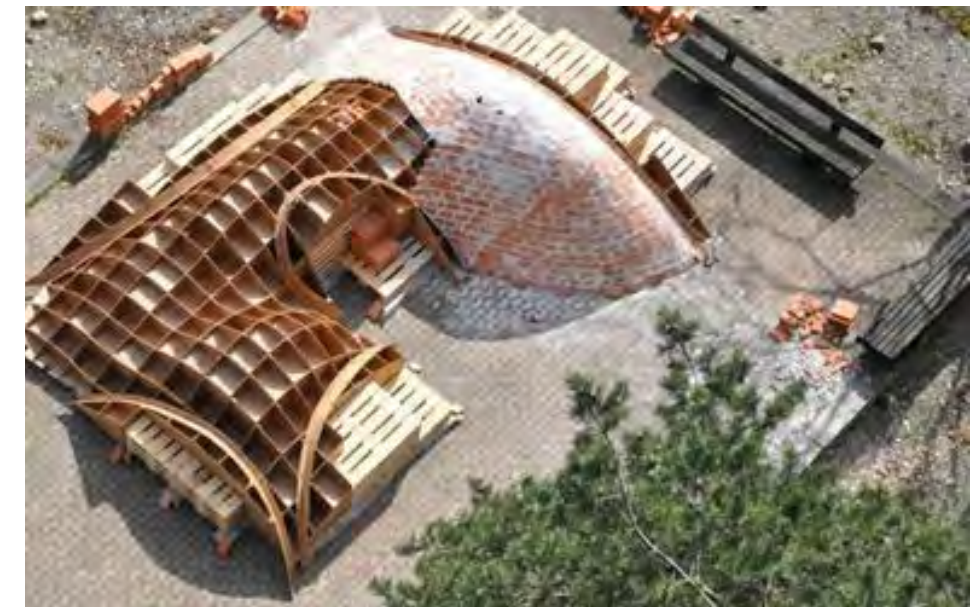
Even advanced digitally designed projects, such as those by the Block Research group, require innovative form work.

-here, the Block Research group at the ETH-Zurich built the formwork on paper tubes in little trays that could soak in water to facilitate removal.

To investigate my hypothesis, this thesis project contributes to industrial ceramic manufacturing, digital design and fabrication processes in the field of architecture, and offers novel ideas to advance methods for building assemblies.



Salginatobel Bridge



Block Research Group

FORM WORK



Eladio Dieste



"Some Images of the Salginatobel Bridge." TWiki. Accessed January 26, 2016. <http://twiki.org/cgi-bin/view/Salgina/ImagesOfTheSalginatobelBridge>.

Anderson, Stanford. *Eladio Dieste Innovation in Structural Art*. New York: Princeton Architectural Press, 2004.

Maillart, Robert. *Engadine: Salginatobel Bridge General View, 1930*, Data From: University of California, San Diego.

Lewis, Miles. "later brick & terra cotta." *History of Building class lecture*, University of Melbourne.

Breitfuss, Klemen. "Free-form Catalan Thin-tile Vault, Zurich, Switzerland." BLOCK Research Group. Accessed January 26, 2016. <http://www.block.arch.ethz.ch/brg/project/free-form-catalan-thin-tile-vault>.

Breitfuss, Klemen. "Free-form Catalan Thin-tile Vault, Zurich, Switzerland." BLOCK Research Group. Accessed January 26, 2016. <http://www.block.arch.ethz.ch/brg/project/free-form-catalan-thin-tile-vault>.

5 PAGE SPREAD

Structural Abstract

Outline of the design proposal
as developed from a structural
ideal.

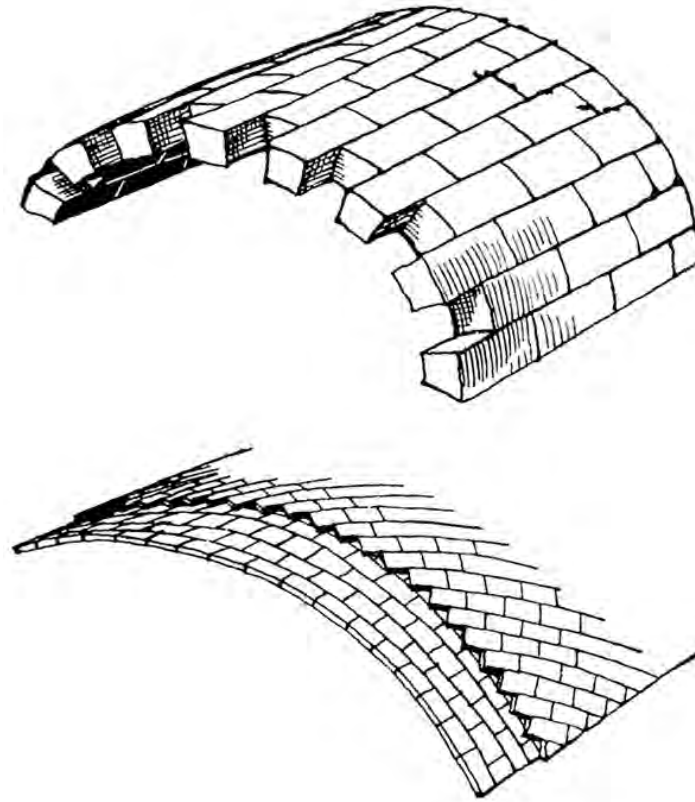


STRUCTURAL ABSTRACT



Construction Concept

Many of us know about the Guastavino family's work at the turn of the century where they developed and patented the construction of "fire-proof" masonry vaults. The catalan vault contributed to the development of my proposal, where I conceptualized a defined arch and infill structure to compose a series of masonry domes.



Ochsendorf, John. "Guastavino Masonry Shells." STRUCTURE Magazine. Accessed January 26, 2016. <http://www.structuremag.org/?p=2046>.

CONSTRUCTION TECHNOLOGY

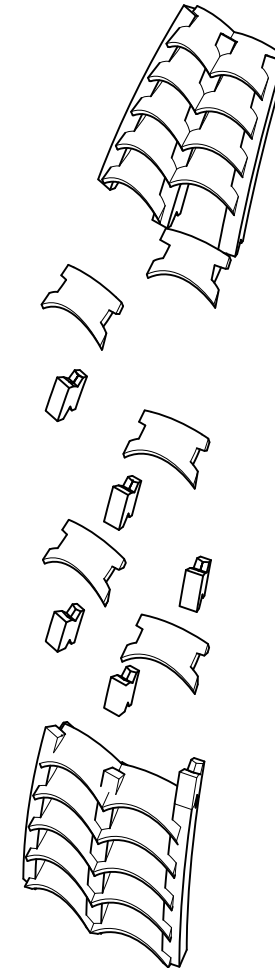


Diagram by Author

Geometric Concept

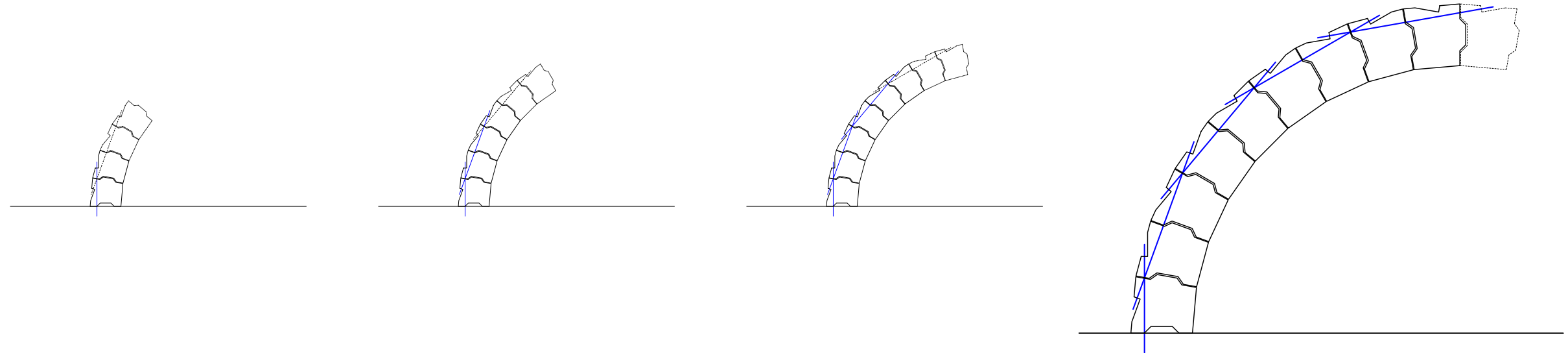
Knowing that I was looking for a novel, only-3D printable geometry, my design was focused on how to built a simple arch with little or no formwork.

The Block Research Group's work illustrated that catalan vaulting can be used as an infill strategy to distribute the building's structural loads.

However, I was reluctant to grab onto the form-active structure in part knowing that I could not offer an accurate computational solution, making me less confident about the overall design.

In any case, I feel that this is could be another research strategy, to custom print rib components and infill with Guastavino-type tiles.

MASONRY FORM WORK



Zurich, Switzerland, 2012



Melbourne, Australia, 2013

Diagram (above) by Author

Images (below):

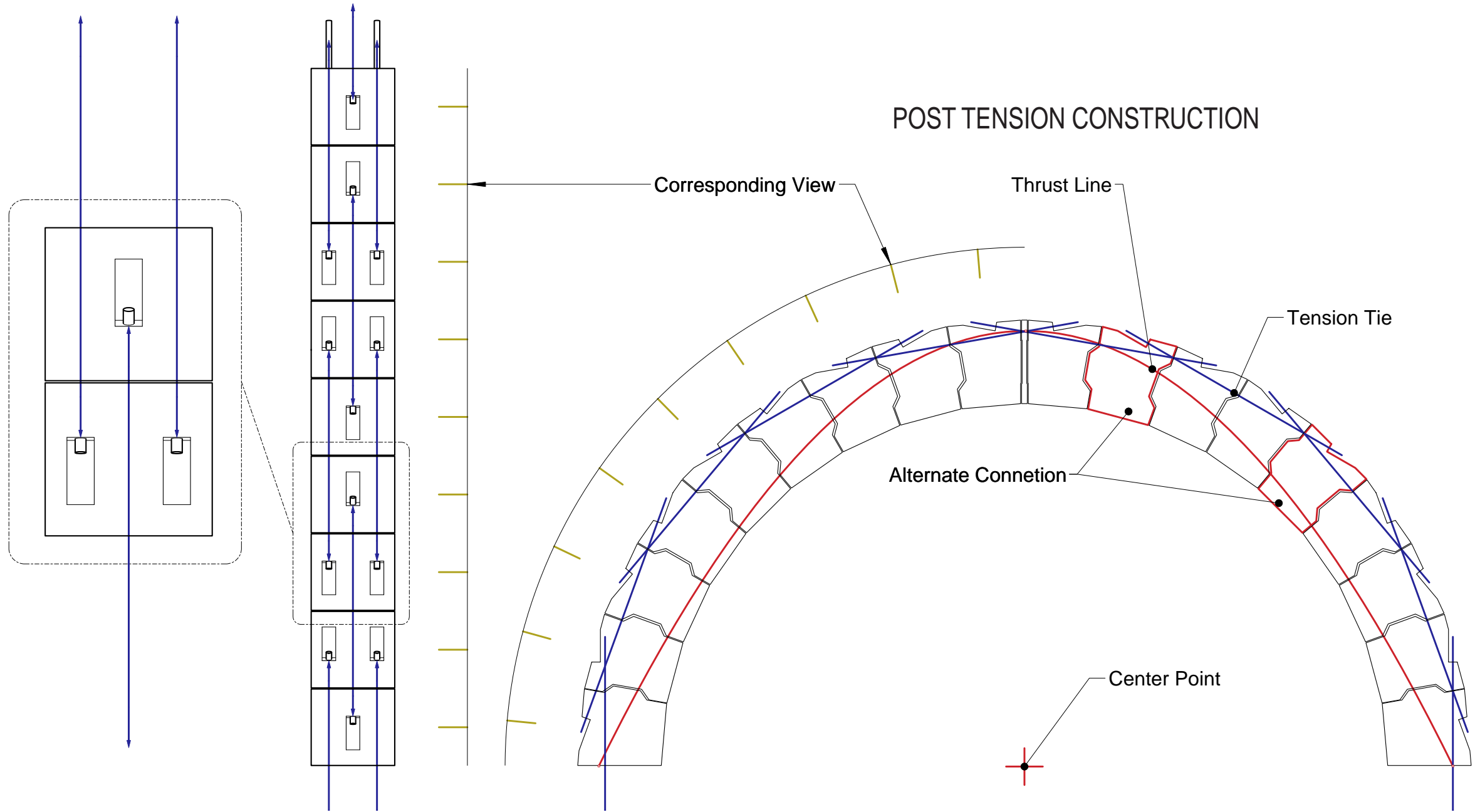
Breitfuss, Klemen. "Free-form Catalan Thin-tile Vault, Zurich, Switzerland." BLOCK Research Group. Accessed January 26, 2016. <http://www.block.arch.ethz.ch/brg/project/free-form-catalan-thin-tile-vault>.

System Premise

Instead, I investigated an idea about a post-tensioned compression structure where a series of cables pull between blocks across the spine of the arch.

Essentially, the first two blocks are tied directly to a concrete foundation with every 4th block above strung together.

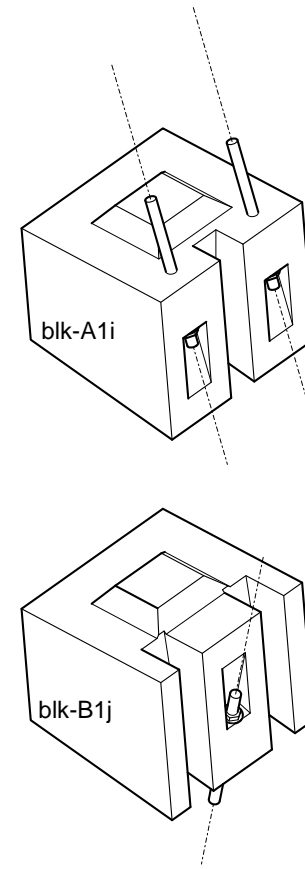
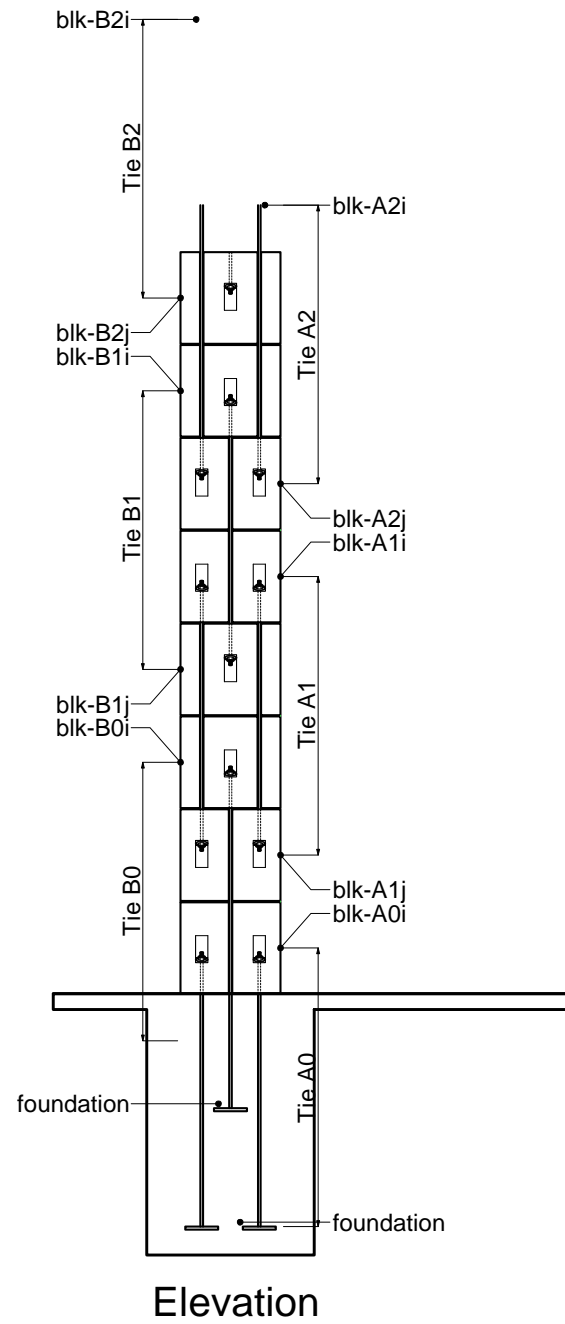
The assembly of the keystone blocks must be well planned and in any case, 4 different blocks can be used to construct this Roman arch of 18 voussoir elements.



System Development

The construction sequence would benefit from a slotted channel (opposed to a hollow chase originally conceived) to run the post-tensioned cable. The cables could be pre-cut, having rigid and threaded ends, bolted into place (shown in later drawing).

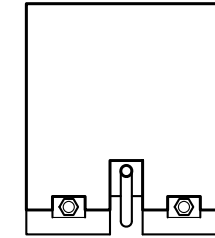
The system, modeled as a square to conceptualize, can be further developed within a design boundary defined by the loads the arch is intended to carry.



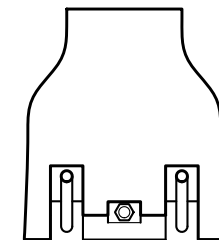
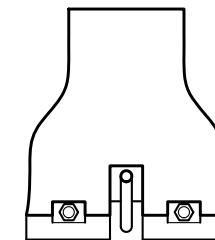
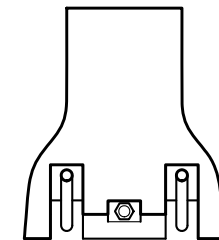
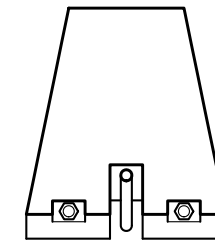
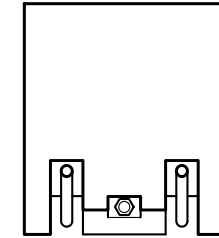
Block Type

BLOCK DEVELOPMENT

Section: blk-A1i



Section: blk-B1j



Speculative Design Boundary

Component Design

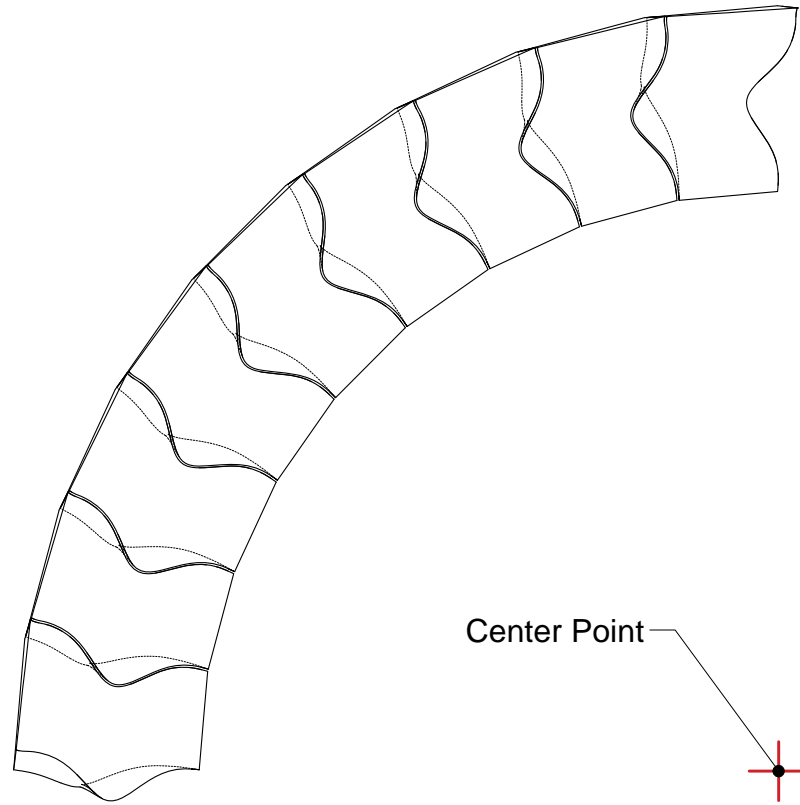
Because the production of geometry is cheap, a saddle, osteomorphic joint can be used to nest the blocks together, adding to the arch's overall stability.

The articulated joint moves the center of gravity of each block, slightly effecting the point of buckling between blocks (diagram not shown).

The benefits of 3D printing contribute to complex, well articulated mating surfaces.

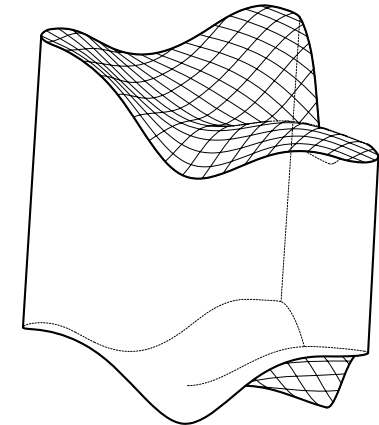
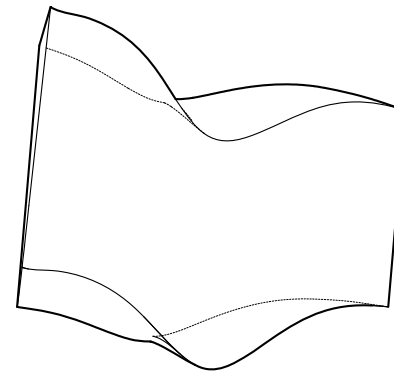
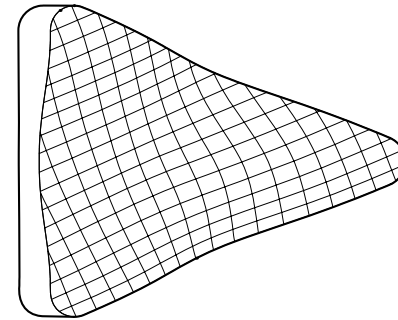
Additional design features to incorporate could include:

- the post-tension slot already described
- water shedding geometry
- connection strategies
- mortar channels + locks
- channel to accept and define the arch of a hand-laid Catalan vault



Center Point

OSTEOMORPHIC NESTING



4 PAGE SPREAD

Structural Proposal

Summary of structural
behavior for design proposal



STRUCTURAL PROPOSAL

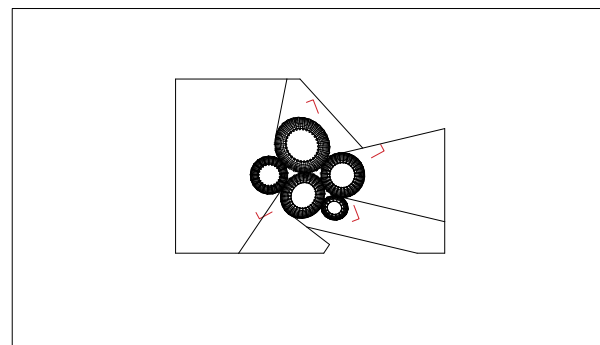


Geometric Concept

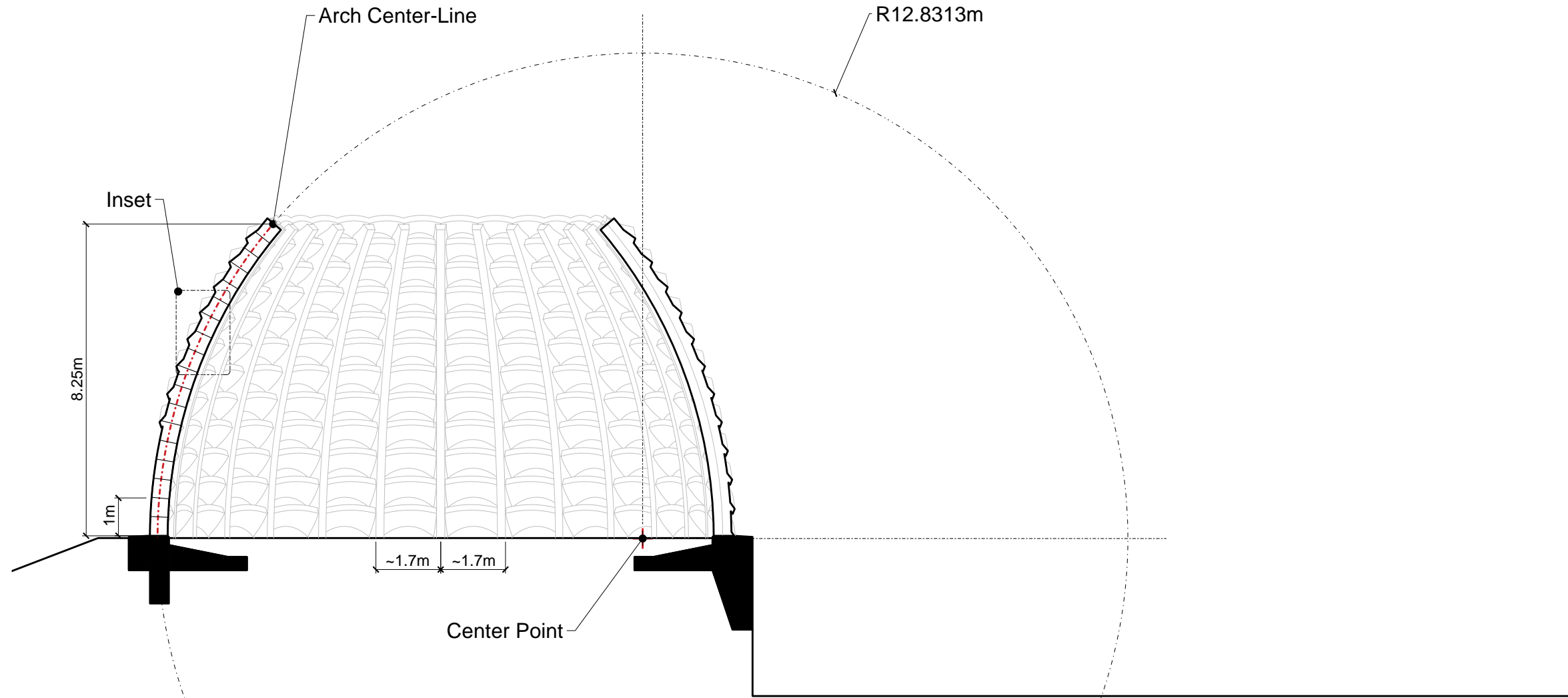
Each dome is organized by a planer circle at the foundation. Each rib is an arc, rotating along the base at about 1.7m intervals.

Although it will be a challenge to print and fire (but possible), I estimate that the ceramic blocks would need to be about 0.5m square to support a structure this size.

Calculations would have to be made by a qualified engineer to confirm the hypothesis



TECHTONICS

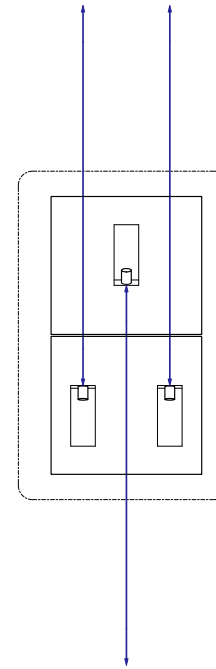
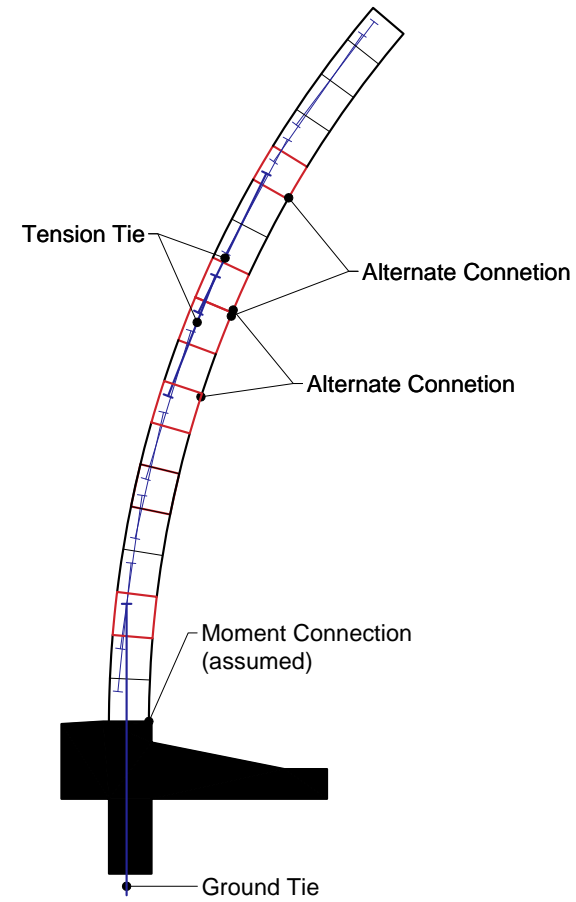


Structural Concept

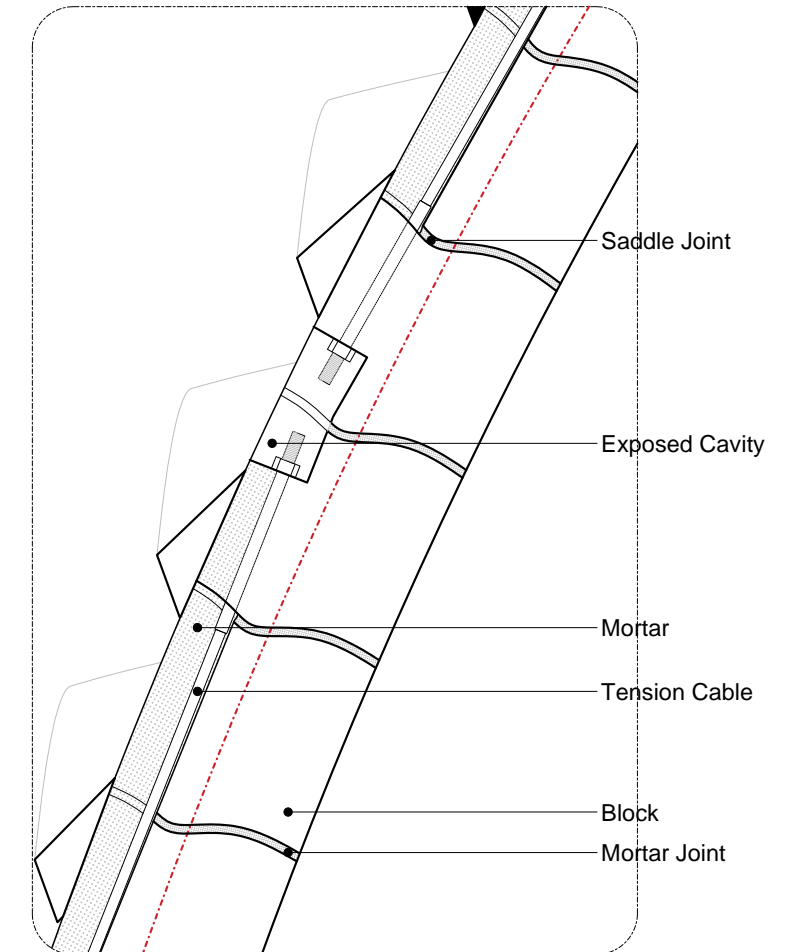
Post-tensioned cables run up the spine as proposed earlier.

Cables are staggered and alternate between the joints of every fourth block.

Once constructed, the cables are encapsulated with mortar for protection, creating a composite with the adjacent voussoir.



CONNECTIONS + POST TENSIONING



Structural Concept

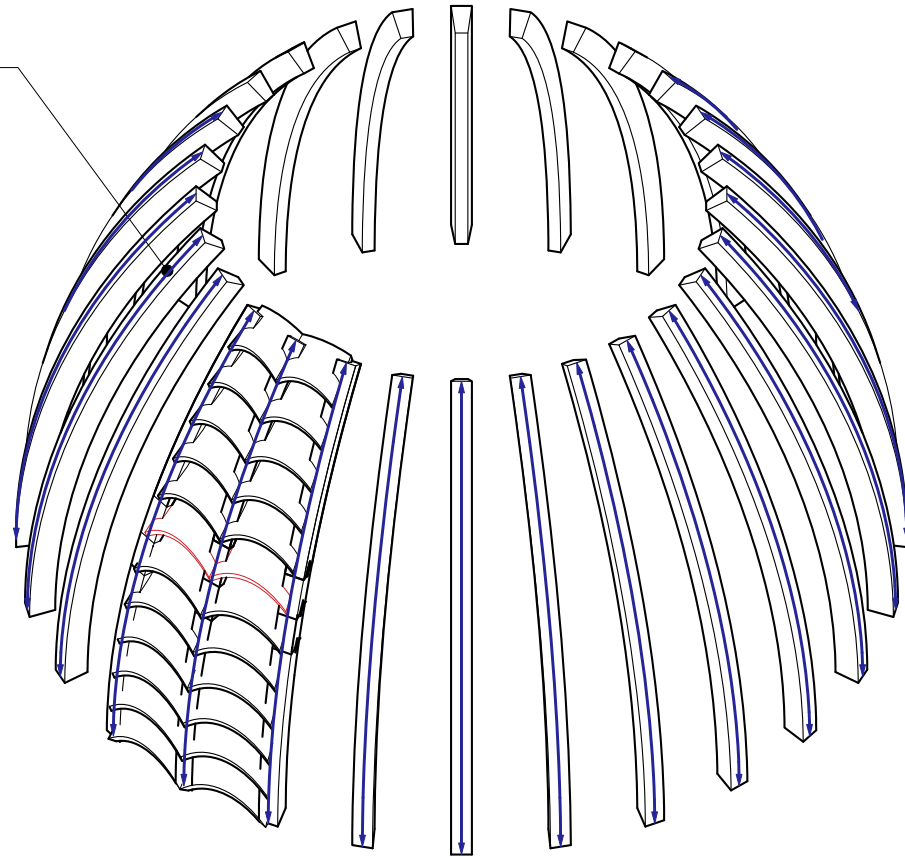
Smaller hyperbolic vaults, hopefully printed (we'll have to see how large a component we can print) spring between single ribs.

The section of each vault is doubly curved and self-stable. This curvature, especially if glazed, should contribute to a softened light rolling over the surface edge.

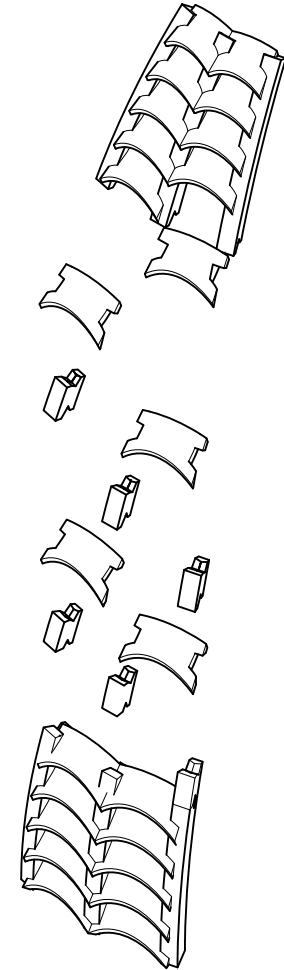
Construction is alternated block, vault, block, etc.

The vaults function to help resist buckling, each engaging two layers of block at each row.

Tension Line

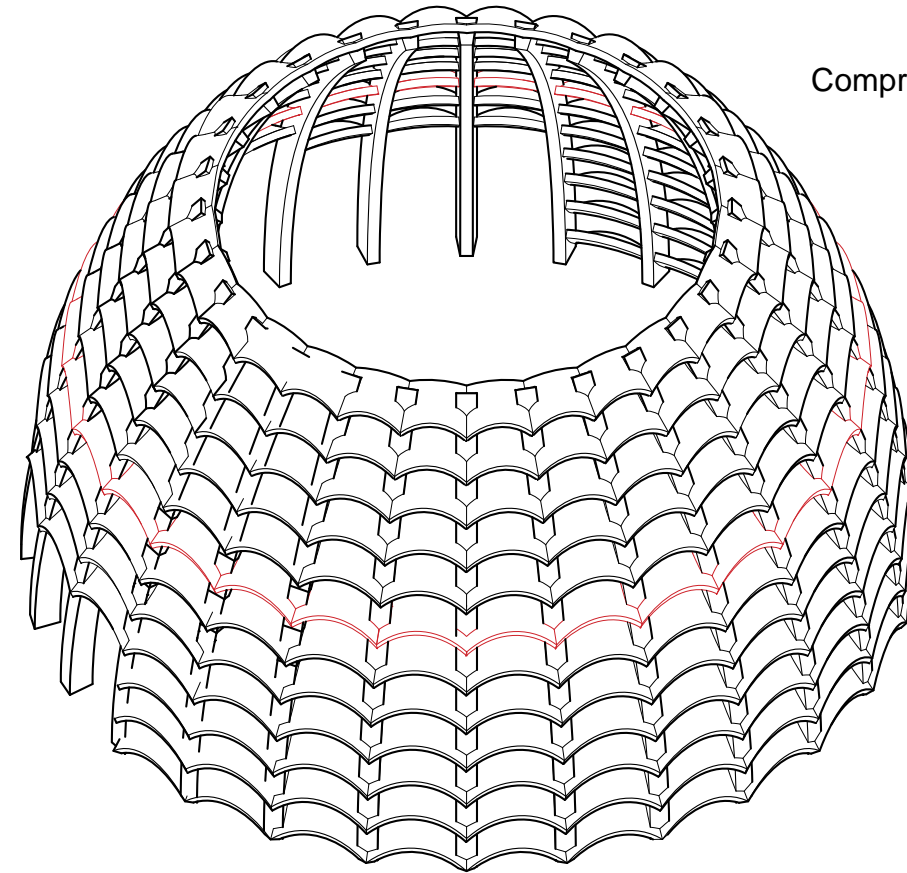


ASSEMBLY



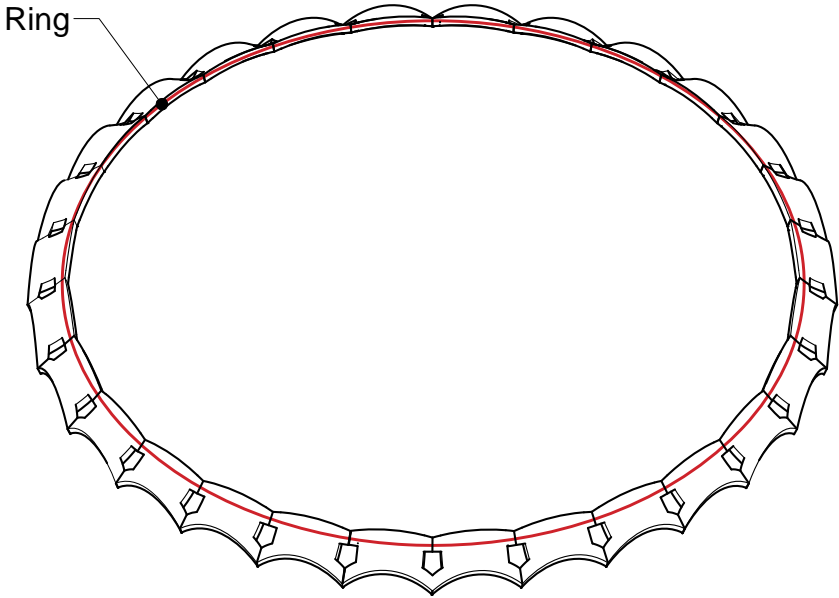
Structural Concept

Vaults and ribs engage each other directly, continuously transferring and distributing loads around each horizontal ring; collapse of the rings inward would be countered by the post-tensioned cables traveling the spine of each rib.



LOAD DISTRIBUTION

Compression Ring



6 PAGE SPREAD

Production Design

Description of the tools and credits to the contributors which formed the base of printer construction.



PRODUCTION DESIGN



Extruder Summary

This chapter outlines a series of existing prototypical machines I reconfigured to fabricate the proposed block geometry.

I began by reconfiguring the MaP+S Research group's existing piston extruder configured to mount on the GSD's ABB-4400-L30.

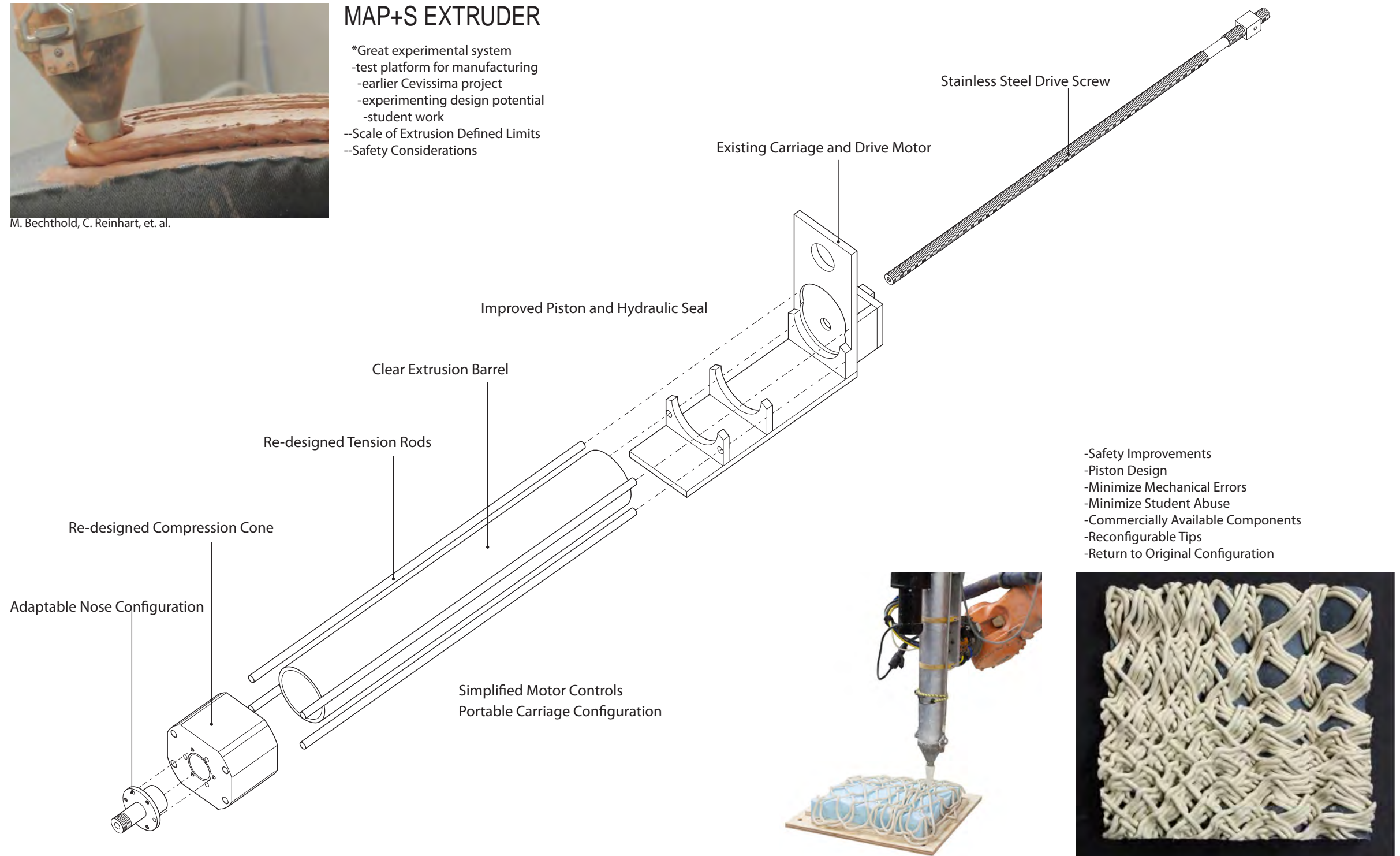
It's size contributes to defined production limits and detailed articulation, effecting design possibilities.



M. Bechthold, C. Reinhart, et. al.

MAP+S EXTRUDER

- *Great experimental system
- test platform for manufacturing
- earlier Cevisima project
- experimenting design potential
- student work
- Scale of Extrusion Defined Limits
- Safety Considerations



- Safety Improvements
- Piston Design
- Minimize Mechanical Errors
- Minimize Student Abuse
- Commercially Available Components
- Reconfigurable Tips
- Return to Original Configuration

"Ceramic Printing." YouTube. June 29, 2011. Accessed July 5, 2015. <https://www.youtube.com/watch?v=alyxH5QwAME>. Harvard Graduate School of Design, Design Robotics Group.

Diagram (center) by Author

Images lower right:
Freidman, Jared, Heamin Kim, and Olga Mesa. "Experiments in Additive Clay Deposition: Woven Clay." Rob|Arch 2014, May 17, 2014.

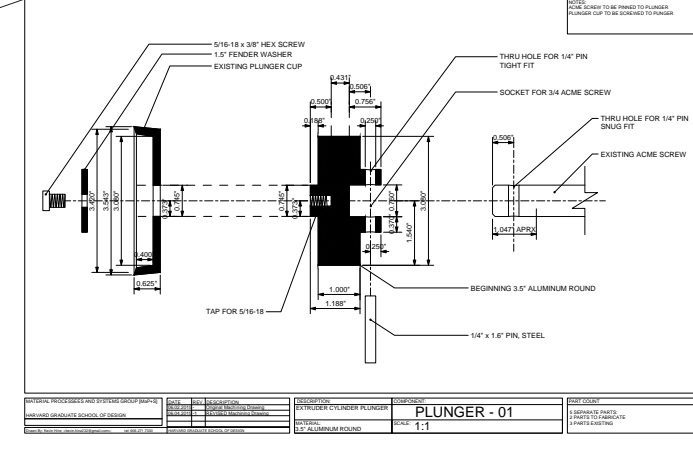
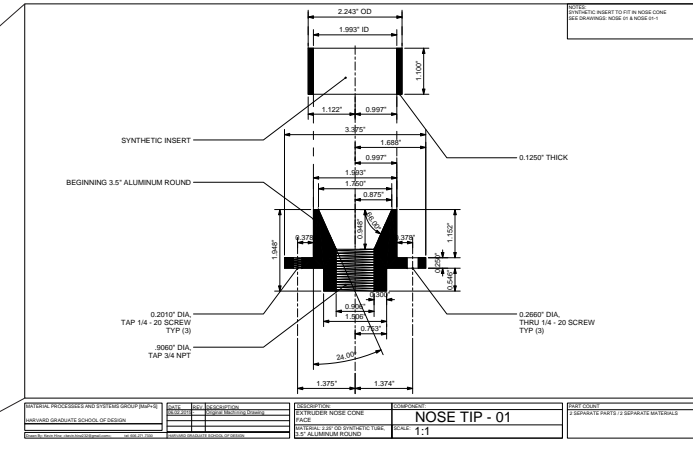
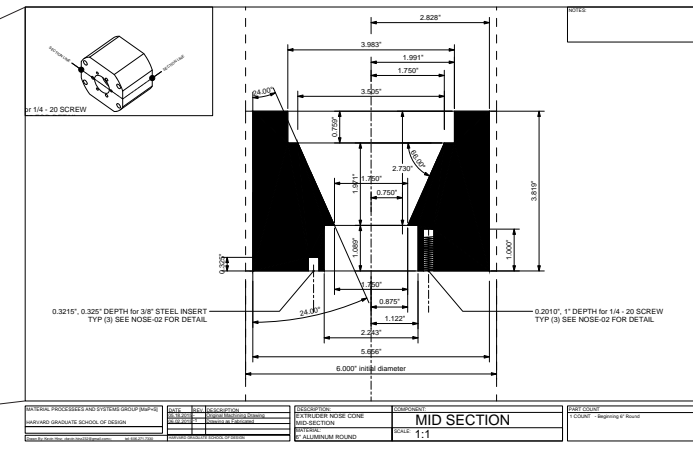
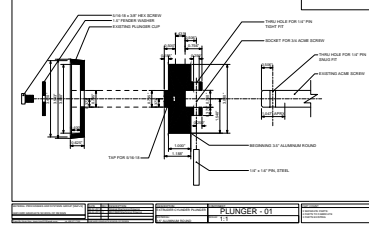
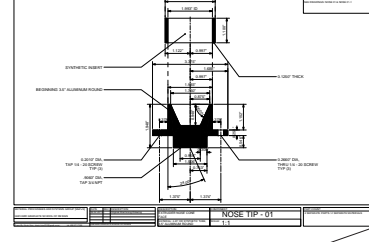
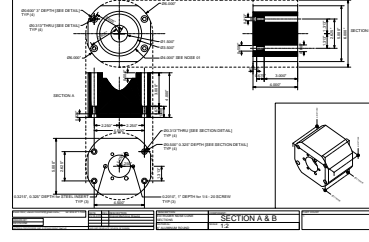
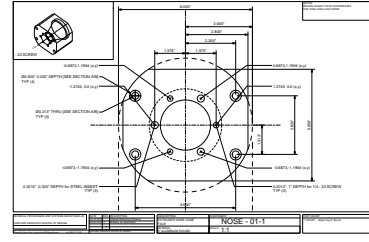
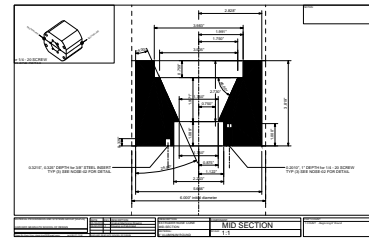
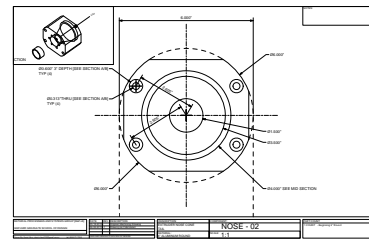
J. Friedman, H. Kim, O. Mesa.

Extruder Summary

Modifications involved a robust compression funnel and integrated feed tube.

Other safety modifications were introduced or redesigned as necessary.

The re-design incorporated off-the-shelf hydraulic piston parts and a precise but adaptable nozzle tip.



- *precise fit and seal parameters
- smooth cone transition
- adaptable attachment configuration

DESIGN FEATURES

- *nylon slip-fit sleeve (should be Acetal)
- integrated nose pull - release
- 3D printable configuration
- standard pipe-fitting attachment

- stainless steel drive screw
- machined piston
- commercial hydraulic piston cup
- *corrosion resistant / washable parts

Diagram (all) by Author, sponsored by MaP+S

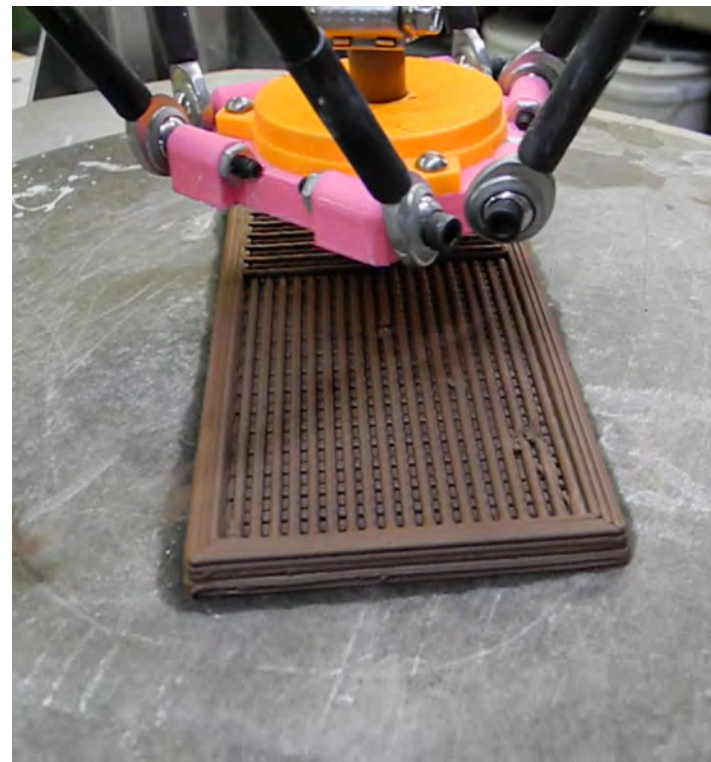
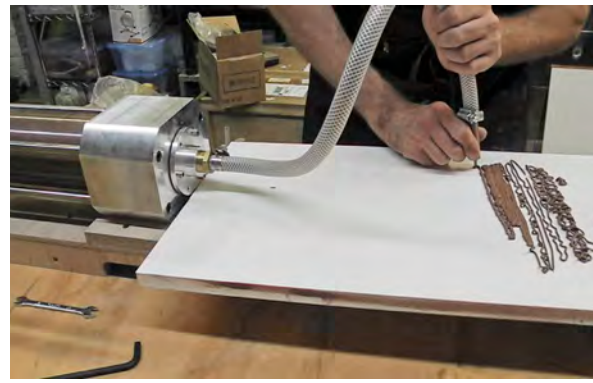
Extruder Summary

It was important for me to integrate existing, ready to find products in the initial stages of the experiments.

With help from Jessica Brandl and Brian Czibesz, I learned techniques to hydrate the clay and load the piston. Essentially, a 25lb bag of clay is perforated and soaked in water for 12 hrs. With this level of perforation, the clay absorbed exactly 2lbs of water.

The result is a plug-and-play system extruding approximately 14lb of hydrated Standard Clay C/04 Red Earthenware before a recharge is necessary.

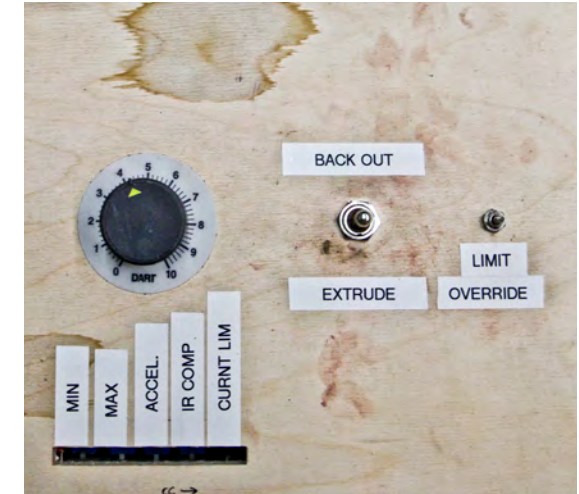
The piston extruder, designed in this case for clay, is actually a multi-material extruder, expanding the possibilities of this research.



HYDRATE



LOAD



PRINT

Printer Summary

The project continued with the deployment of an opensource CNC configuration to test the material parameters.

My early research, sponsored by Prof Bechthold, was supplemented by technical knowledge from Daekwon Park, GSD DDes and ceramic artists Jessica Brandl and Brian Czibesz whom I met at the Harvard Ceramics Lab in Allston.

They are an endless source of knowledge to begin the process of understanding the clay's material properties.

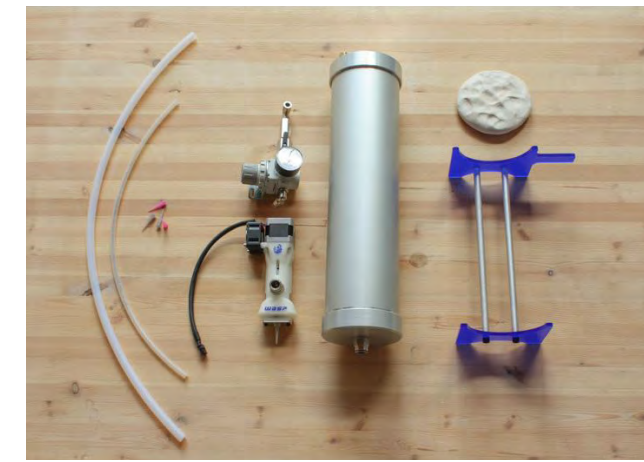
Other contributions involved the WASP Project's open source extruder stylus, a component I reverse engineered and fabricated with help from Harvard fabrication facilities.



Image (left) by Author



<http://www.wasproject.it/w/en/>



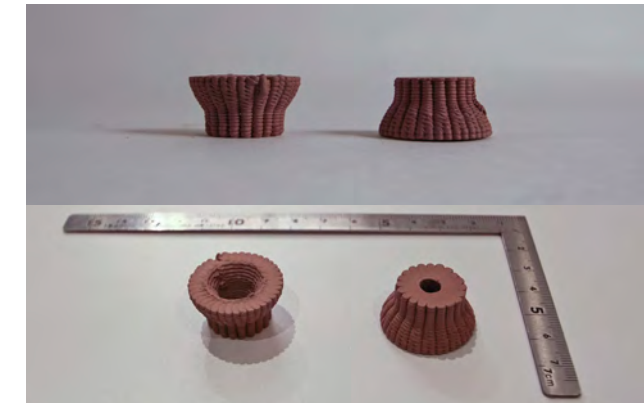
Commercially available screw auger. €650. WASP, Massa Lombarda, Italy.

WASP (World's Advanced Saving Project) is using the development and sale of Delta-Style 3D printers and printer components to fund a socially conscience agenda for affordable housing. Current research includes a 12m tall Delta-style printer and 3D printed concrete beam components. The WASP housing is now open-source, not including the critical transmission component.

Mobile Printer Configuration

MaP+S sponsorship
Daekwon Park contribution
--Jessica Brandl and Brian Czibesz
Open Source Delta Configuration
--online files & plug + play components
Affordable test bed
Highly mobile machine
Assistance from Harvard Ceramics
-Kathy King

Marlin Firmware
-delta printer
Johnathan Keep
-ceramic printing + delta summary
Slic3r
-g-code generator
WASP
-(almost) open source auger extruder



OPEN SOURCE + COMMERCIAL COMPONENTS

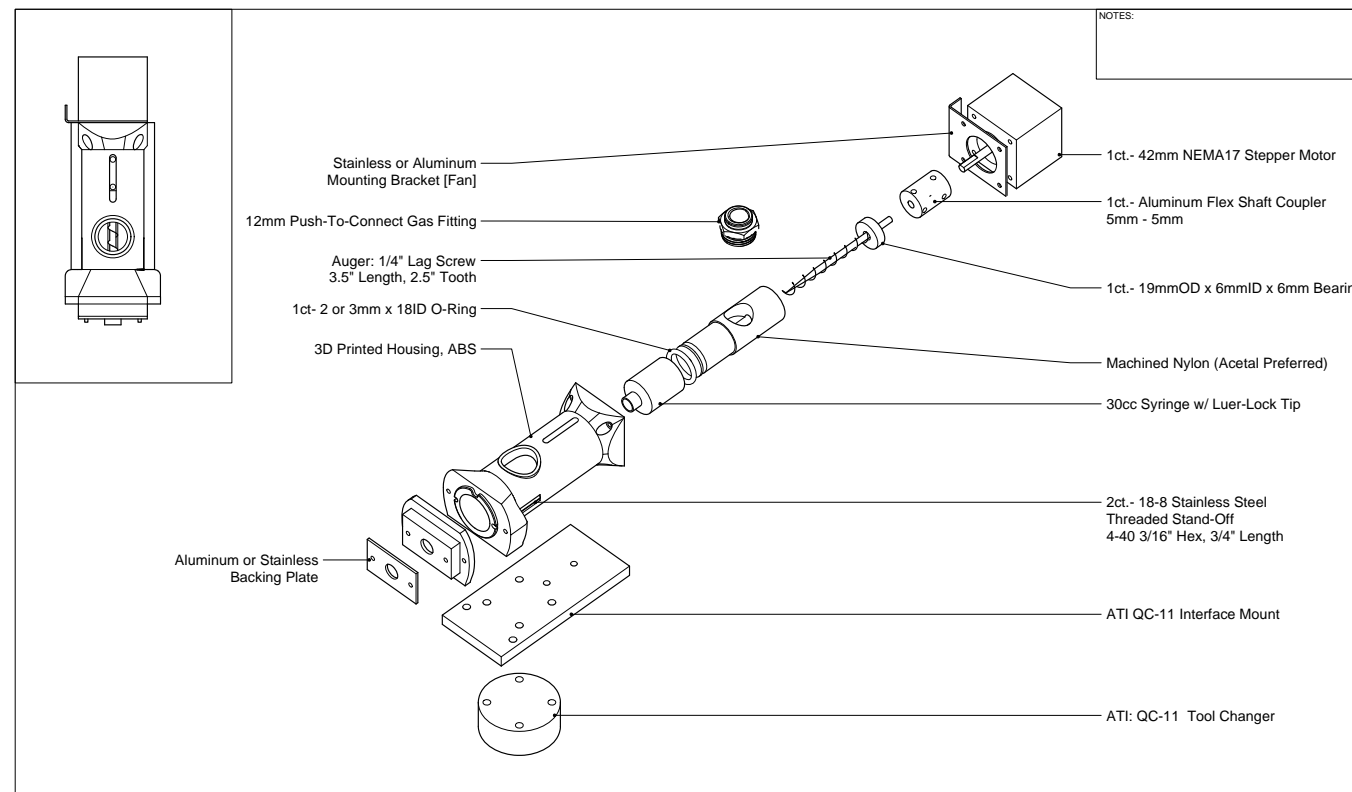
Images top:
"Clay Extruder Kit 2.0." WASP. Accessed September 10, 2015. <http://www.wasproject.it/w/en/>.

Image low right, by Author.

Printer Summary

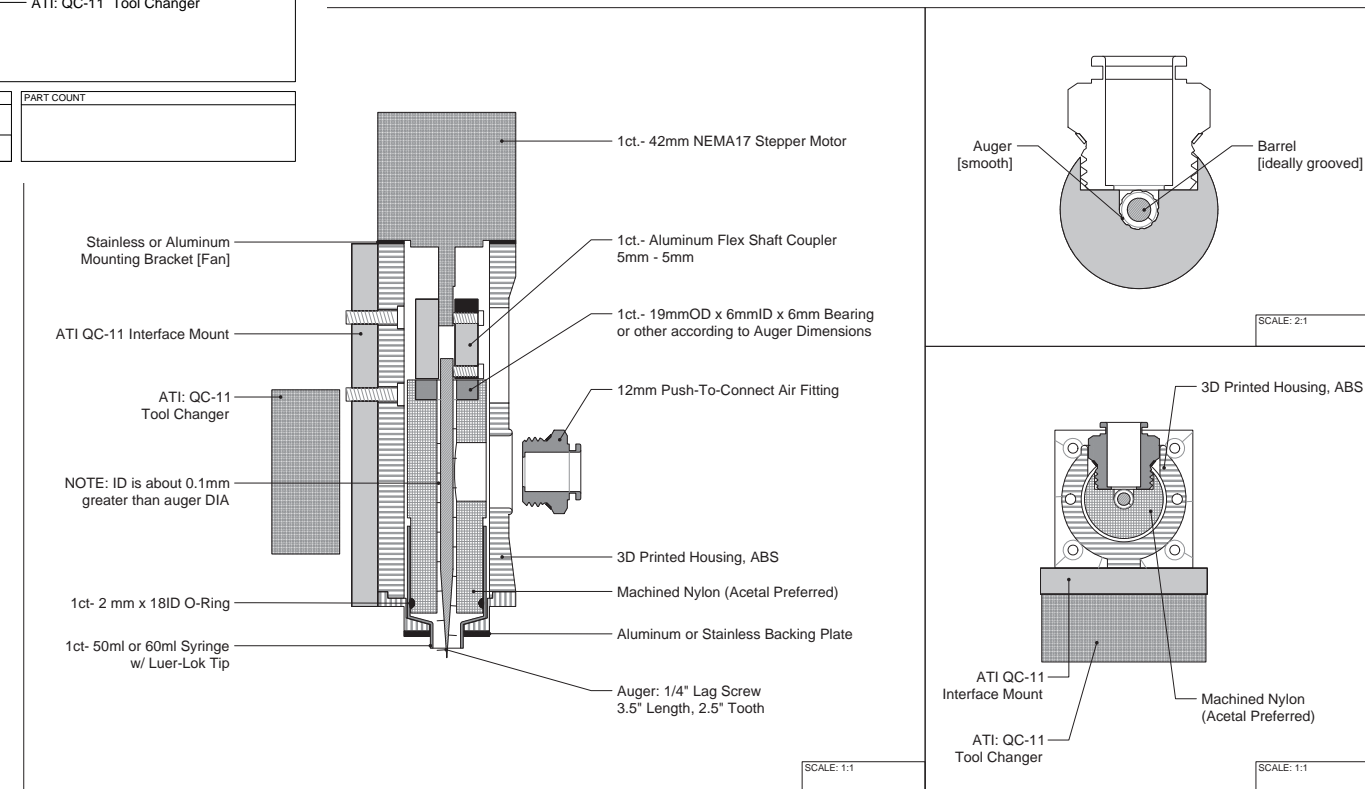
The extruder stylus uses an off-the-shelf stepper or DC motor to accurately control the feedrate of the clay body “piped-in” from the piston extruder.

More affectionately named the *Gimlet*, a small T-shaped cork screw tool for boring holes, the extruder body is configured to be mounted on either the 3-Axis Delta-style printer or to a standard ATI-QC-11 Interface puck for the ABB robotic arm.



MATERIAL PROCESSEES AND SYSTEMS GROUP [MaP+S]	DATE	REV	DESCRIPTION	DESCRIPTION:	COMPONENT:	PART COUNT
HARVARD GRADUATE SCHOOL OF DESIGN	10.06.2015		AXONOMETRIC DIAGRAM	AUGER EXTRUDER	AUGER DIAGRAM	
Drawn By: Kevin Hinz -<kevin.hinz232@gmail.com>	tel: 606.271.7330		HARVARD GRADUATE SCHOOL OF DESIGN	MATERIAL: MULTI	SCALE: NONE	

AUGER EXTRUDER / PRINT STYLUS



MATERIAL PROCESSEES AND SYSTEMS GROUP [MaP+S]	DATE	REV	DESCRIPTION	DESCRIPTION:	COMPONENT:	PART COUNT
HARVARD GRADUATE SCHOOL OF DESIGN	10.06.2015		AXONOMETRIC DIAGRAM	AUGER EXTRUDER	AUGER DIAGRAM	
Drawn By: Kevin Hinz -<kevin.hinz232@gmail.com>	tel: 606.271.7330		HARVARD GRADUATE SCHOOL OF DESIGN	MATERIAL: MULTI	SCALE: AS NOTED	

Images by Author, sponsored in part by MaP+S

6 PAGE SPREAD

Multi-Axis Extrusion

Analysis of precedents and discourse outlining parameters around multi-axis printing strategies.



MULTI-AXIS EXTRUSION



3D Extrusion

I discovered that the components composing my prototypical architecture are complex enough that it would be difficult to produce with existing 3-Axis extrusion technologies. One of the sample blocks I printed illustrated that difficulty.

A quick examination of extrusion precedents shows this: the surface of Prof. Bechthold's 4-Axis extrusion (from what I observe) is much more articulated and precise curvature than achievable by a 2D layered extrusion.

For definition and clarification:
--WASP
(World's Advanced Saving Project)
*open source foundation, now focused on large size (12m printer), now moving to 3D printed concrete.

I combined these two projects to develop my conclusions for this thesis.



Bechthold et al, Cambridge, 2011

"Ceramic Printing." YouTube. June 29, 2011. Accessed July 5, 2015. <https://www.youtube.com/watch?v=alyxH5QwAME>. Harvard Graduate School of Design, Design Robotics Group.



WASP, Italy, 2014

"Novità da WASP - Stampanti 3D." WASP. Accessed August 16, 2015. <http://www.wasproject.it/w/argilla-2/>.

CLAY EXTRUSION PRECEDENTS

Extrusion Precedents

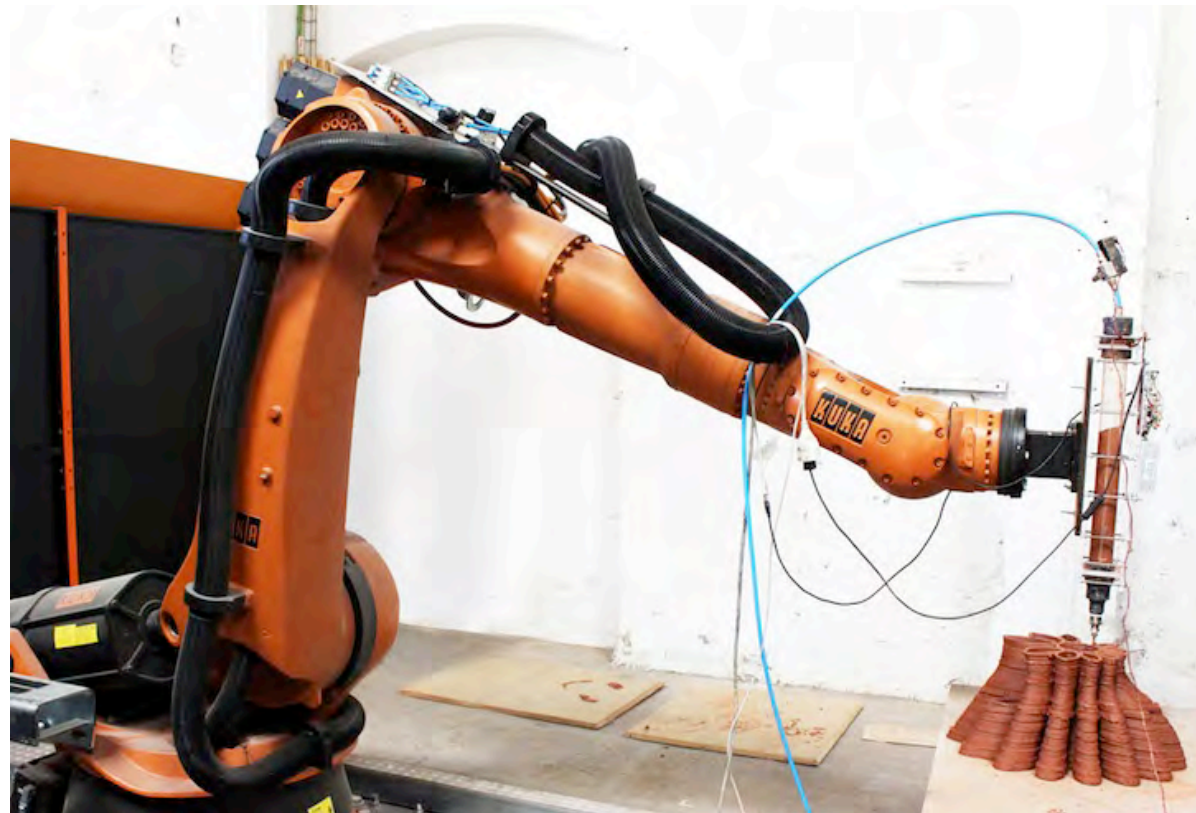
Most of the extruded ceramic printing I encountered deployed 6-Axis robotic arms to print in 3-Axis.

The IAAC in Barcelona has developed these processes further than anyone. Their current research is integrating speed and column-like components to develop novel structural geometries not unlike what we see hear.

The most interesting project I uncovered was in Buckinghamshire, UK where they used a Kuka and a sausage extruder to print columnare structures.

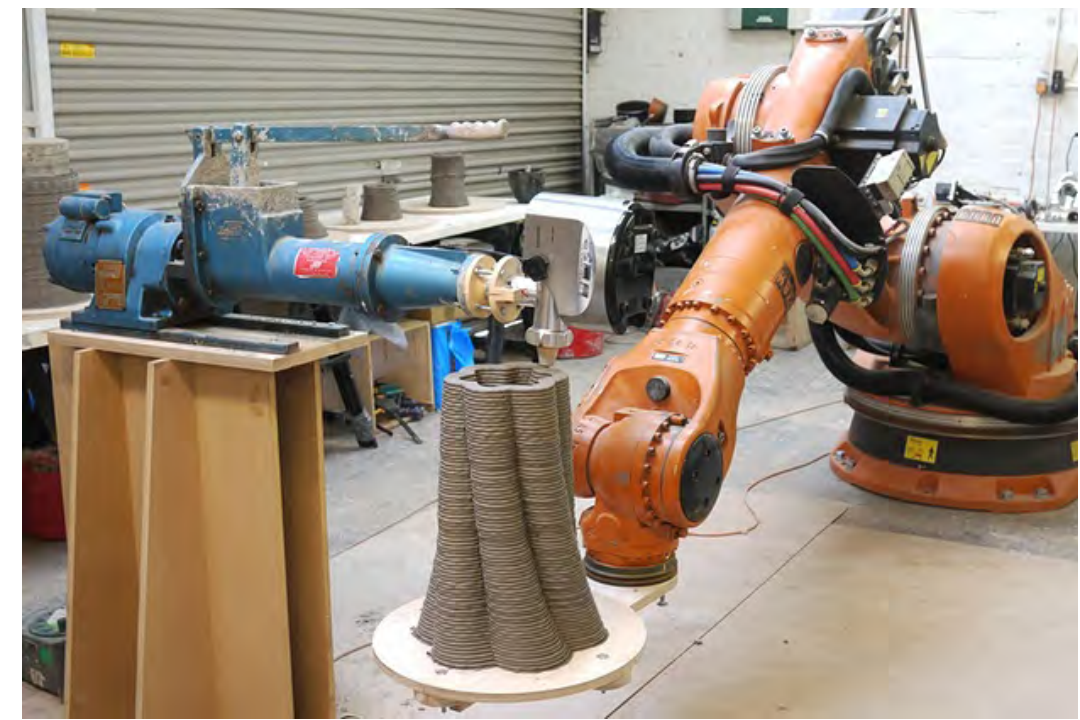
These examples prove that there are many innovations possible and many directions to turn for research.

THREE AXIS PRINTING



Barcelona, 2013

Naramore, Cameron. "Towards Automated Clay Home Construction, with FabClay," 3D Printer. February 4, 2013. Accessed December 1, 2015. <http://www.3dprinter.net/automated-clay-home-construction-with-fabclay>.



Buckinghamshire, UK, 2014



Barcelona, 2015

Wainwright, Oliver. "Clay Robotics: The Future of Architecture Is Happening Now in a Chilterns Farm." *The Gaurdian*. August 8, 2014. Accessed December 1, 2015. <http://www.theguardian.com/artanddesign/architecture-design-blog/2014/aug/08/clay-robotics-architecture-chilterns-farm>.

"PYLOS PROJECT'S SUSTAINABLE HOUSE 3D PRINTING GROWS TALLER - Microfabricator.com." *Microfabricator.com*. Accessed December 1, 2015. <http://microfabricator.com/articles/view/id/561d3ab43139447d238b4567/pylos-project-s-sustainable-house-3d-printing-grows-taller>.

Multi-Axis Extrusion

Let me iterate the differences of multi-axis printing techniques and the strategize they support:

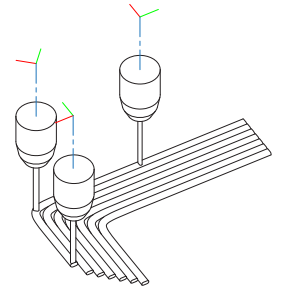
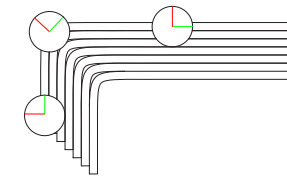
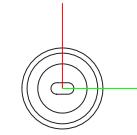
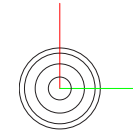
3-Axis is simple X,Y,Z movement of the print head.

5-Axis rotates the tip in a local X-Y coordinate system, in sync with XYZ table travel.

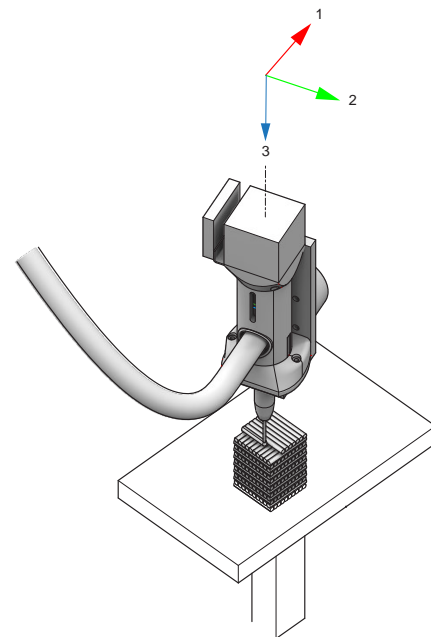
6-Axis printing is realizable only with an articulated print nozzle, where the orientation of a shaped nozzle influences the cross section of an extrusion coil.

I choose to stay with the cylindrical extrusion nozzle to limit complexity.

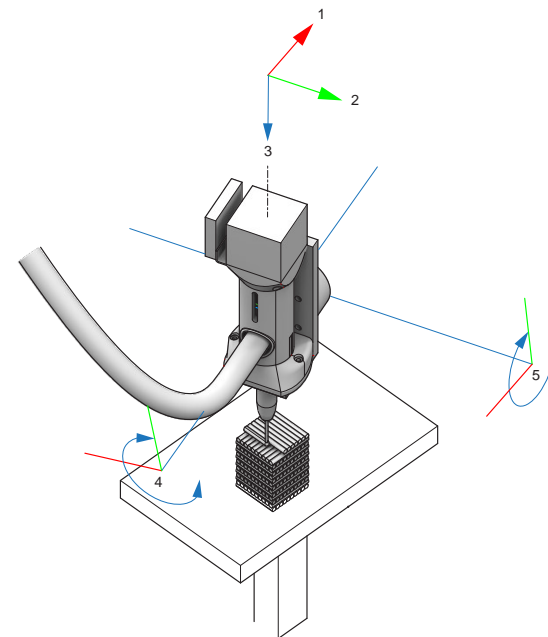
THREE AXIS PRINTING



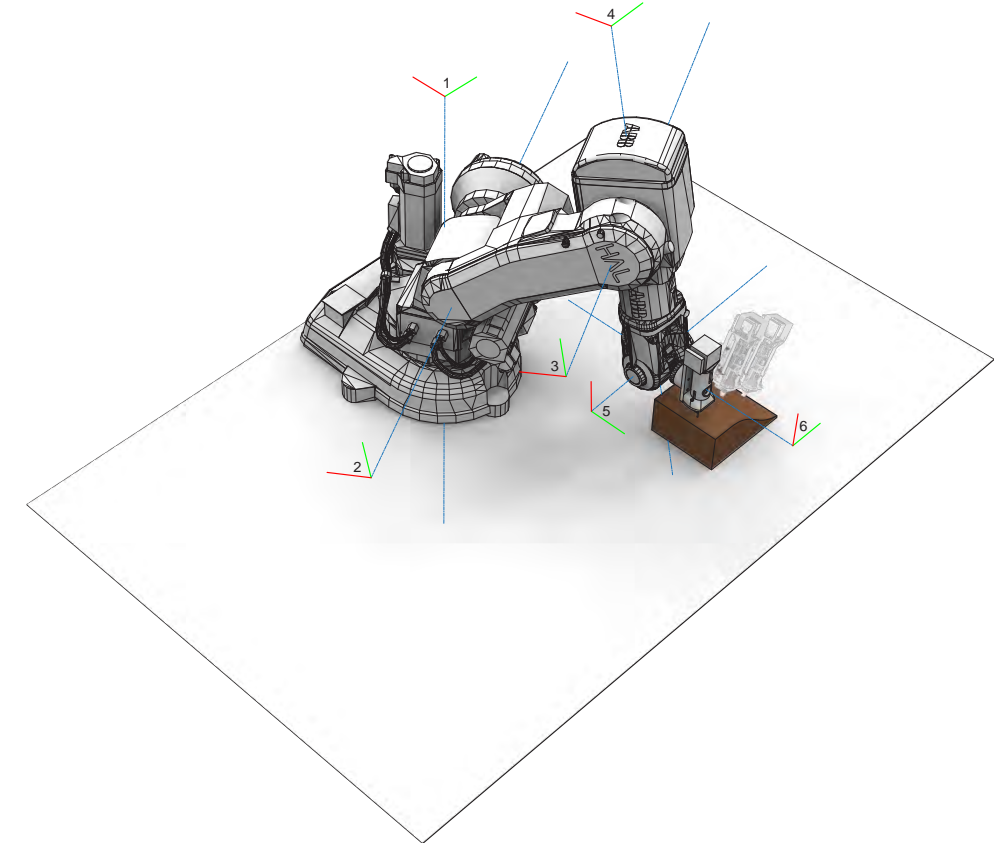
3-AXIS



5-AXIS



6-AXIS

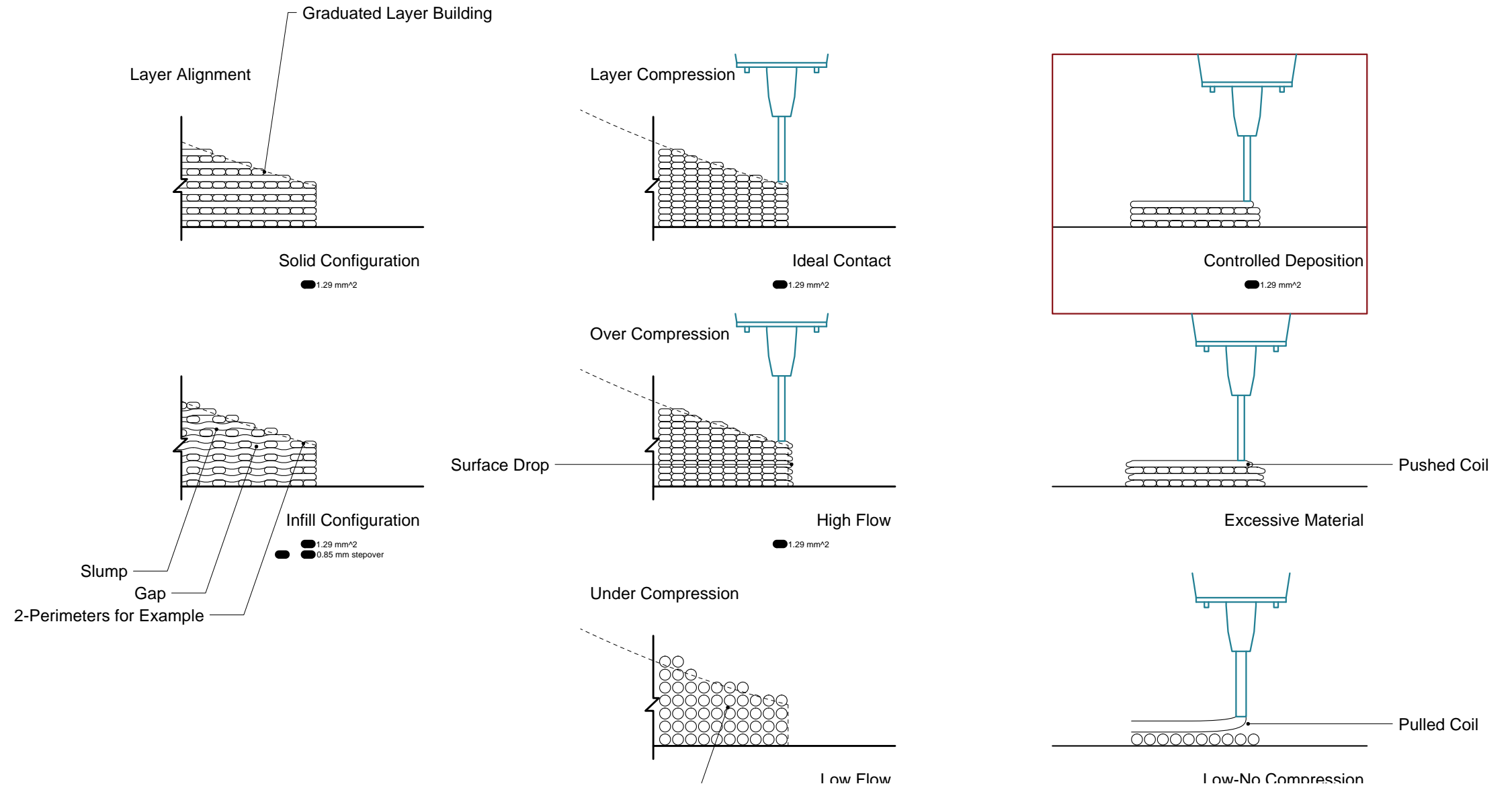


CERAMIC TOOLING

“Ceramic” Tooling

Basic layering strategize were identified and properly articulated to achieve satisfactory results.

All of these parameters, layer height, step over, overlay, coil size, flow rate, can be predicted and controled.



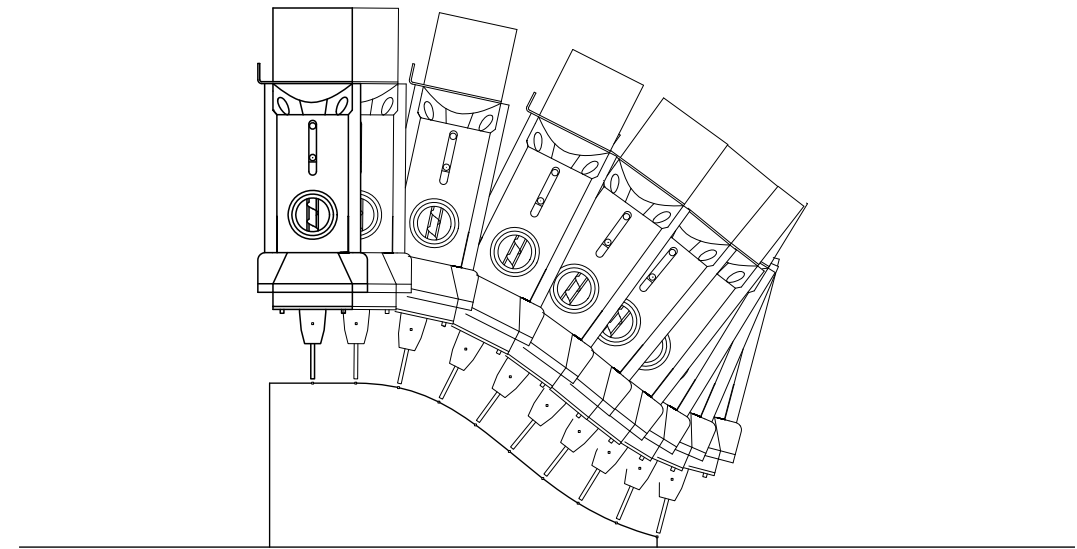
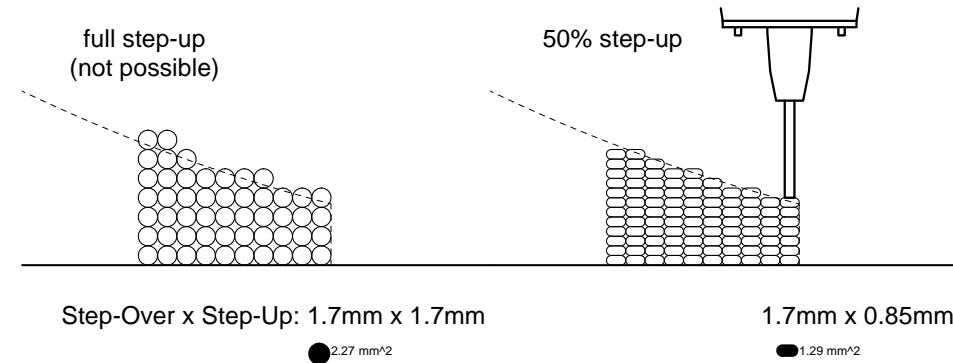
MULTI AXIS ADVANTAGE

5-Axis Advantage

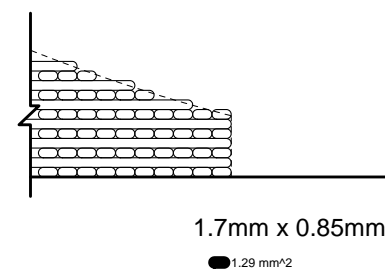
One of the most significant contributions to 5-Axis technology contributes to the resolution of the final product, especially when producing complex geometric shapes.

Similar tooling parameters exist between 3 & 5-Axis printing (stepovers, layer height, overlap, etc).

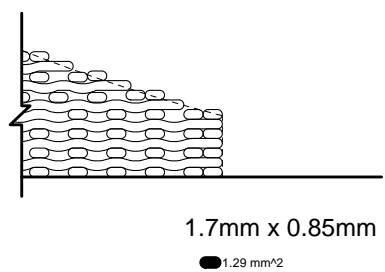
The most influential result is the final plane of surface contact between the print nozzle and already laid extrusion coil.



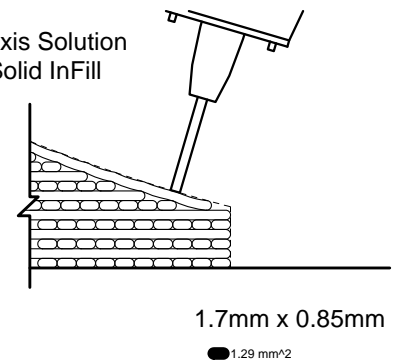
Solid Configuration



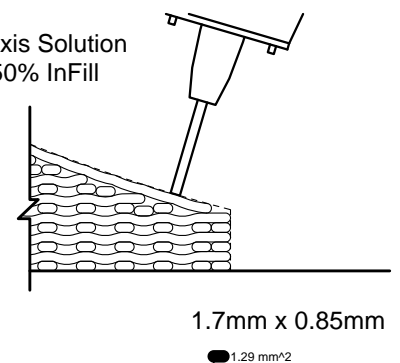
50% InFill



5-Axis Solution Solid InFill



5-Axis Solution 50% InFill



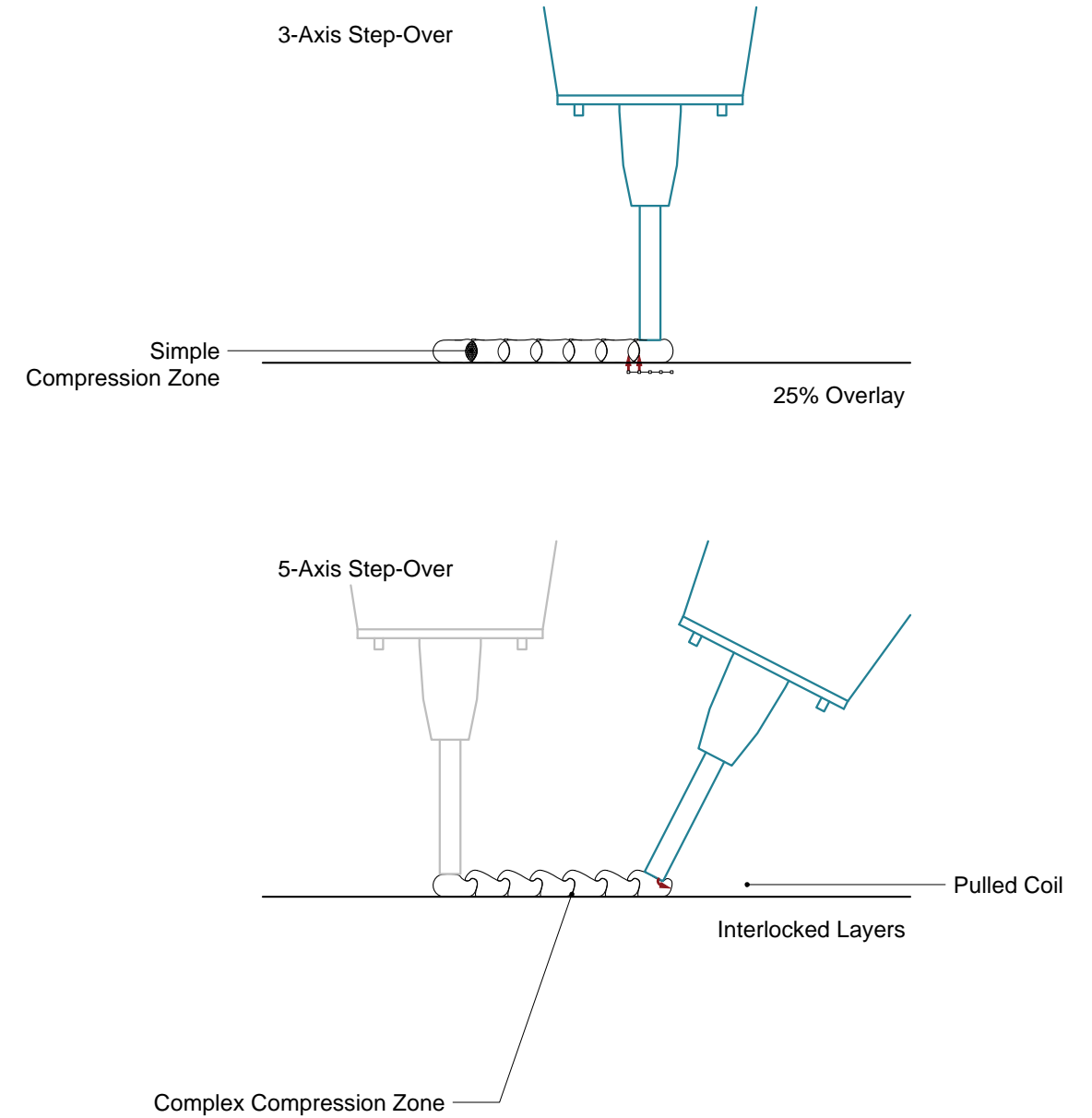
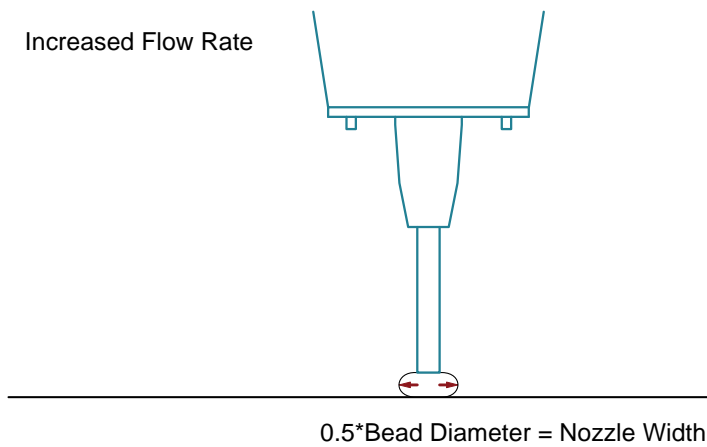
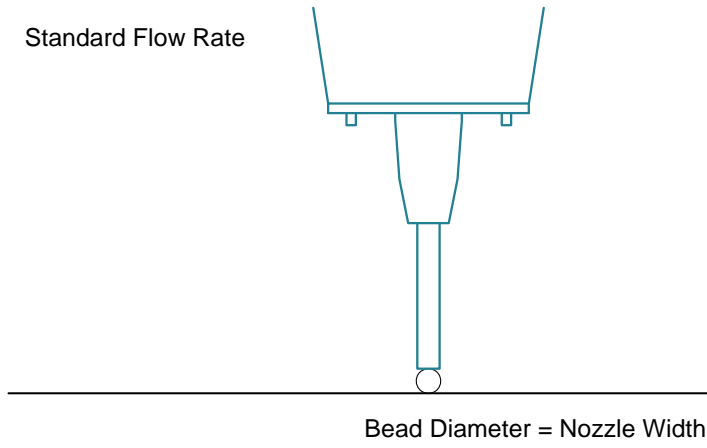
MICRO-EFFECT

5-Axis Advantage

The most significant contribution could be the articulation of the tooled ceramic coil.

Flow-rate has the most profound effect on coil compression but it can be messy and often uncontrolled.

5-Axis articulation modifies the way successive coils are compressed together, having a significant effect on the arrangement of the ceramic medium's micro-structure. I will briefly explain the platelet structure in a moment.



9 PAGE SPREAD

Process Design

Flow and the material properties effecting tooling and the architectural result.



PROCESS DESIGN

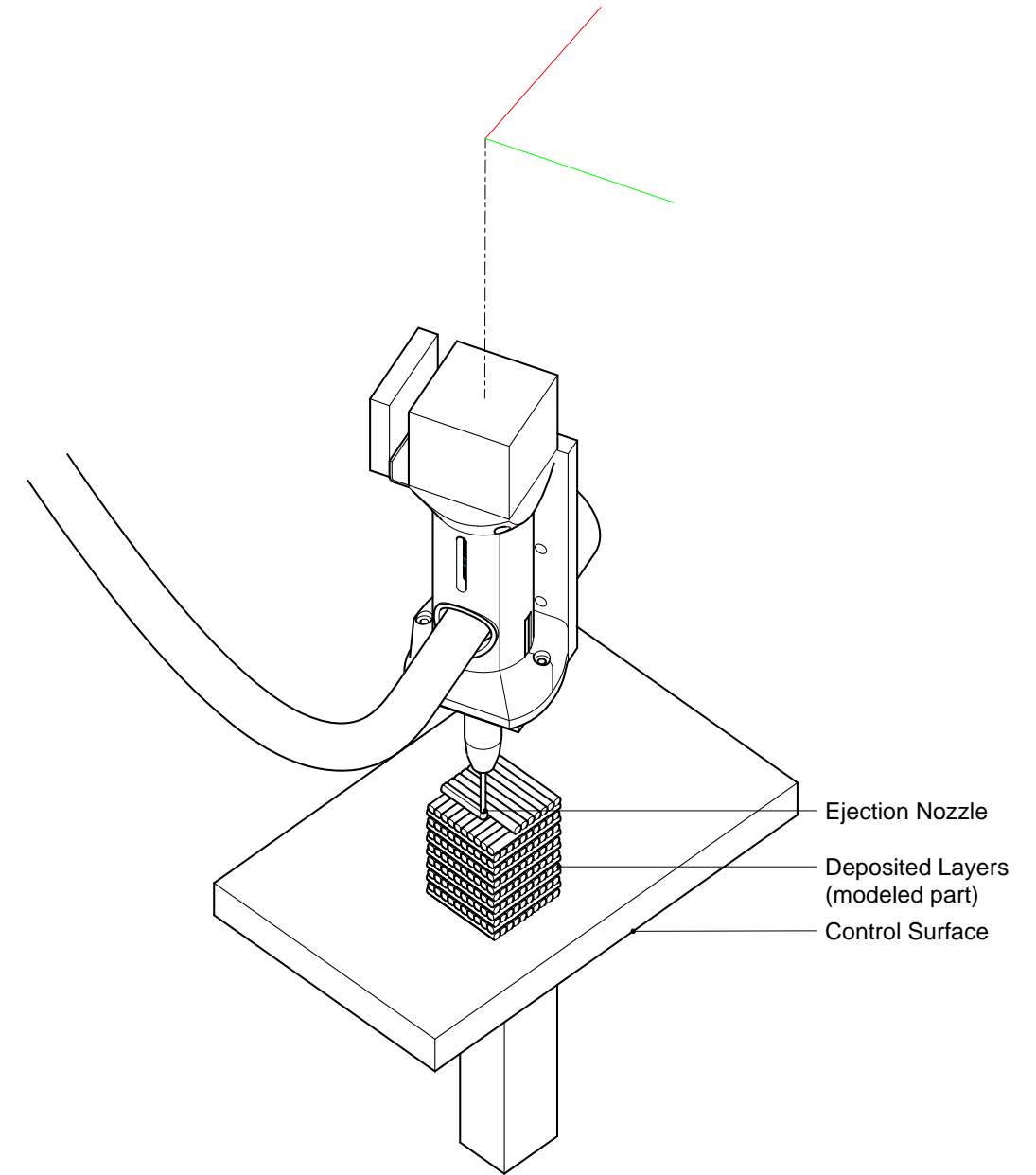
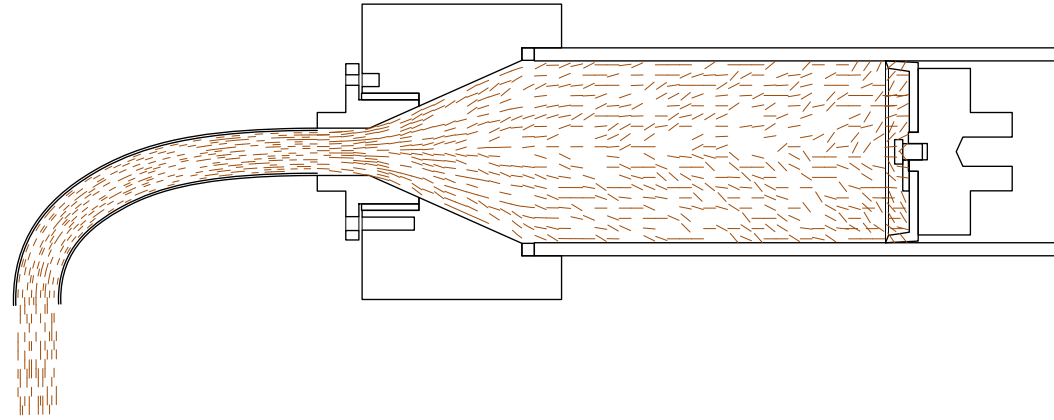


Flow Technology

Clay bodies have a platelet micro structure. These platelets are naturally misaligned but organize when flowing during the extrusion process. They become even further aligned with extensive flow.

This platelet structure has a greater capacity to resist compression when they are stacked flat against each other. This should contribute to the structural capacity of bricks extruded in this manner.

**Material properties have a profound effect on architectural design.



DRAG, SHEAR AND STRUCTURE

Flow Technology

The material flow and toolpath coordination between the piston extruder and, in this case, the ABB robot, can be accurately calculated and controlled.

Part of my work included thinking through a redesign of particular machine components, including a ready to install gear reduction decreasing the speed of the piston extruder significantly (avoiding stalling). The higher degree of motor speed control at the piston will support a more stable flow rate.

The interface for the extruder to sync with the robot includes a plug-and-play Arduino motor controller reading a digital output signal from the ABB controller.

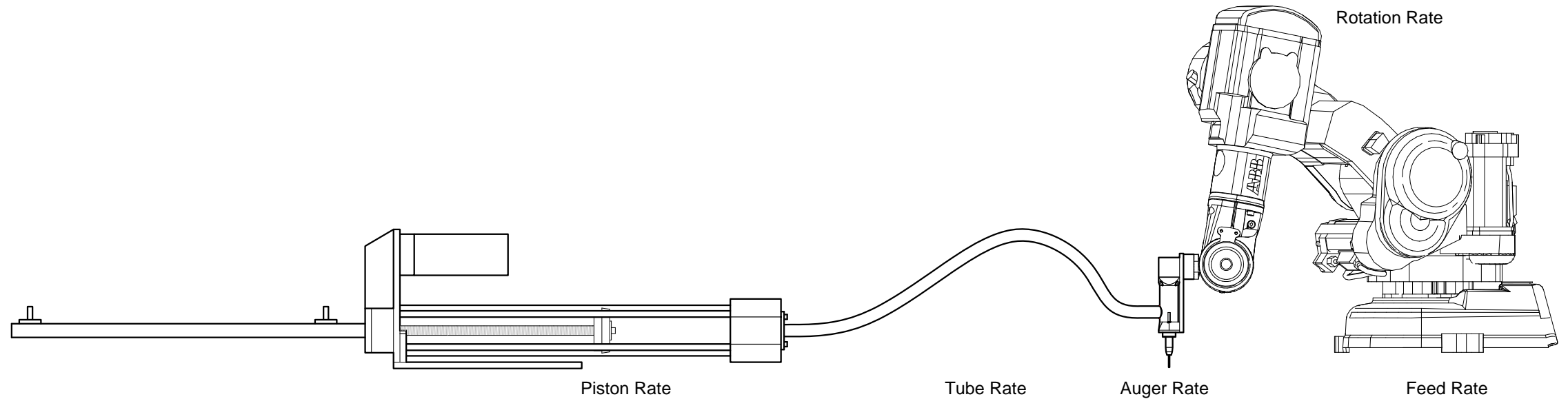
Deposition Volume:
 -body of material to be deposited / second for given motor speed
 --Auger Pulse: required Auger revolutions / second

Deposition Flow = Tube Flow = Auger Flow = Piston Flow

Definitions

Auger Shaft: center shaft supporting auger
 Auger Flight: screw coils around the auger shaft
 Auger Pitch: distance between two flights
 Extruder Column Length (E_L): length of column around auger for pitch
 Pitch Volume (H_V): volume of clay body between two flights
 $H_V = E_L - \text{Shaft Volume} - \text{Flight Volume}$
 Deposition Volume (D_V): Pitch Volume * E_L
 Deposition Flow (D_F): Deposition Volume * Revolution / Sec
 Rev / Sec = D_F / D_V

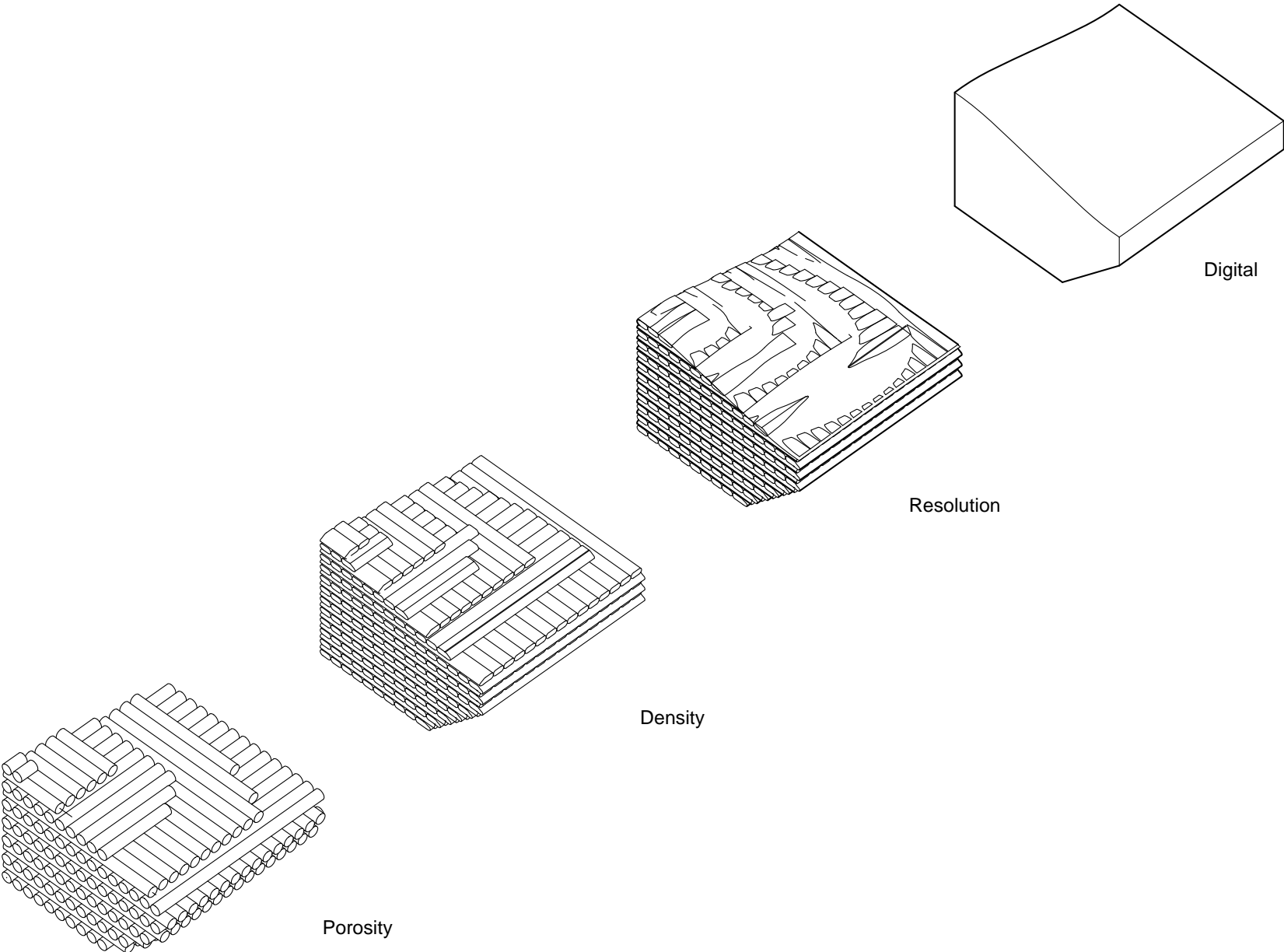
Piston Length:	P_L	Piston Volume:	$P_V = P_A * P_L$
Piston Area:	P_A	Piston Flow:	$P_F = P_V * P_S$
Piston Volume:	P_V	Tube Volume:	$T_V = T_A * T_L$
Piston Flow:	P_F	Tube Flow:	$T_F = T_V * T_S$
Piston Speed:	P_S		$T_F = P_F$
			$P_F = T_V * T_S$
Tube Length:	T_L	Tube Speed:	$T_S = P_F / T_V$
Tube Area:	T_A		
Tube Volume:	T_V		
Tube Speed:	T_S		
Tube Flow:	T_F		
		Pitch Volume (per pitch):	$H_V = B_V - S_V - F_V$
Auger Speed:	G_S	Deposition Volume:	$D_V = P_V * E_L$
Auger Volume:	G_V		
Auger Flow:	G_F		
Pitch Volume:	H_V	Deposition Flow:	$D_F = D_V * \text{Rev} / \text{Sec}$
Barrel Volume:	B_V		$\text{Rev/Sec} = D_F / D_V$
Shaft Volume:	S_V		
Flight Volume:	F_V		



SYSTEM FLOW

Flow Technology

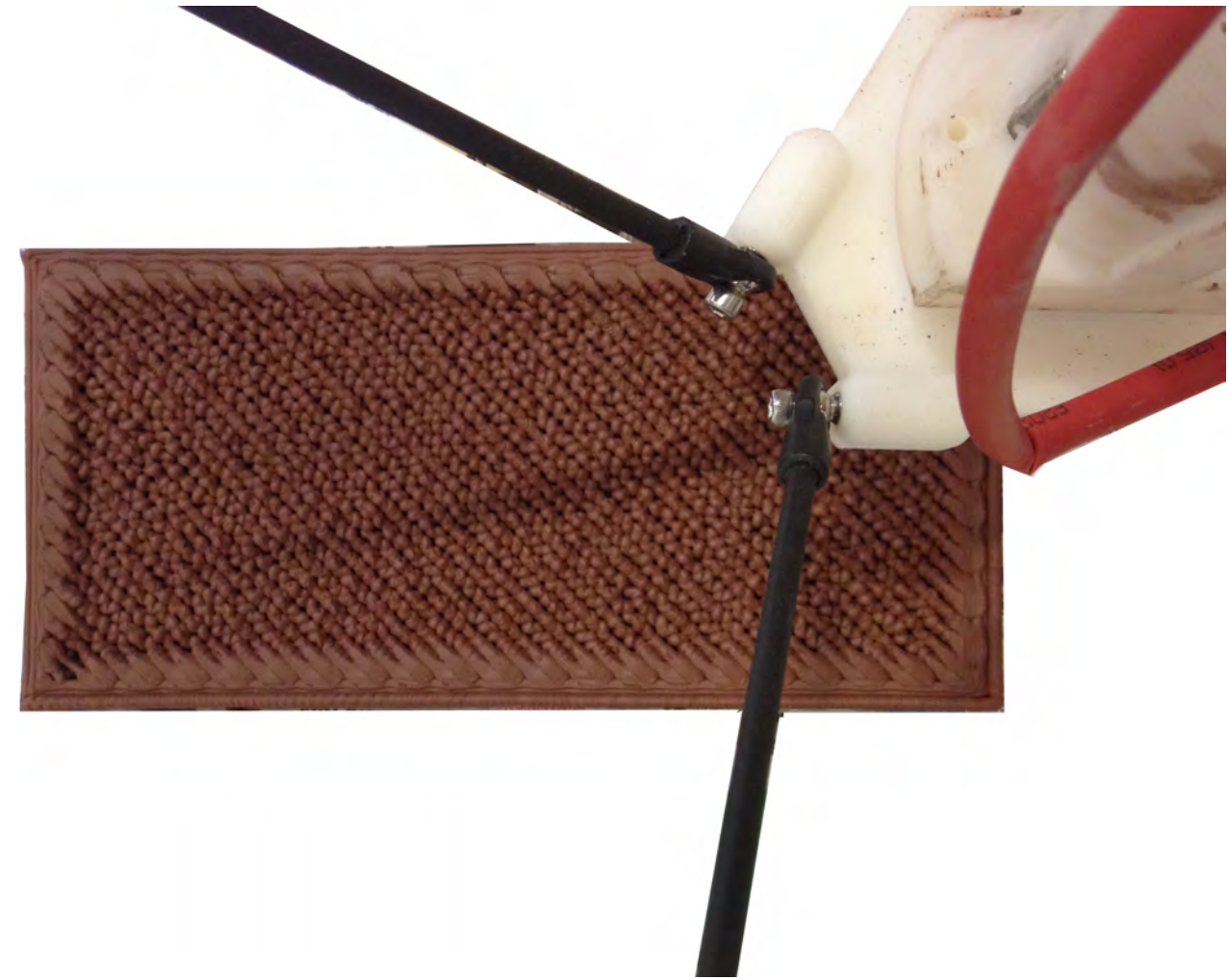
These parameters are very important to control because they, when combined with the toolpath and nozzle parameters outlined earlier, profoundly effect the resulting product.



MACHINE EFFECT

Flow Technology

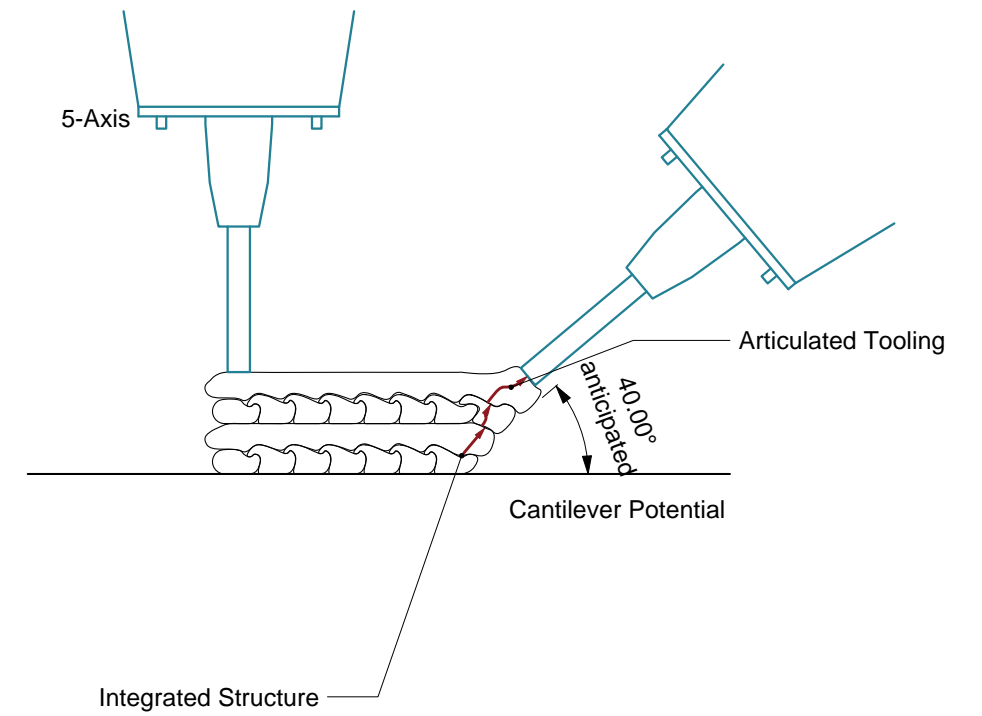
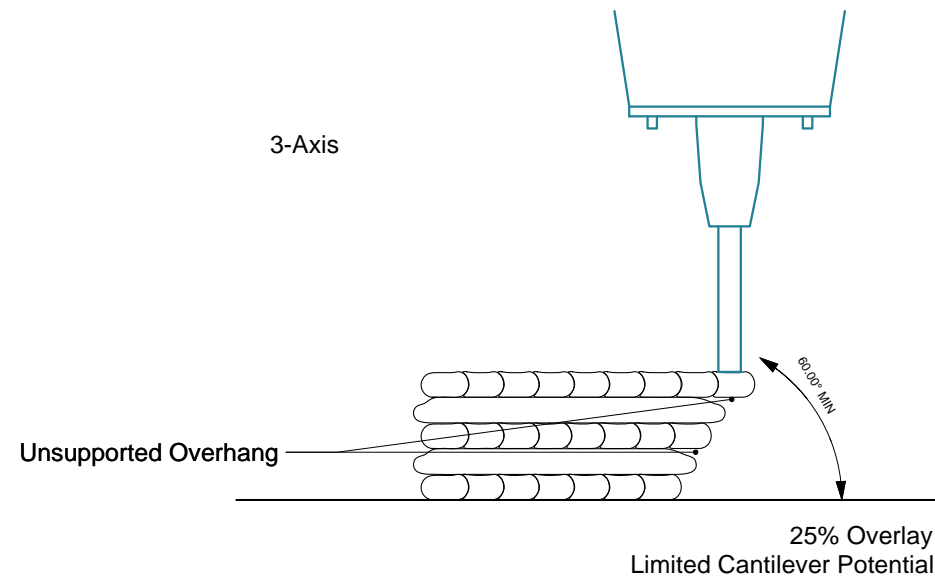
Flow rates, a relationship between auger speed and feed rate, are the greatest contributing factor to the resulting material surface, including this articulated (and calculatable) looping pattern.



MATERIAL AFFECT

Flow Technology

5-Axis tooling should allow a greater range of geometric opportunities, expanding the range of un-supported cantilevers in component design.



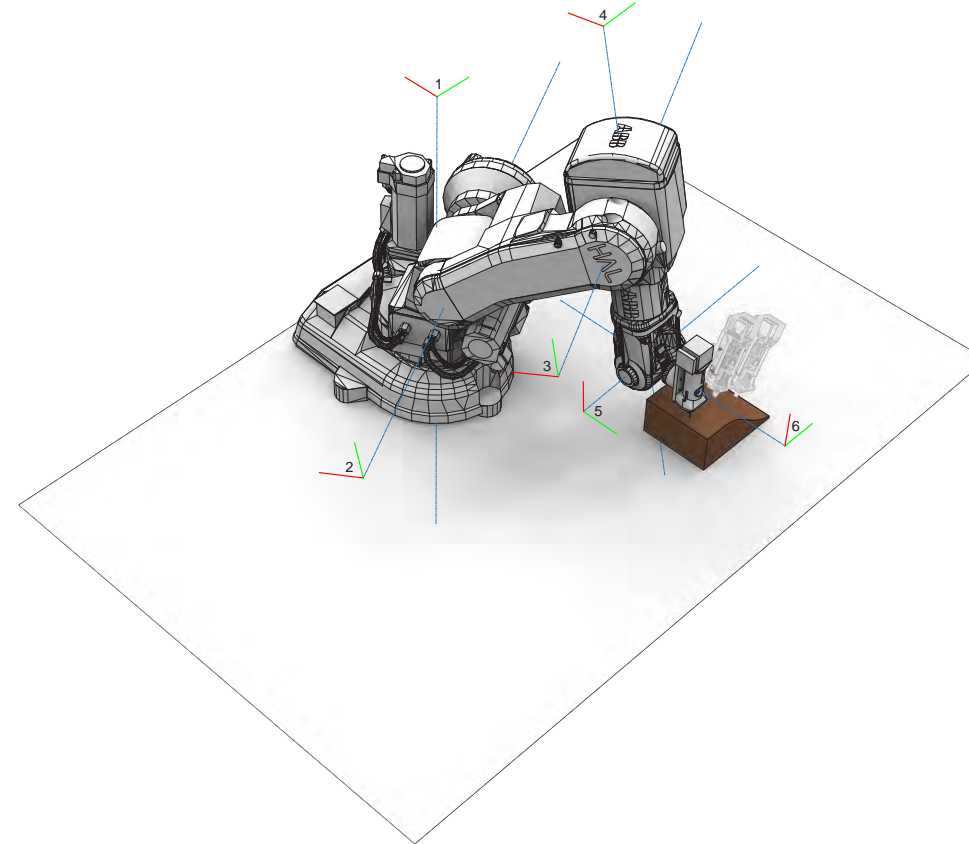
MACHINE ARTICULATION

Flow Technology

The development of a multi-axis extrusion is the major contributing body of work to this production technology. The way robots handle code effect their potential to be integrated into production, a point to pause and consider before proceeding.

As the test block was designed, the toolpath has over 65000 targets; processing this amount of information is difficult for the controller on hand.

To test the proposed CNC design methods, I simulated just 700 targets, offering a more simple understanding of the processes employed. My initial assessment suggests that a 5 or 6-Axis gantry would provide a more easily programmable platform to continue this research direction.



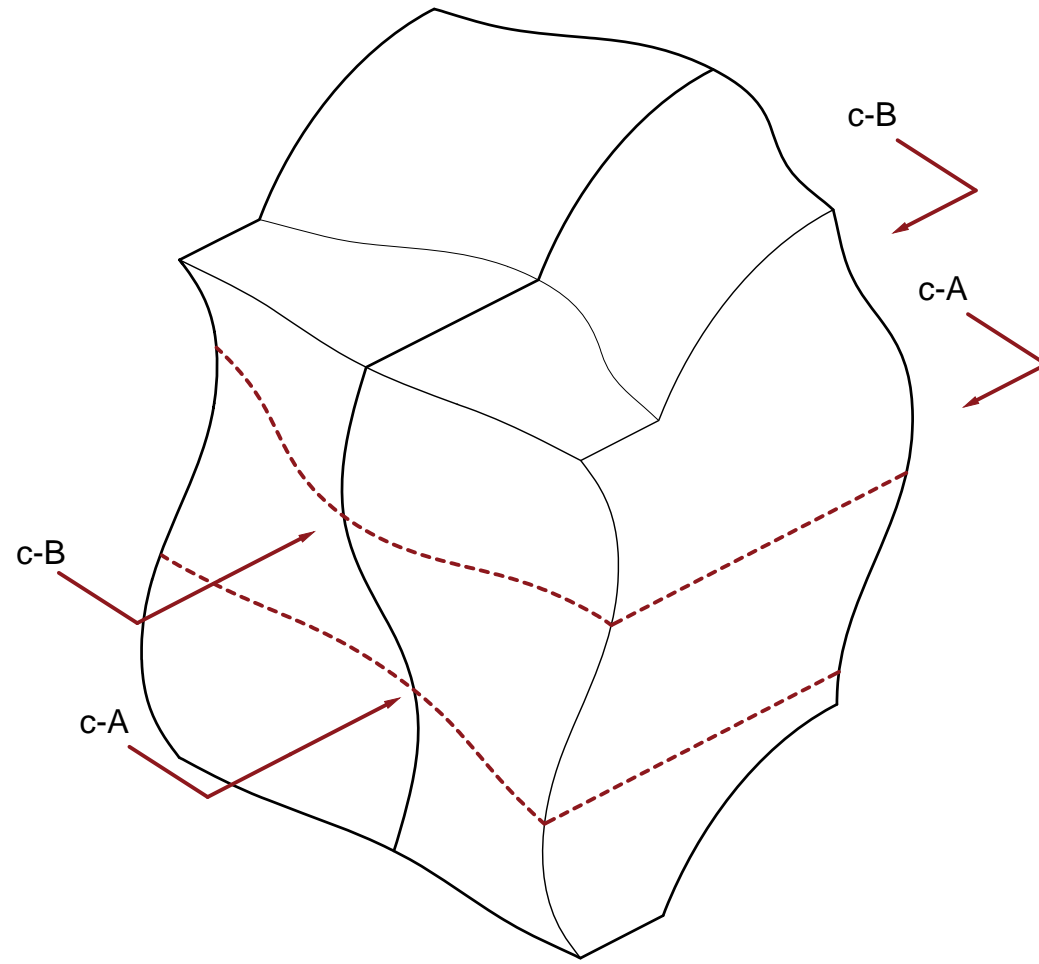
MACHINE ARTICULATION

Test Block

To test my observations,
I developed a simple
osteomorphic block that had
the geometrical characteristics
that would be encountered in
the design proposal.

The following section drawings
are shown here.

5-Axis Tooling



PROTOTYPICAL BLOCK

Tooling Strategy

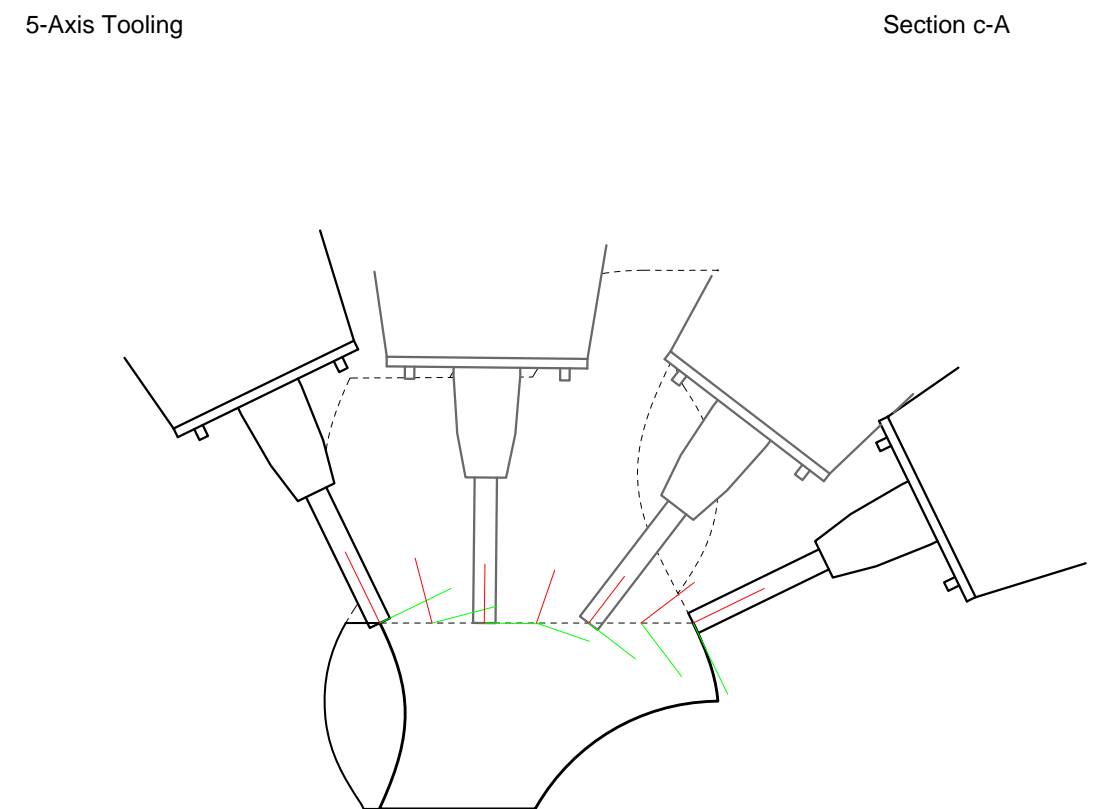
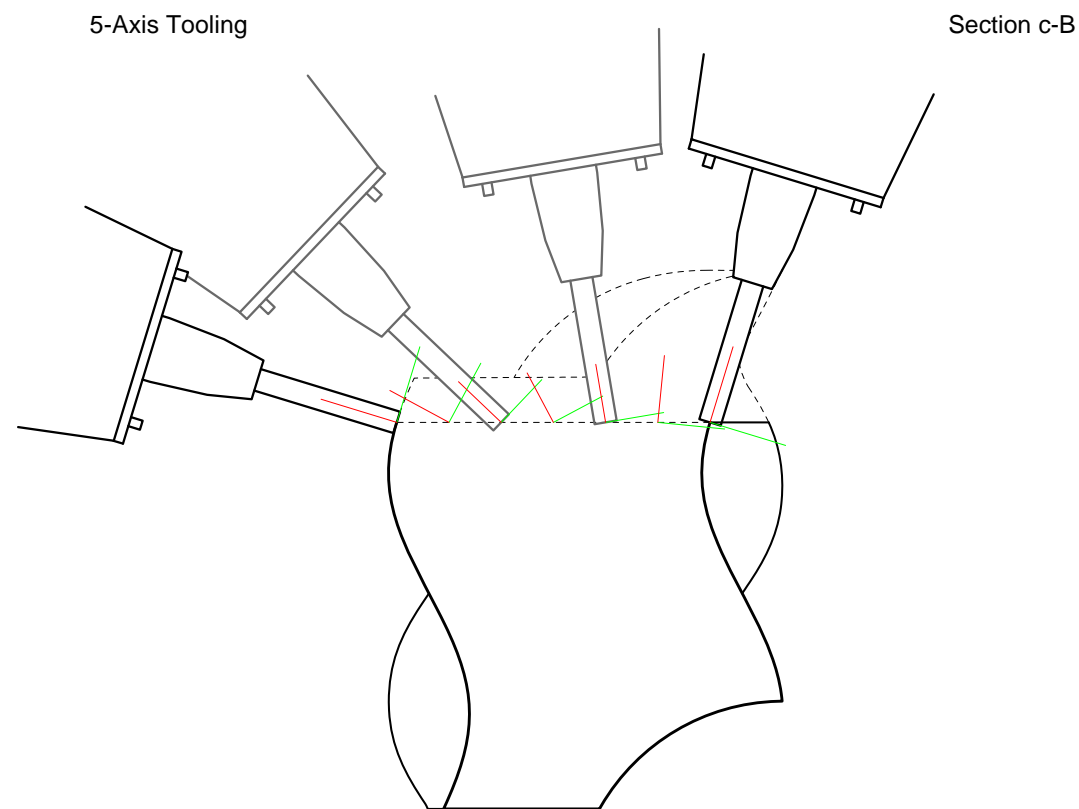
The initial tooling strategy I composed involved a simple linear interpolation of the part's cross section. The intersection of the tool path with the geometric surface was interpreted.

If the surface's vertical section was convex (when viewing from the part center), the tool path would be orientated toward the surface normal.

If the surface's vertical section was concave (when viewing from the part center), the tool path would be orientated toward the surface tangent.

The interstitial tool path would be an interpolation between the opposing orientations.

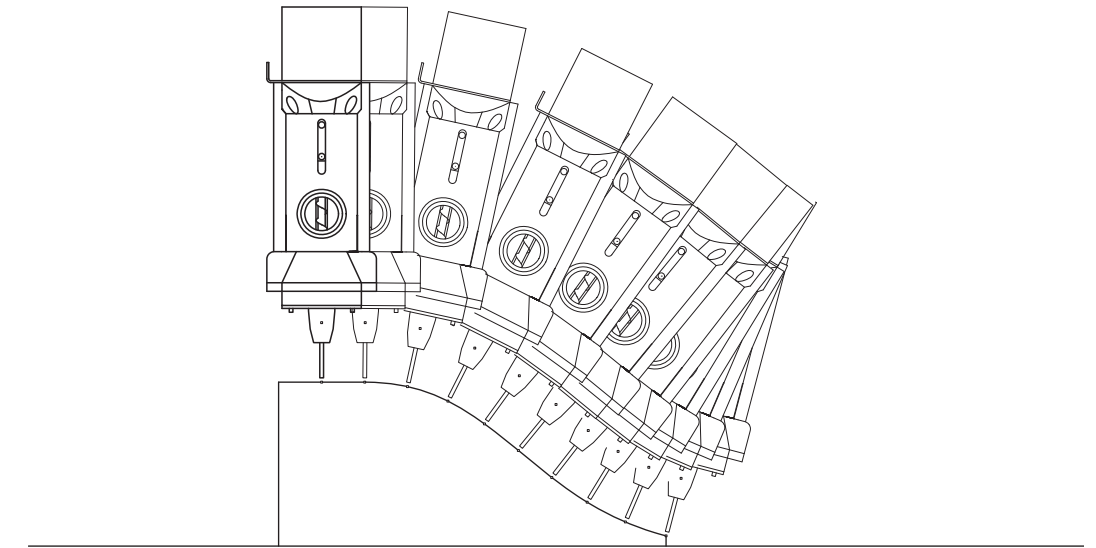
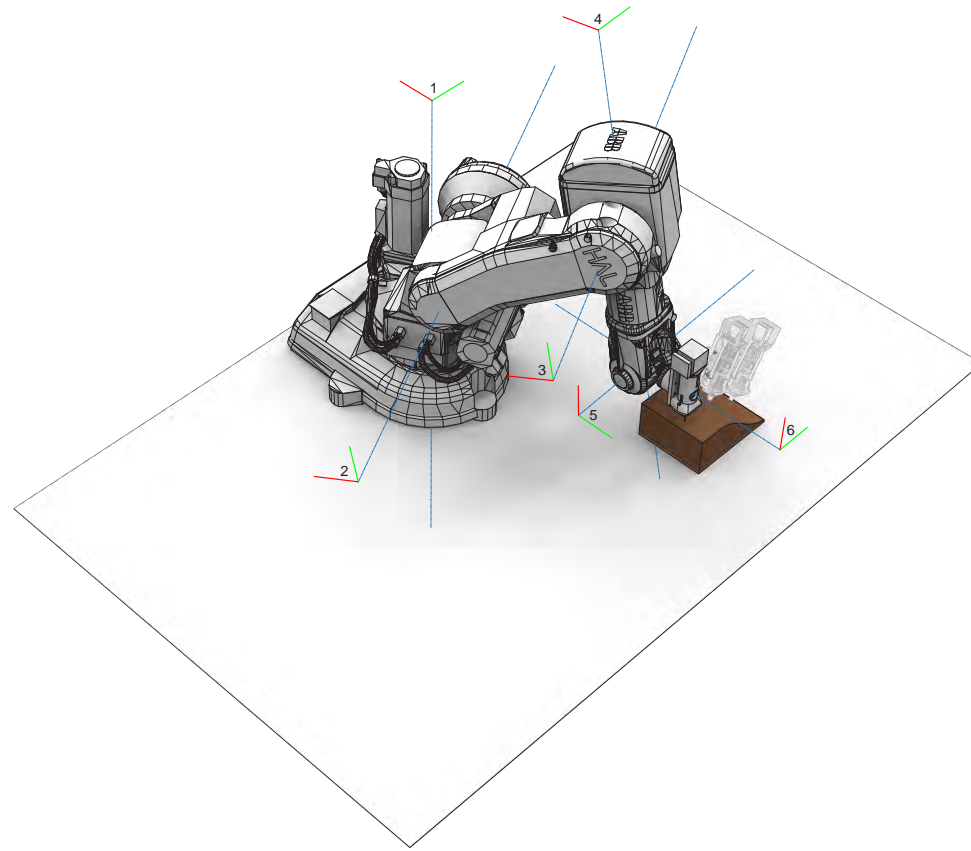
Target count, and computational weight, would be determined by the desired part resolution.



TOOLING STRATEGY

Tooling Strategy

This strategy proved to create problems for ceramic extrusion at the test resolution (aprox. 1-5mm). Nevertheless, the investigation and subsequent discussion with contributors proved a valuable part of the research, highlighting future avenues of exploration. These ideas and concepts will be investigated in the coming months and released in a forthcoming publication.



FUTURE ARTICULATION

4 PAGE SPREAD

Design Proposal

These pages showcase a few possible scenarios for the design proposal; an illustration of what sort of architecture is possible using this type of technology.

Brandon Johnson is the major contributor for the rendering artistry shown in the following images.



DESIGN PROPOSAL

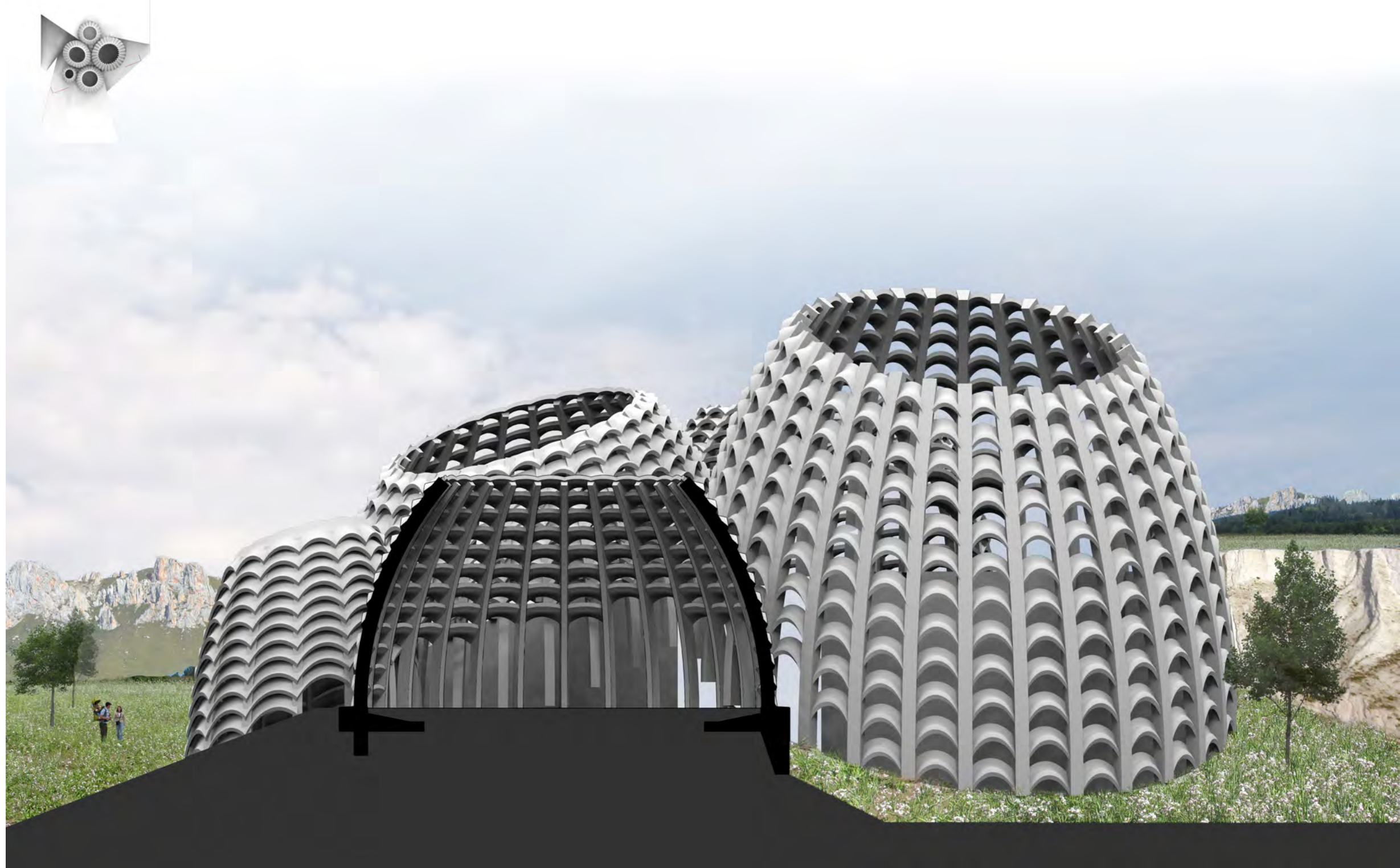




Design Proposal

Section view.

Brandon Johnson, architectural rendering artist.



Design Proposal

View 01.
Brandon Johnson, architectural
rendering artist.



Design Proposal

View 02.

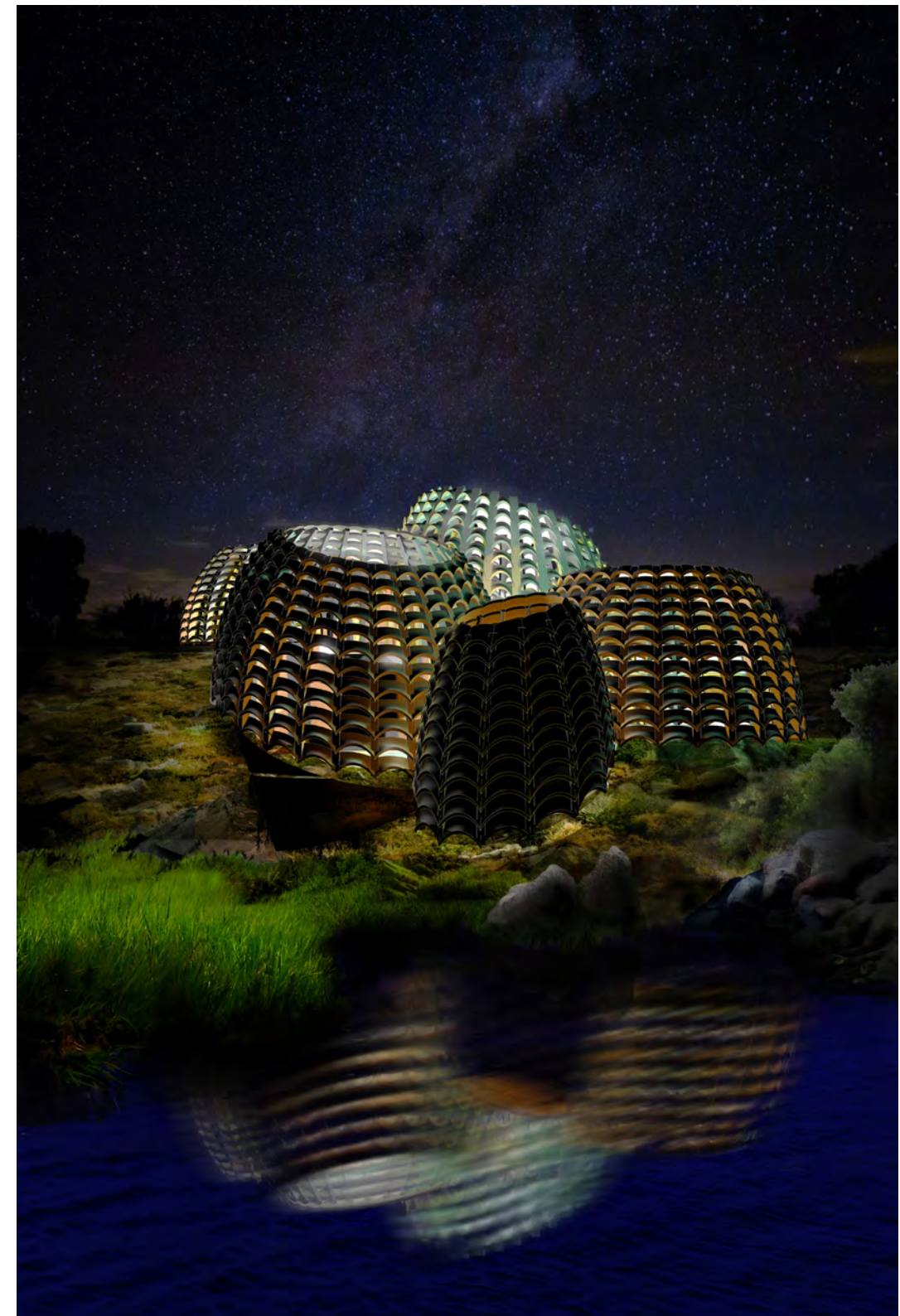
Brandon Johnson, architectural rendering artist.



Design Proposal

Night view.

Brandon Johnson, architectural rendering artist.



6 PAGE SPREAD

Realization + Representation

These pages showcase a small portion of the items produced to realize this thesis, including the machines and ceramic bricks printed during the semester.

In addition, a model was made to highlight the final design proposal, also shown in photographs here.



MATERIALIZATION



Machines

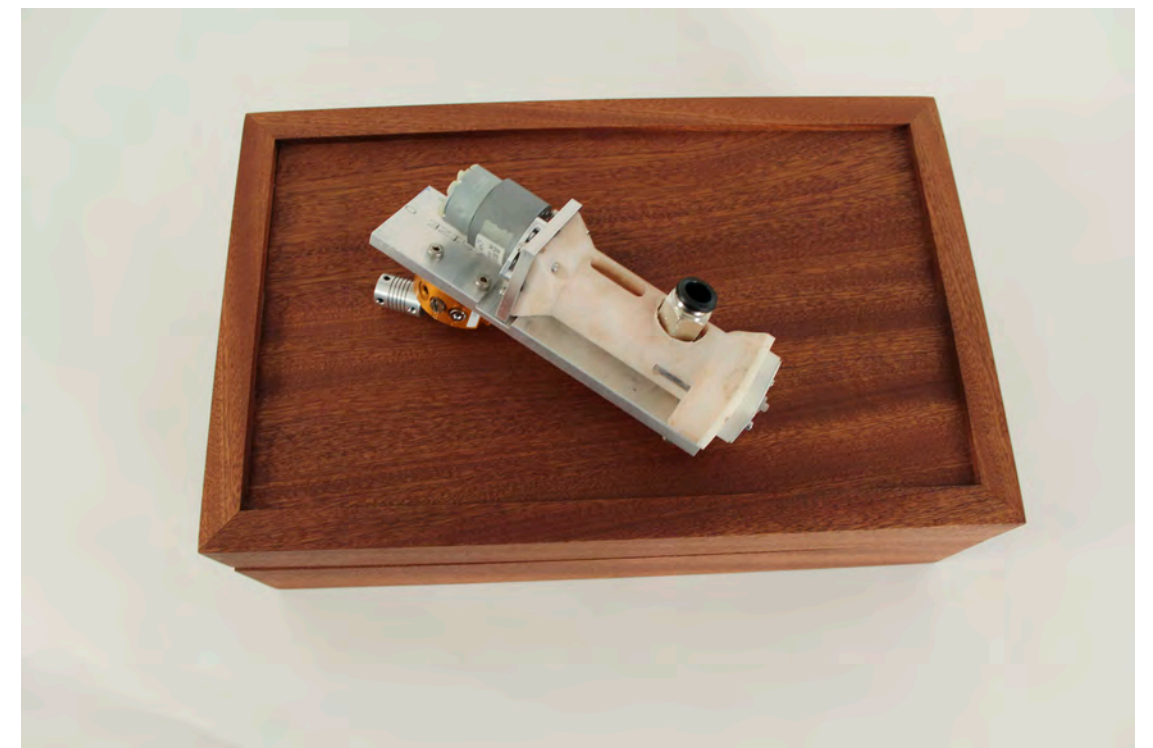
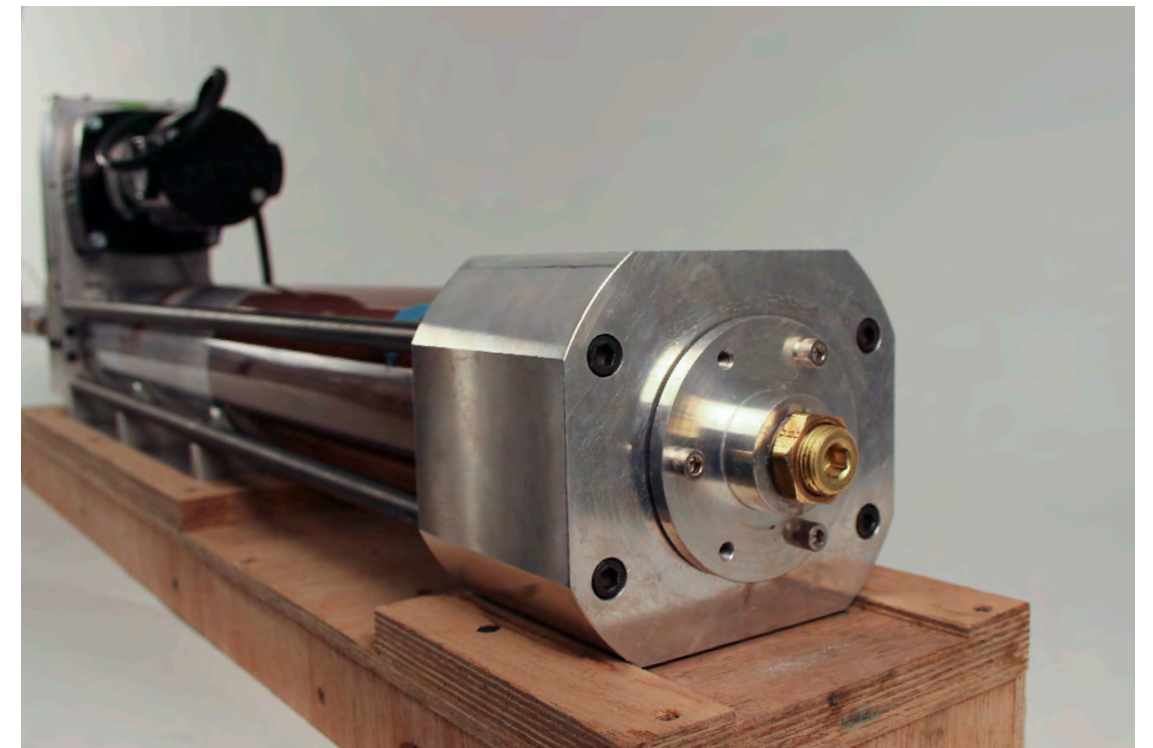
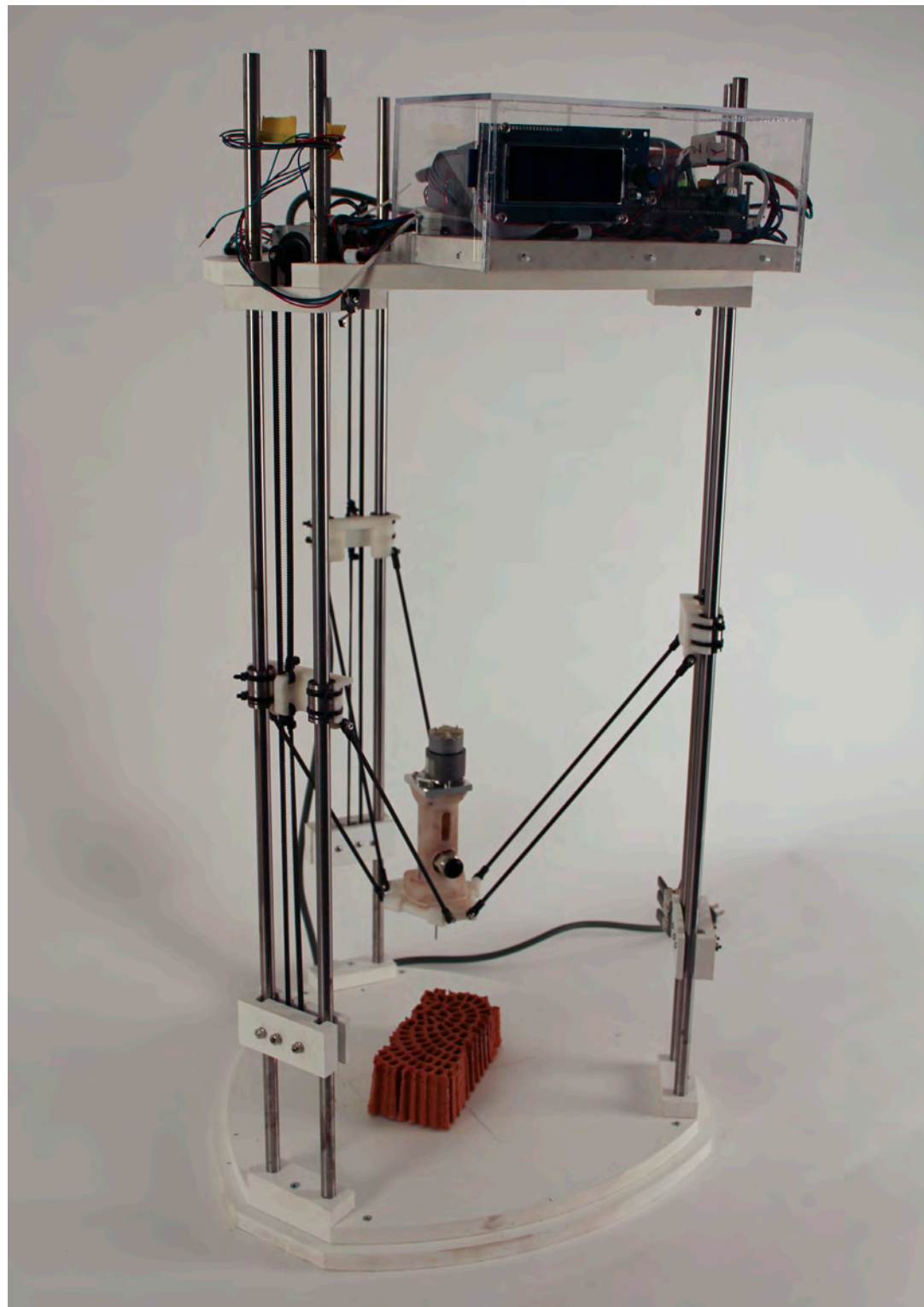
Clockwise from left:

The Delta-Style 3D printer and piston extruder was sponsored by the Harvard Graduate School of Design MaP+S group.

Daekwon Park, GSD DDes, contributed logistic and technical support during the construction of the Delta printer. Build files were modified by the author, originally constructed from technical information provided by Johnathan Keep and Brian Czibesz.

Staff in the GSD FabLab contributed to the reconfiguration of the piston extruder.

The auger extruder shown here was modified by the author from an open-source design released by WASP.

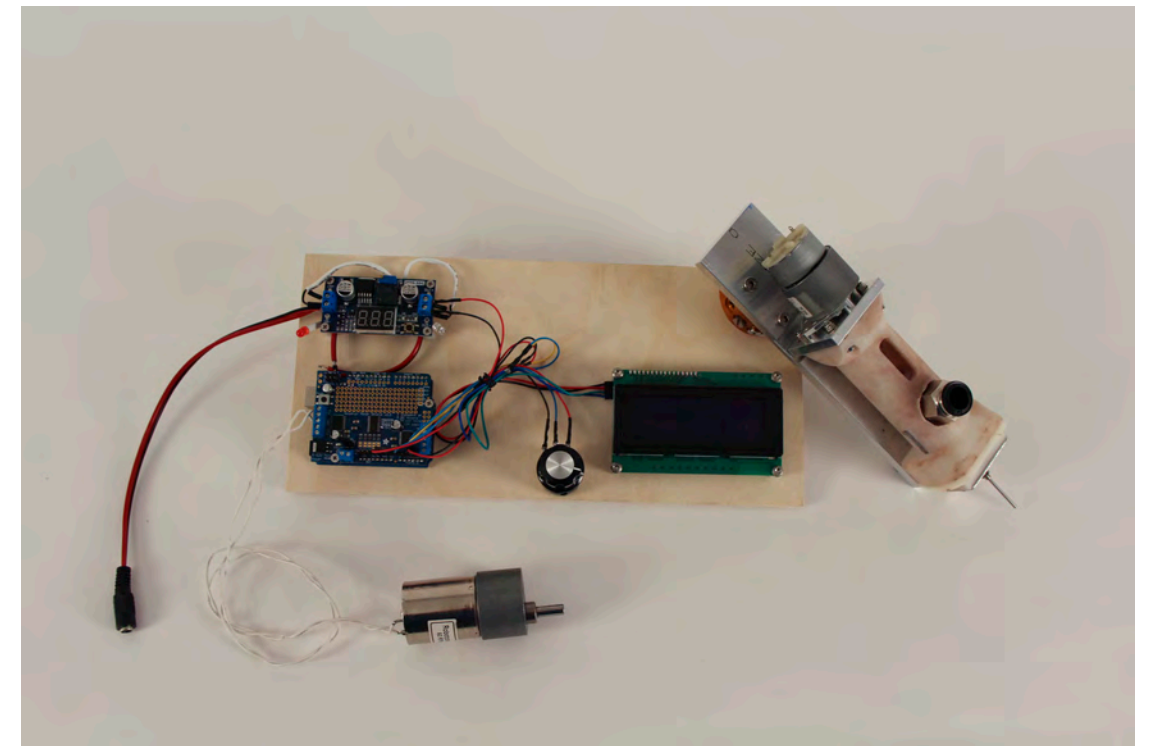
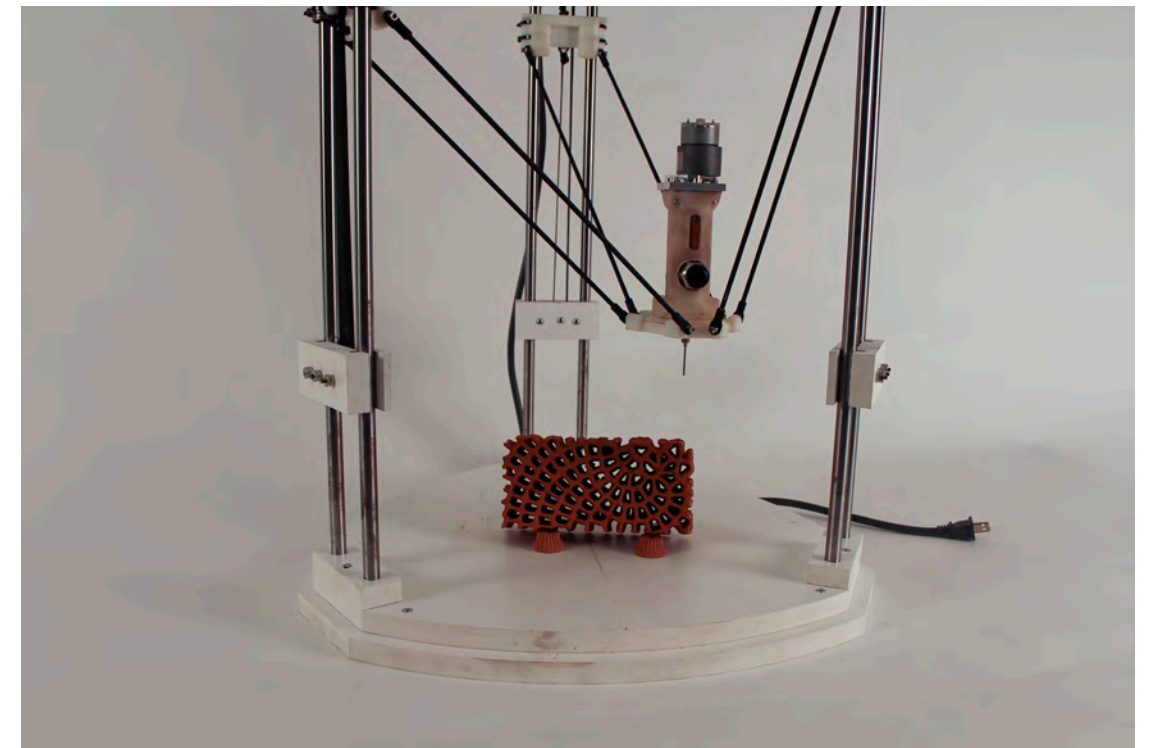
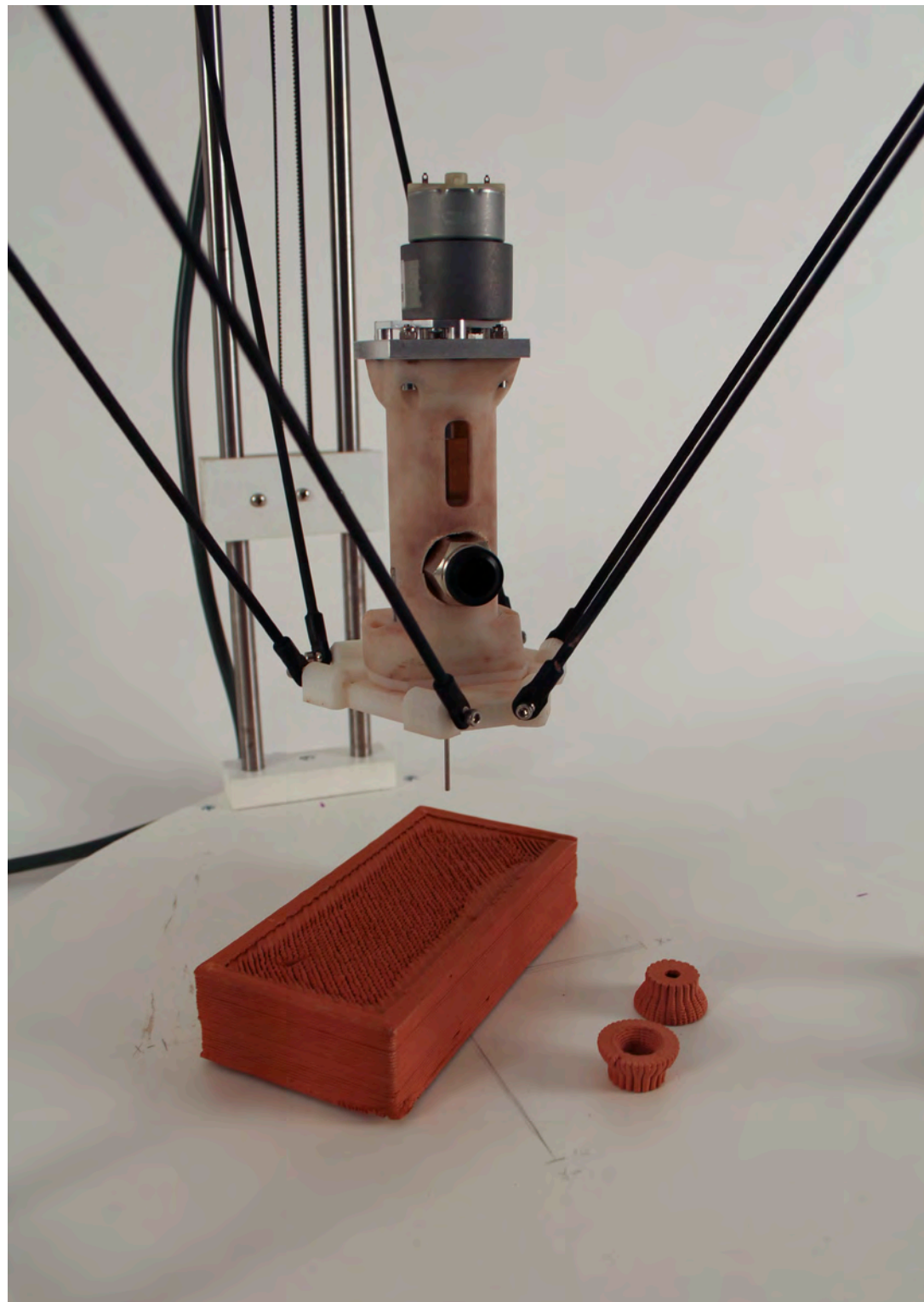


Printer Configuration

Clockwise from left:
Auger extruder mounted above brick06. The surface is textured by modifying the ratio of flow and feed rate, resulting in a predictable loop pattern for the deposited coil. The smaller 'buttons' are test prints looking at the articulation of the extruder's print resolution.

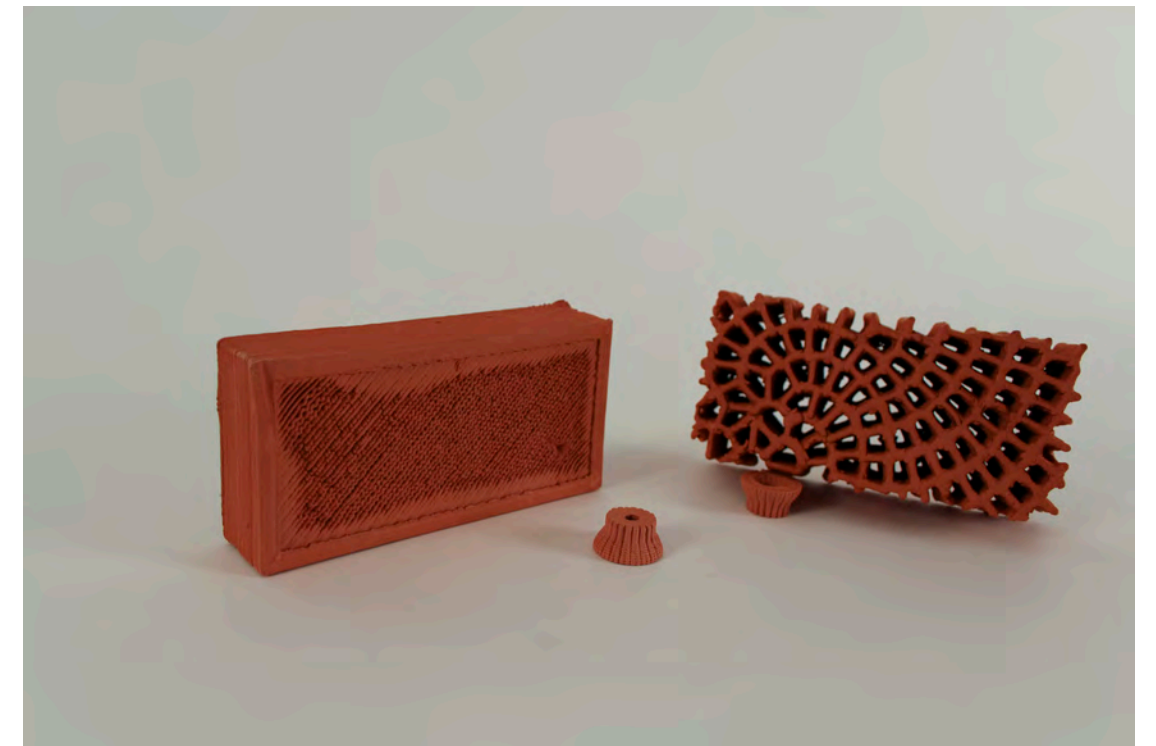
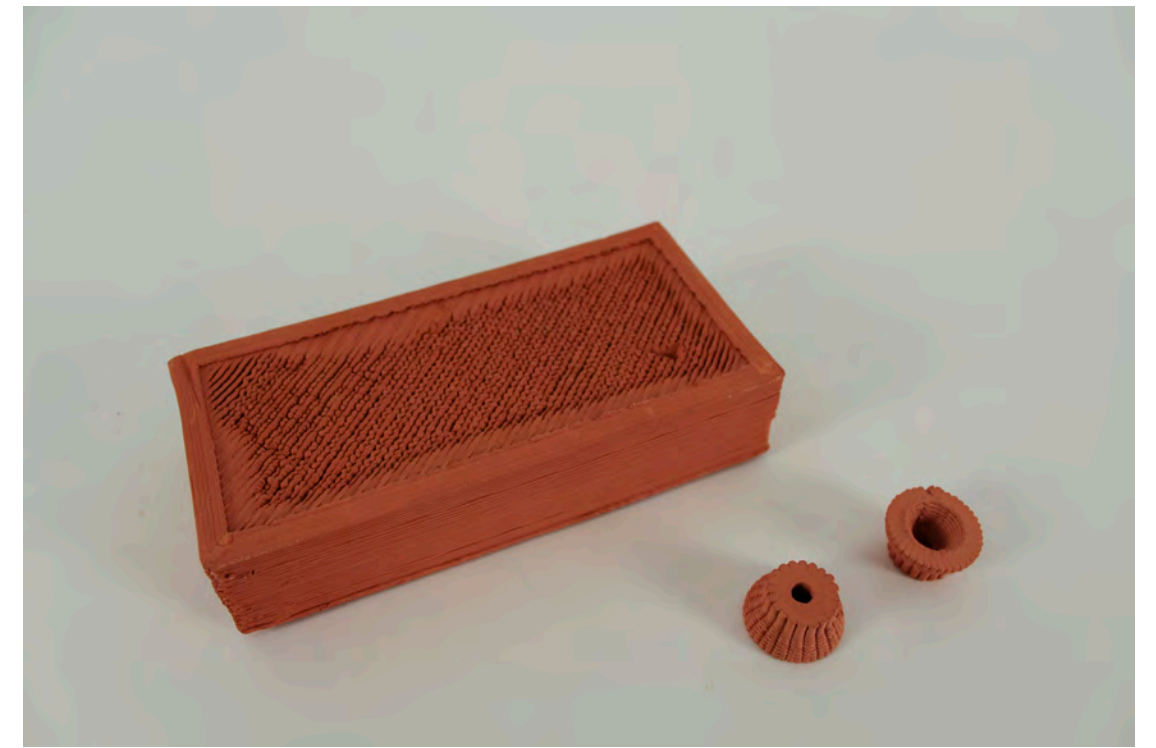
The auger extruder above brick05, a sample geometry illustrating an easily achieved resolution and geometric detail.

The auger extruder shown with digital output control panel designed by the author. The device regulates the speed of auger rotation while responding to a digital output signal sent from the ABB robotic arm controller. Nathan Melenbrink, GSD MDes, contributed to the Arduino setup and component design.



Text Prints

These 8 bricks were printed with using the above Delta printer.



Display Case +
Concept Model

Clockwise from left:

Auger Extruder box by Michael
J. Smith.

ABS print. Osteomorphic
test bricks representing a
geometric structure having
the qualities of the proposed
design.

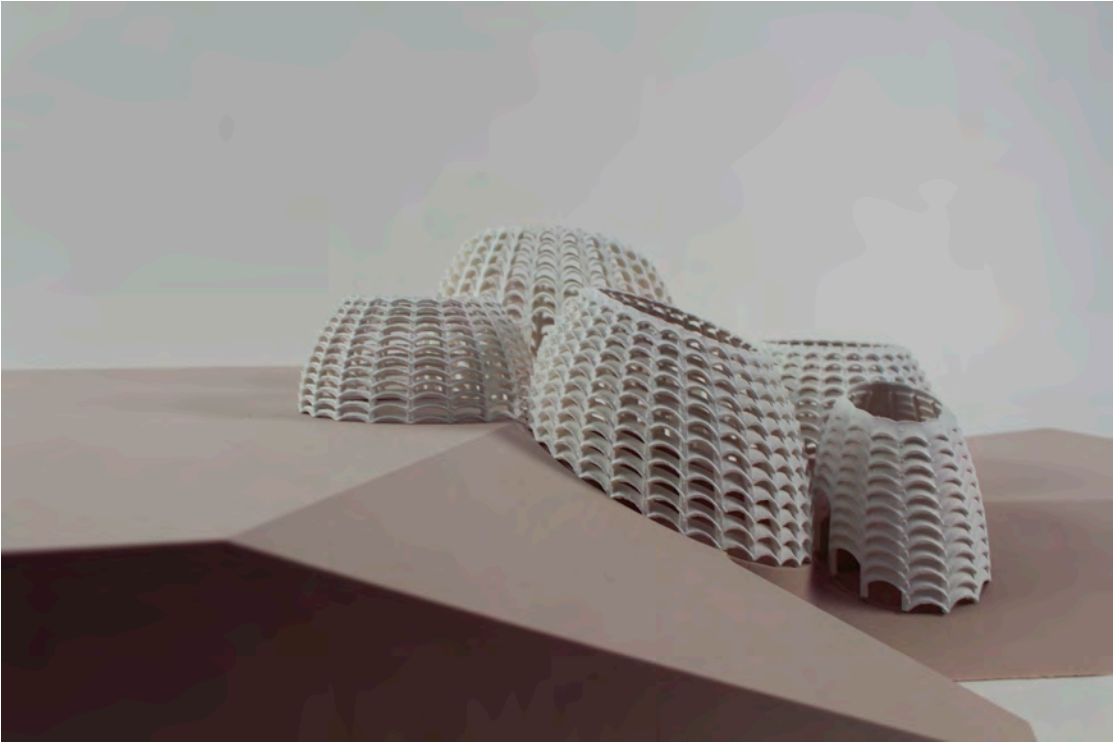
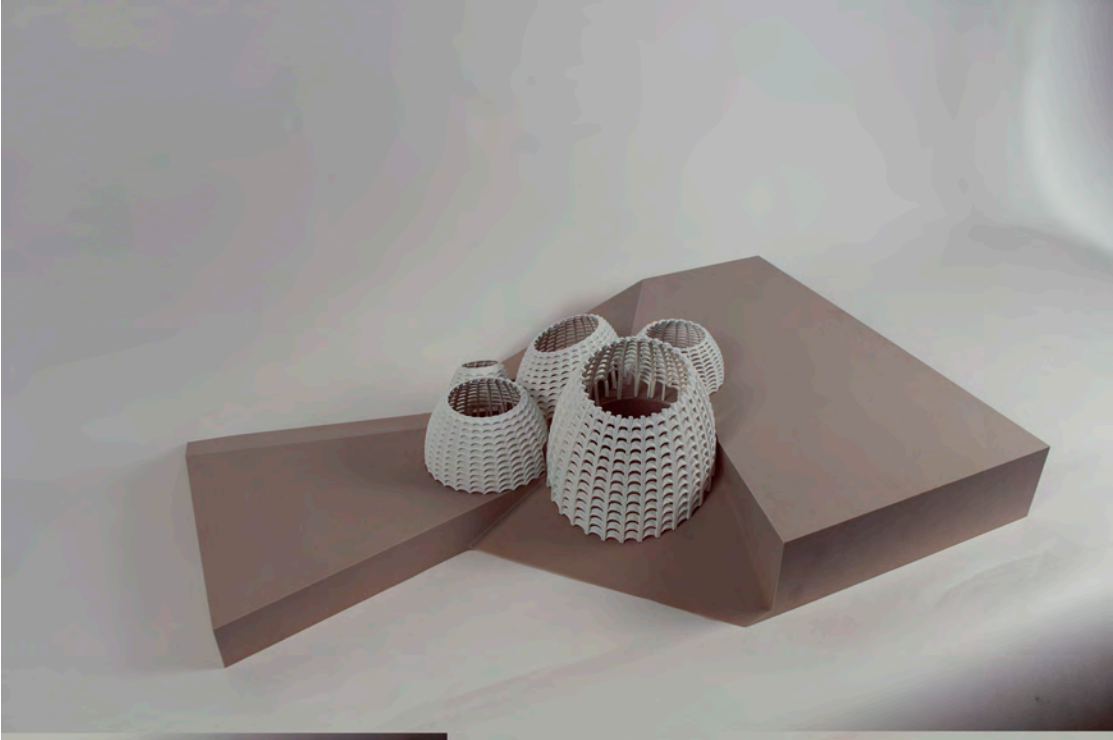
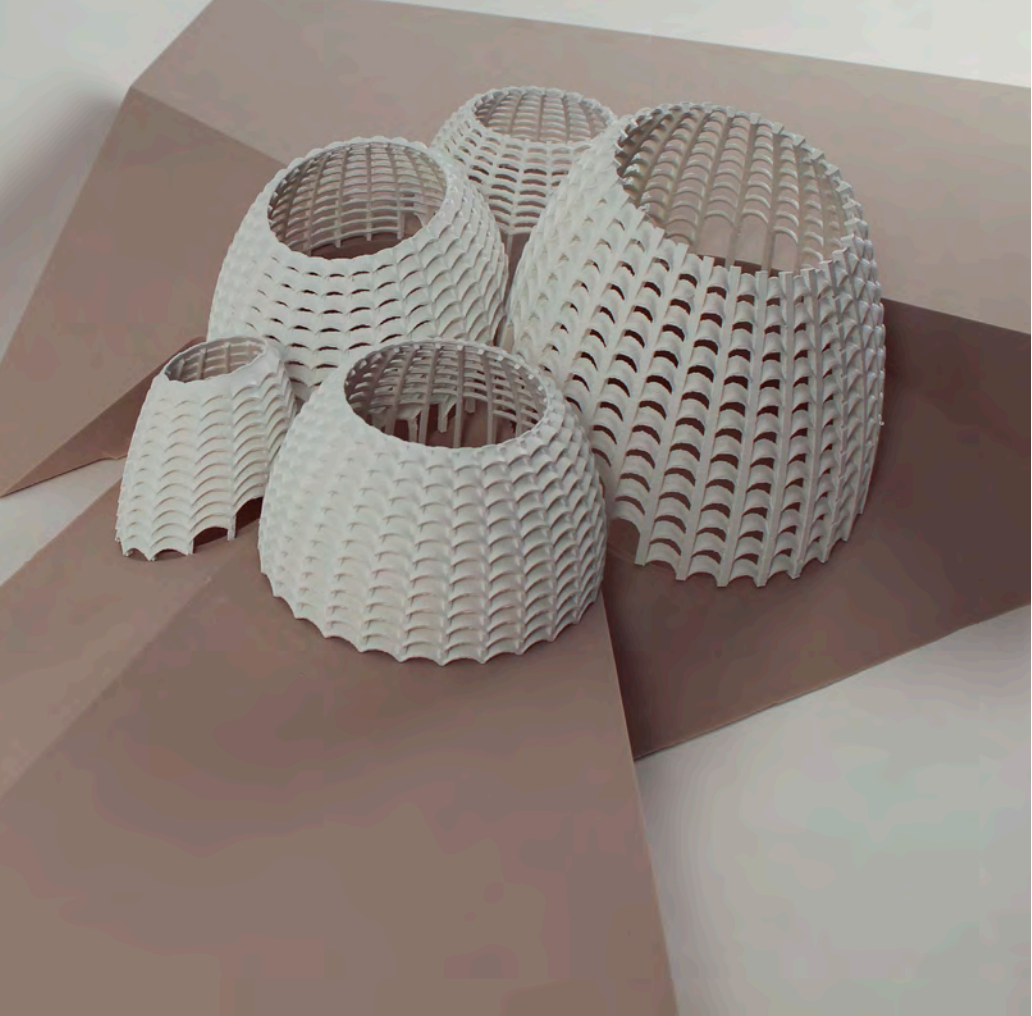
ABS print, stainless steel and
nylon hardware. Concept block
showing a post-tensioned arch.



Design Proposal

ABS print, high density foam

1:100 model of the overall design proposal deploying this 3D ceramic printing technology.

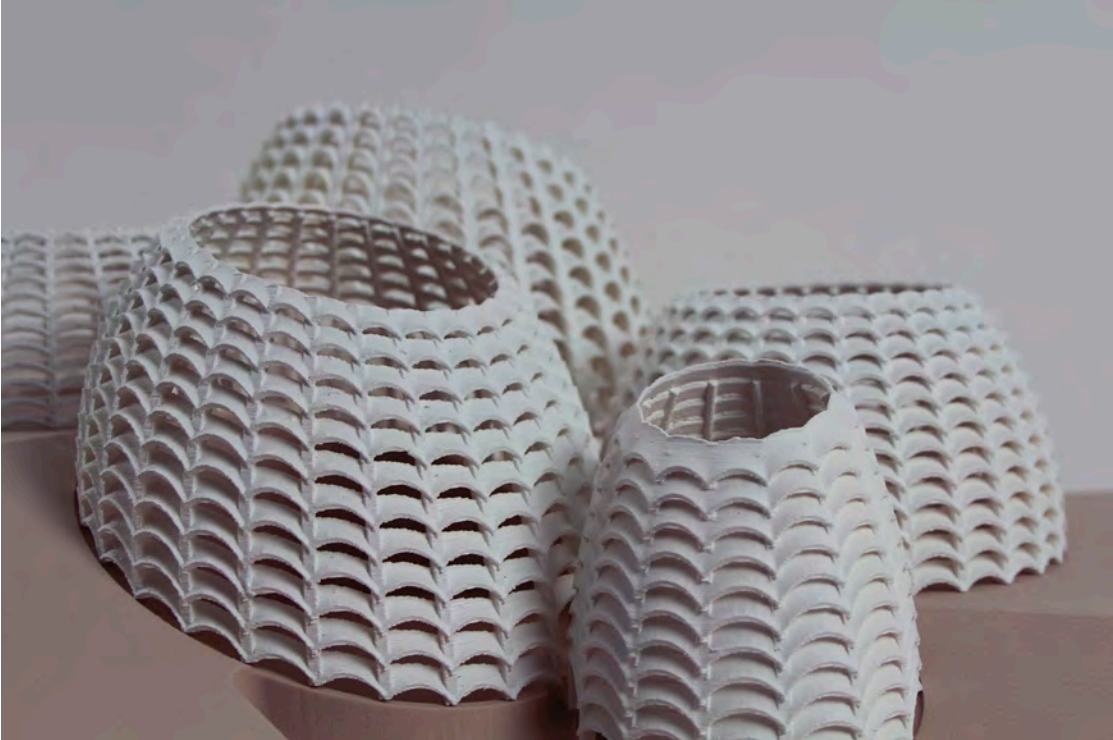
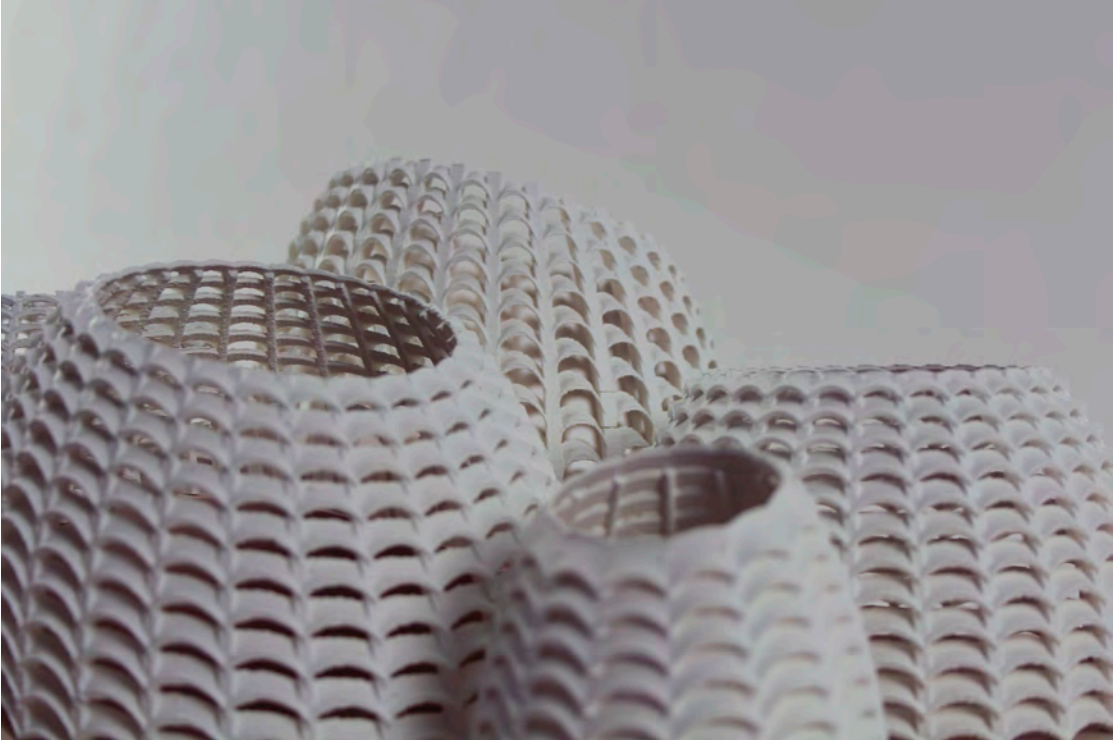
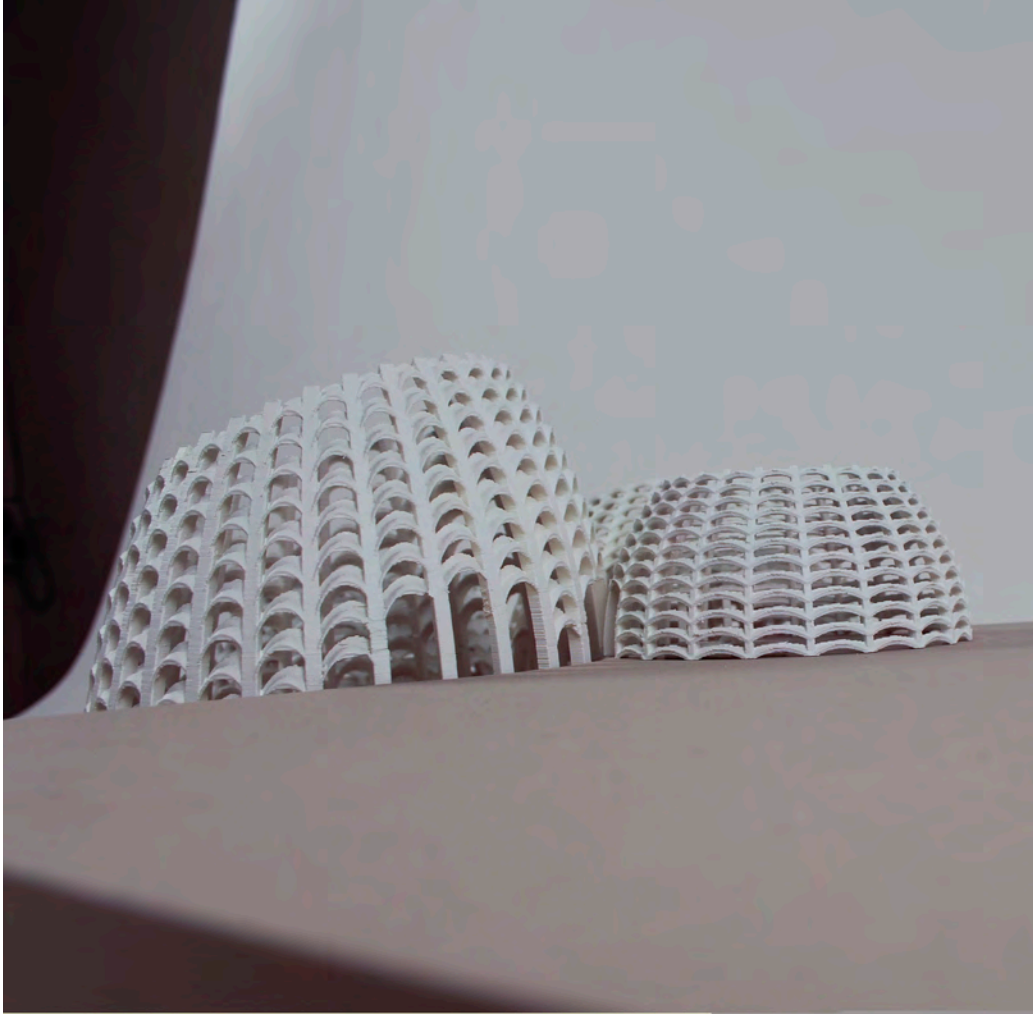


Design Proposal

ABS print, high density foam

1:100 model of the overall design proposal deploying this 3D ceramic printing technology.

Sarah Norman, GSD DDes, model repair.



2 PAGE SPREAD

Representative Work

Two A-1 panels printed for the grading session following the reviews.



GRADING SUBMISSION



