# Mass Customization [I~IV]

*As computational design techniques and the concept of mass-customization challenges the norms of conventional building modules in architecture to accommodate more geometry freedom and variations, one persisting challenge faced with the off-site fabrication of unique concrete building components with complex shapes has been the manufacturing of formwork.*

## [I] Rockery

*In handcrafting of the screen wall blocks, stretch fabric is utilized to provide architectural components more geometric freedom, and modular design is employed to make molds more reusable.*

## [II] Bush

*This research presents the result on the development of an additive manufacturing approach to fabricate topology optimized concrete components, discuss the challenges associated with the clay mould printing process and its assembly.*

## [IV] Hybrid

*This research presents a hybrid formwork fabrication method utilizing additive manufacturing with clay on top of curved foam surfaces robotically fabricated with hot wire.*
*The primary focus of this study is to develop a relatively efficient and highly sustainable formwork manufacturing method capable of producing geometrically complex modular architectural components.*

## [III] Emerging

*Rolling hills emerge through the desk, she sails through the air light as wind.*
*Carbon fiber sheets and resin cure in foam molds to form the furniture; the foam molds are pre-cut with a hot wire and milled by a robotic arm.*

## BACKGROUND

***The advent of the digital age has led to a gradual shift away from the regular, easily measurable geometric tendencies of architectural form. At the same time, its influence on construction techniques has driven contemporary architectural forms to gradually abandon traditional construction paradigms and simple geometric rigidity.***

### 01 Related Fabrication History & Background

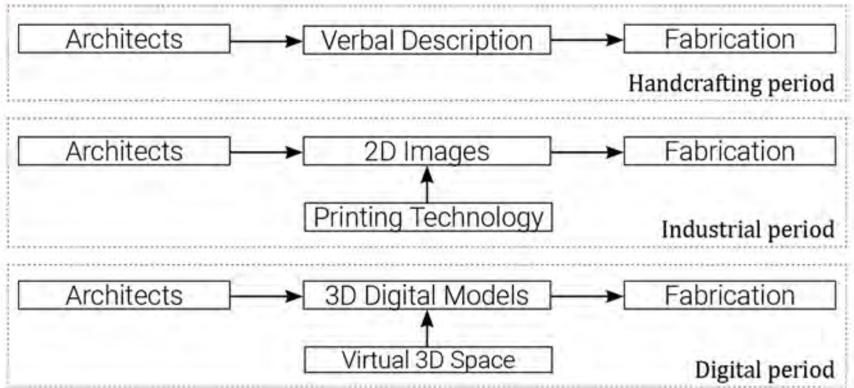
*Reconstruction of the map and drawing device following the methods and coordinates supplied in Alberti's Descriptio urbis Romae. Images by and courtesy of Bruno Queysanne and Patrick Thépot.*

#### Why Free-form? Inverse geometrization of architectural forms

The advent of the digital age has led to a gradual shift away from the regular, easily measurable geometric tendencies of architectural form.

***Mario Carpo*** explains this shift in architectural form and style in his book ***"The Alphabet and the Algorithm"*** in terms of two-dimensional image translation. In the pre-modern period, architects had to be present to guide the craftsmen in the construction due to the difficulty of ensuring that the hand-copied architectural drawings were exactly the same as the designer's first draft. The invention of the printing press solved this problem and separated the design process from the construction process. The only intermediary between design and construction was the ***drawing***, in which the translation of images directly influenced the transformation of architectural forms into ***easily measurable, more precisely expressed forms***.

The digital age has broken this mode of production based on the translation of two-dimensional images, and the ***virtual three-dimensional*** digital space allows the design results to be recorded and transmitted in their full form again. At the same time, from the parametricism of semantic semiotics to the ***performance-based formal goals*** of the new materiality influenced by ***Deleuze***, the sense of ***non-simple geometric*** sculpture has regained attention.




#### Why Robotic Methods? The lag of traditional construction methods and the opportunities presented by CNC machines

Under the influence of modernism, the rationality of fabrication tended to favor ***geometric simplicity*** over ***complexity***, while often tending to favor ***repetition*** over ***uniqueness***, (e.g. mat-building, Amsterdam Orphanage). This phenomenon stems from the ***standardization*** brought about by industrialization, which is precisely a phenomenon of lag.

The construction process tends to lag relative to technological and material

*Dunlap's Creek Bridge*

*Timber formwork construction and casting of Isler shells (taken from Bösiger, 2011)*

*Amsterdam Orphanage (Aldo van Eyck, 1960)*

*Renzo Piano's prototype for a flexible mould, used for shaping of plastic (Piano, 1969)*

developments; This phenomenon continues from medieval stone-cutting, which caused emerging materials to be used in a delayed and unnatural way (e.g., ***Dunlap's Creek Bridge*** had its structure and nodes modeled on wood structures). Likewise, our important current mold technology still lags relative to the digitization of drawing information. For example, we still choose to use wooden mold plates to cast curved concrete surfaces, a method that is ***expensive, wasteful of materials, costly in labor, costly in time, and low in reusability***.

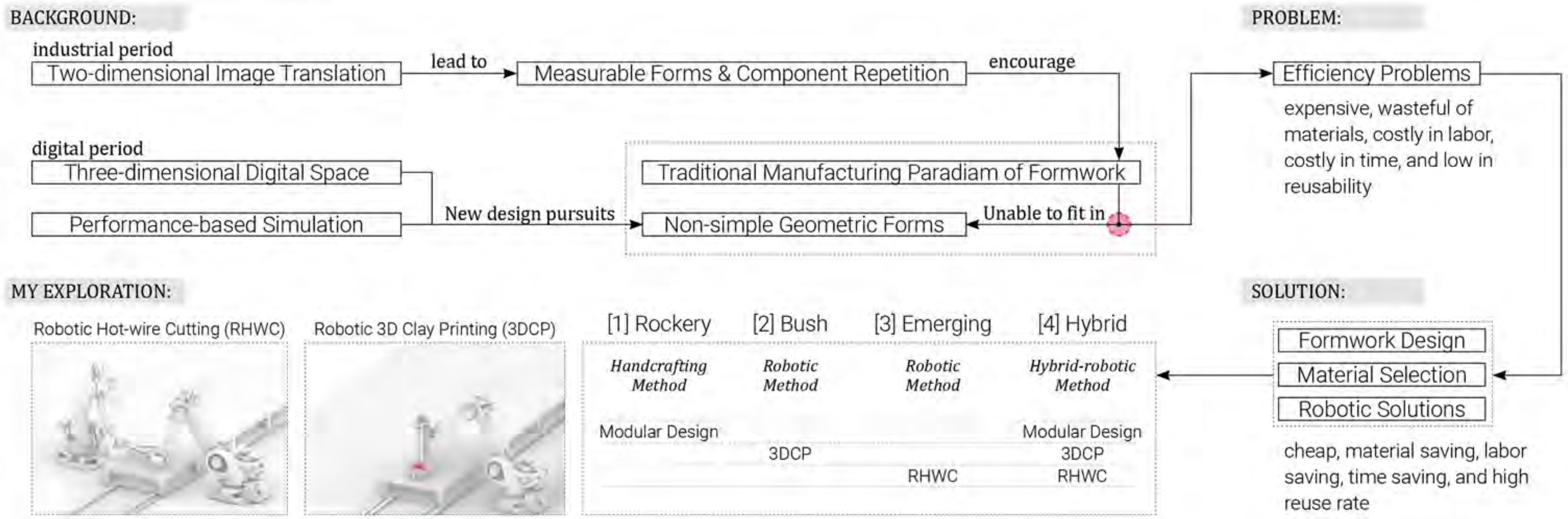
However, with the development of computer technology, manufacturing technology, and the material discipline, these rigidities of production will be no longer necessary, as digitally-controlled machinery can fabricate unique, complexly-shaped components at a cost that is no longer prohibitively expensive; "individual components could be ***mass-customized*** to allow for optimal variance in response to differing local conditions in buildings" (***Branko Kolarevic***).

#### With the Changing Times, Geometric Features of Building Components

| | Information Transmission | Fabrication Principle | Geometric Complexity or Simplicity | Component Repetition or Uniqueness |
|---|---|---|---|---|
| Handcrafting Period | Verbal Description | Customization | Complexity | Uniqueness |
| Industrial Period | 2D Images | Standardization | Simplicity | Repetition |
| Now | 2D Images Generated by 3D Models | Customization | Simplicity | Uniqueness |
| Post-industrial Period | Parameters Exported from Models | Mass Customization | Complexity | Uniqueness |

Digital design is essentially closer to the pre-modern period of medieval construction methods, and that the so-called "modern" is in fact only a small interlude between the history of handcrafting that preceded it and the digital era that replaced it.

### 02 Problem Statement & Robotic Solutions



**EXPLORATION** | *In this series, I try to explore the possibilities of digital technology in mass production of molds through the construction of four of my works about furniture or architectural components. This possibility refers to enhancing the diversity and geometric freedom of architectural components in our living environment without compromising construction efficiency.*

## 03 My Exploration List

One of the key issues in off-site fabrication of complex shape concrete building components is the manufacturing of formwork. Widely adopted methods among finished buildings include hand crafting and CNC milling, of which the cost and sustainability are often challenged due to long manufacturing time and low mold reusability. Recent studies in computer aided manufacturing (CAM) have proposed alternative methods in both directions for improvement, such as using hot wire foam cutting to reduce mold production time, and developing adjustable mold or additive manufacturing methods with reusable materials to increase formwork reusability. However, most studies thus far have sought either efficiency or recyclability, and few combinatory solutions have been proposed and experimented on.

In this series, I try to explore the possibilities of digital technology in mass production of molds through the construction of four of my works about ***furniture or architectural components***.

I blended the non-modern nature of ***freeform*** with the ***utility*** encouraged by modernity in my researches. I wanted to keep the industrial legacy of reusing low-cost mass-produced components while removing the geometric simplicity and rigidity of the "modernity interlude" manufacturing based on two-dimensional image transmission and translation through digital means. The ***variety's richness and geometric free*** will no longer jeopardize ***manufacturing efficiency and economics***.

### Rockery
2018.09-2018.12

**Instructors:**
Ottevaere Olivier Patrick; Weishun Xu

**Team Member:**
Zixun Huang; Zhao Yu; Xing Zhen

**My Role:**
Concept, Design; Formwork Design & Modeling; Handcrafting (Formwork Manufacturing & Assembing, Casting, Demolding);

### Bush
2018.09-2018.12

**Our Publication (IASS 2019):**
Fabrication of Topology Optimized Concrete Components Utilizing 3D Printed Clay Mould

**Instructors:**
Raspall Felix; Sihan Wang; Weishun Xu

**Team Member:**
Zixun Huang; Kunshen Huang; Zaixi Li; Xizhi Zhang; YuFeng Ding; Housen Liu

**My Role:**
Concept, Form Finding & Design;
Digital Fabrication (Printing, Assembling, Casting, Demolding);

### Emerging
2019.03-2019.06

**Design & Manufacturing:**
Zee Liang; Zixun Huang; Peiyi Huang; Feifan Song

**My Role:**
Concept;
Robotic Hot-wire Cutting Method Optimization;
Foam Molds' Design & Robotic Manufacturing;

### Hybrid
2019.12-2020.04

**Our Publication (SIGraDi 2020):**
Robotic Fabrication of Sustainable Hybrid Formwork with Clay and Foam for Concrete Casting

**Project Instructor & Paper Author:**
Weishun Xu; Zixun Huang

**Fabrication:**
Zixun Huang; Liyang Feng; Ning yuan Li; Siyu Lu; Zhenyan Liu; Yating Jiang; Jie Ying; Xiaowan Xu; Yuqi Xu

**My Role:**
The Whole Fabrication Workflow Development;
Robotic Method Development (RHWC & Curved Surface 3DPC);
Led Fabrication Process;
Worked on Paper;

## 04 Material Table

**Product Material:**

**Rocky**
**Bush**
**Hybrid**

Self-compacting Concrete


Glass Fiber

**Emerging**

Clear Epoxy Resin

Carbon-fiber Fabric

**Formwork/Mold Material:**

**Rocky**

Clear Epoxy Resin

Polyester Elastic Fabric

**Bush**

Clay

**Emerging**

Polystyrene Foam Blocks



**Hybrid**

Polystyrene Foam Blocks & Clay

## 05 Objective Table

| | Objective |
|---|---|
| **Rockery** | *Enhance efficiency and geometric diversity with modular design and fabric formwork.* |
| **Bush** | *Increase fabrication efficiency of topology optimized components without losing accuracy.* |
| **Emerging** | *Improve manufacturing efficiency of curved molds over geometric spans using foam hot-wire cutting.* |
| **Hybrid** | *Enhance efficiency with hybrid method capable of producing geometrically complex components.* |

## 06 Geometric & Maufacturing Efficiency Evalution (Desirable Results)

| | Geometric Free & Variety's Richness: | *Variety's Richness* | *Geometric Free* | Manufacturing Efficiency & Economics: | *Handcrafting / Automation* | Sustainability: *Mold Resuability* | Sustainability: *Material Resuability* | *Manufacturing Time* | *Formwork Removability* |
|---|---|---|---|---|---|---|---|---|---|
| **Rockery** | 4/8 | ★★☆☆ | ★★⯪☆ | 0.5/12 | ☆☆☆☆ | ★★★☆ | ☆☆☆☆ | - ★★★★ | ★⯪☆☆ |
| **Bush** | 6.5/8 | ★★★⯪ | ★★★☆ | 10/12 | ★★★☆ | ☆☆☆☆ | ★★★★ | - ★☆☆☆ | ★★★★ |
| **Emerging** | 6/8 | ★★★⯪ | ★★⯪☆ | 6.5/12 | ★★⯪☆ | ★★★☆ | ☆☆☆☆ | - ★★☆☆ | ★★★☆ |
| **Hybrid** | 7/8 | ★★★⯪ | ★★★⯪ | 9.5/12 | ★★★☆ | ★★☆☆ | ★★☆☆ | - ★⯪☆☆ | ★★★★ |

## FABRICATION WORKFLOW

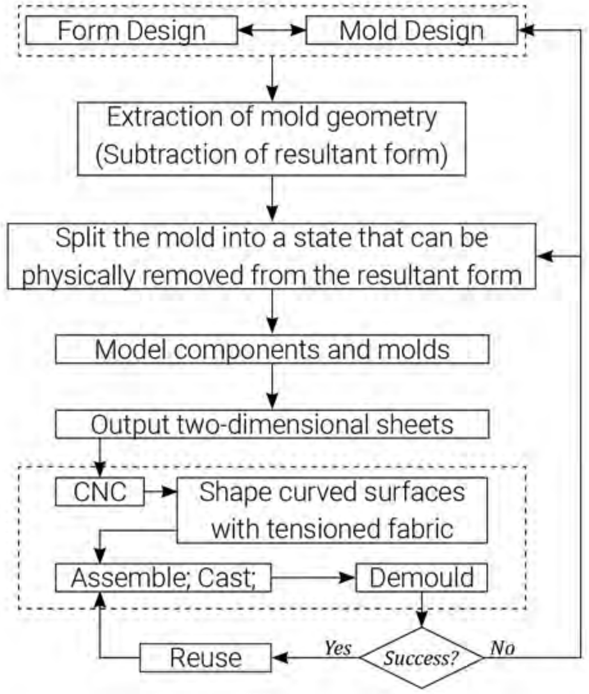
***This section describes the workflow of four projects from design to digitization and explores the feedback of the manufacturing workflow on the possibility range for product geometry including germetric free and variety's richness.***

### Rockery
2018.09-2018.12

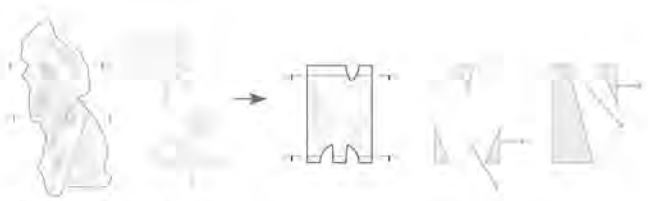
*Possible Geometric Range*

(1) Are the molds easily removed? (2) Can the molds be reused? (3) Can the curved part be simulated by the tensioned fabric between 2D geometries?

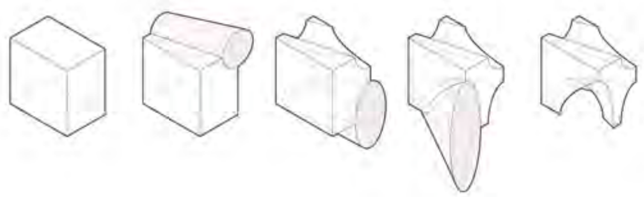
*Methodology*




*Hand-crafting in Digital Space*



Sightline Analysis

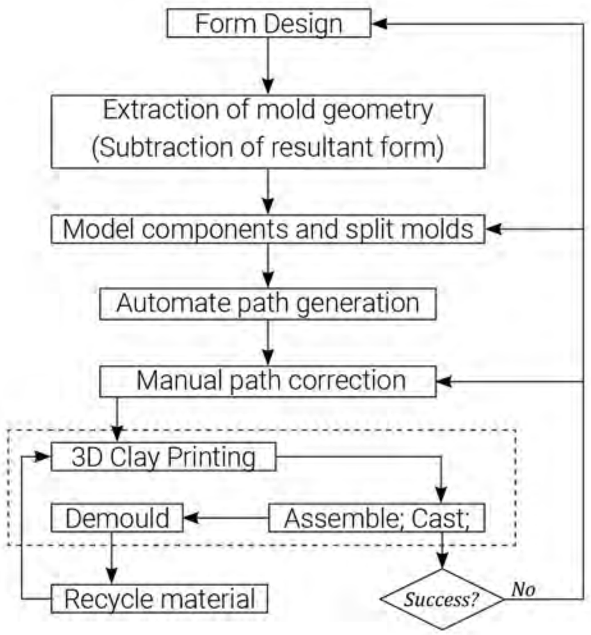


### Bush
2018.09-2018.12

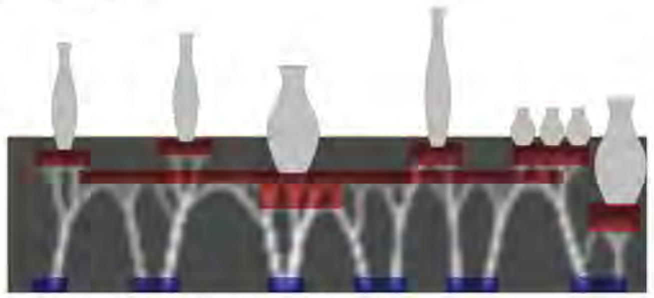
*Possible Geometric Range*

(1) Is it possible for the mold to have a continuous print path? (2) Is the mold scale too large and will the stresses generated during construction exceed the material capacity?

*Methodology*




*Form-finding*



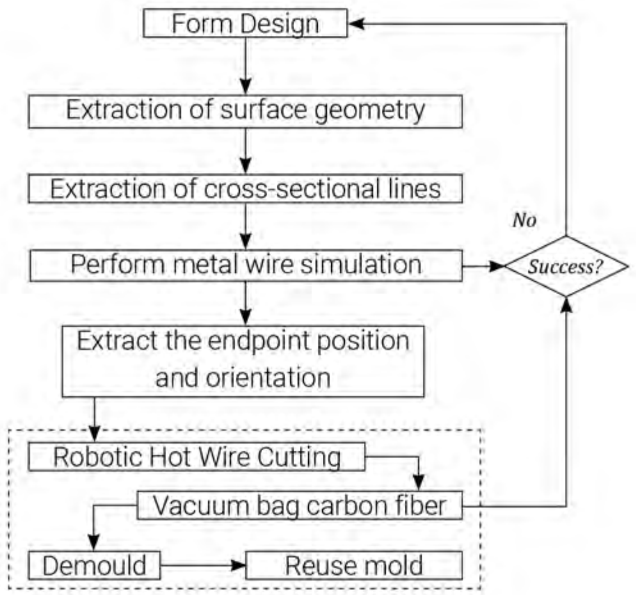
Topology Optimization Using Millipede

### Emerging
2019.03-2019.06

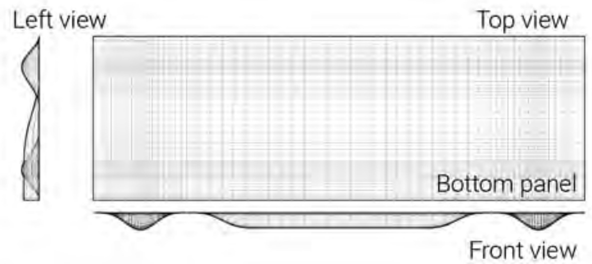
*Possible Geometric Range*

Can the curved surface mold be simulated by a swiping curve of an elastic hot wire of finite length?

*Methodology*




*Hand-crafting in Digital Space*



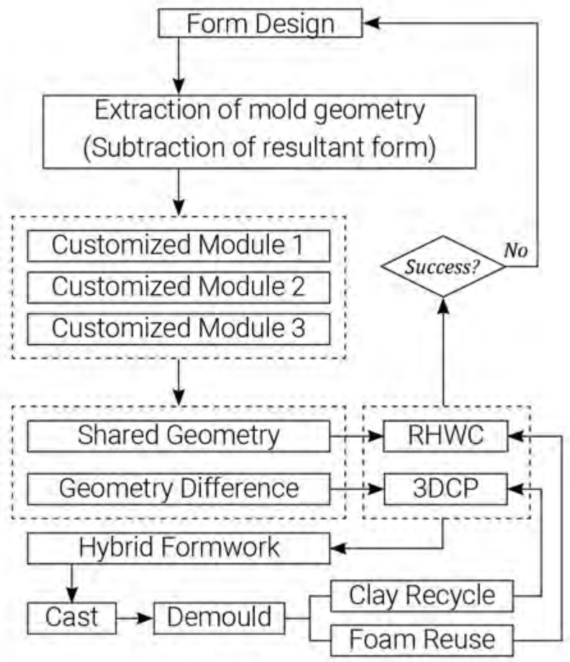


### Hybrid
2019.12-2020.04

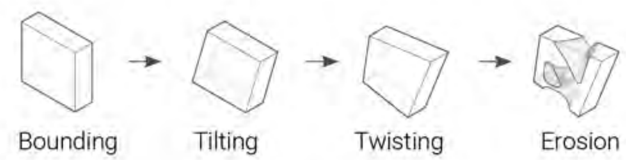
*Possible Geometric Range*

Combines the geometric space achievable by RHWC and 3DCP; Whether the geometry can be disassembled into a gentle geometry and a relatively variable part? The former made of foam and the latter made of clay.

*Methodology*

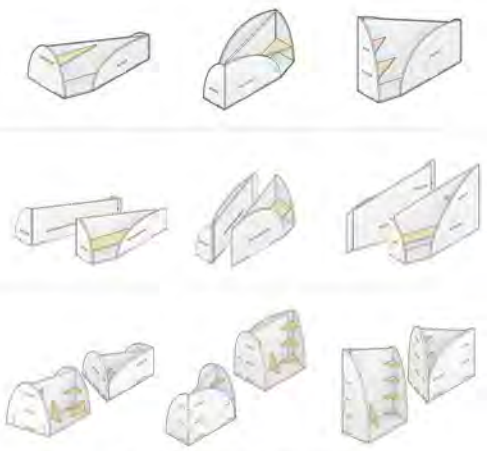



*Form-finding*

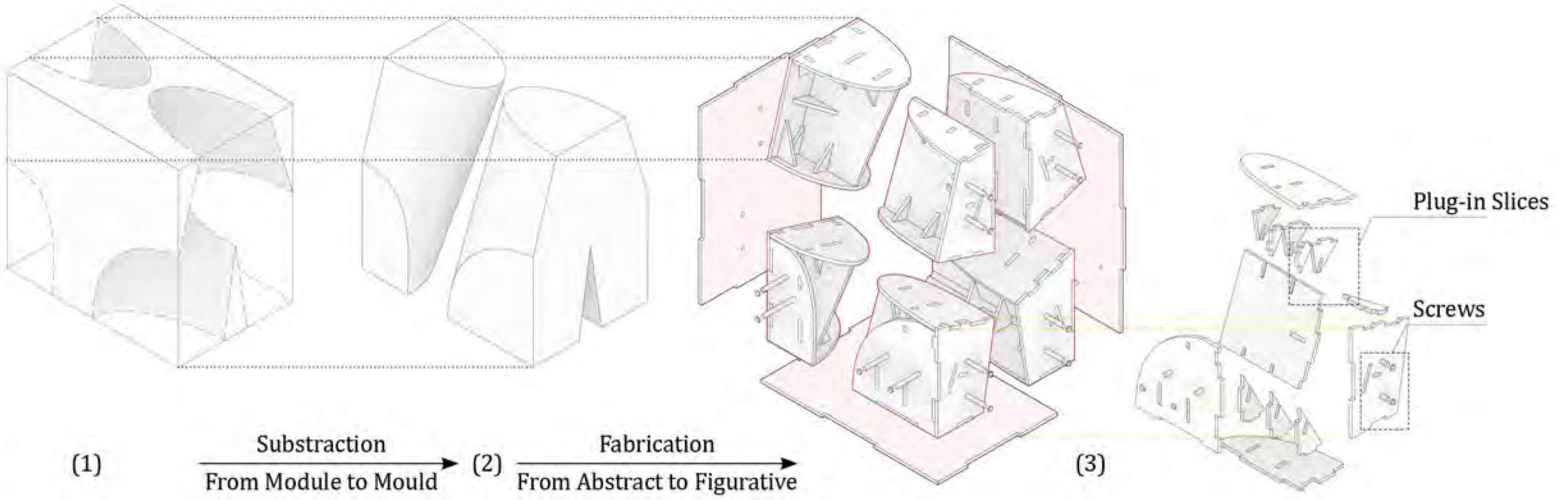



## DETAIL - MOLD DESIGN

***This section presents the mold design of three projects: Rockery, Bush, Hybrid. The other project: Emerging's mold design is quite simple, being directly vacuum pressed by a foam mold with the same shape as the product.***



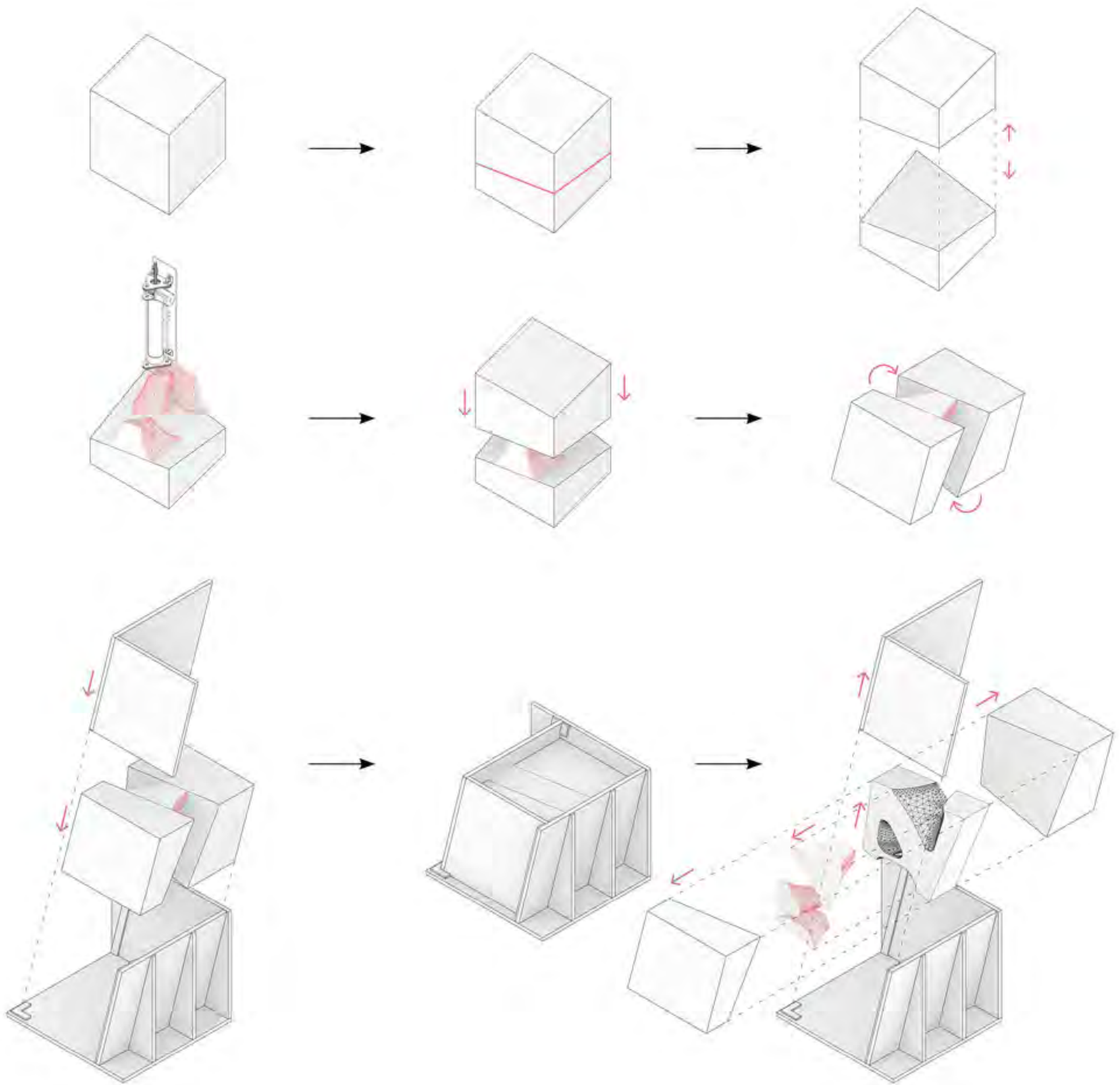
Mould Design Strategies




### 07 Rockey

Many attempts were made to design Rockery's molds so that the concrete components could be removed smoothly from the molds without damaging them.

In the end, we divided the mold into 6 pieces as shown in the picture on the left. Each mold consisted of 2mm thick wooden boards and a tension cloth mold; the cloth was coated with resin to harden; the fabricated molds were finally assembled by bolting them to the outer boards.



### 08 Hybrid

Hybrid mold method enhances the manufacturing efficiency of diverse mold forms by extracting common geometry.

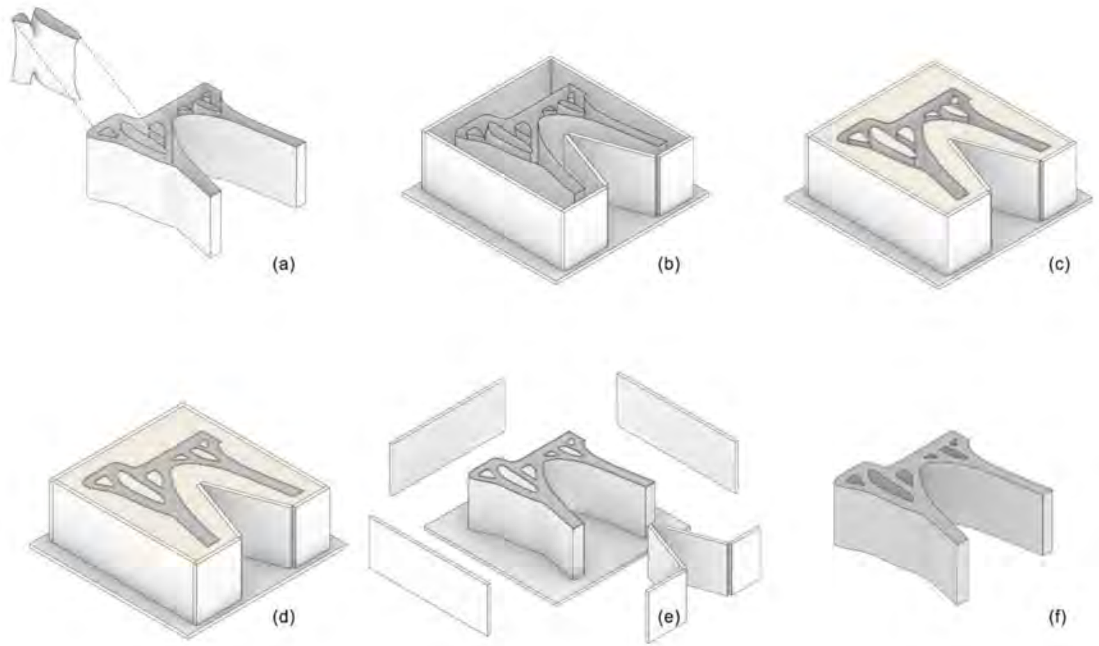
For example, in our experiments, we extract the saddle surface as a simple geometry common to concrete blocks, and this part of the mold is produced by a foam hot-wire cutting method, while serving as a substrate for subsequent clay printing on curved-surface.

The clay molds are printed in layers and will adhere firmly to the foam molds. Finally the hybrid molds are sealed and positioned by wooden boards.

### 09 Bush

Bush's molds consist mainly of clay, with sand and wooden boards as supports. Here is how a concrete component is made.

(a) Assembling 3D printed clay components into the mould for monolithic casting, (b) Surrounding the mould with MDF, (c) Filling the gap between clay and MDF with sand, (d) Casting concrete, (e) Removing sandbox support, (f) Demoulding clay. Photos on the right are fabrication in progress.




# MECHANICAL SYSTEM - RHWC

***This section illustrates the range of geometric forms that can be produced by the Robotic Hot-wire Cutting (RHWC) method by introducing its mechanism and the projects: Emerging and Hybrid.***

## 07 The Simple Mechanism of RHWC

Possible Sweeping Trajectory of the Bent Wire

↑

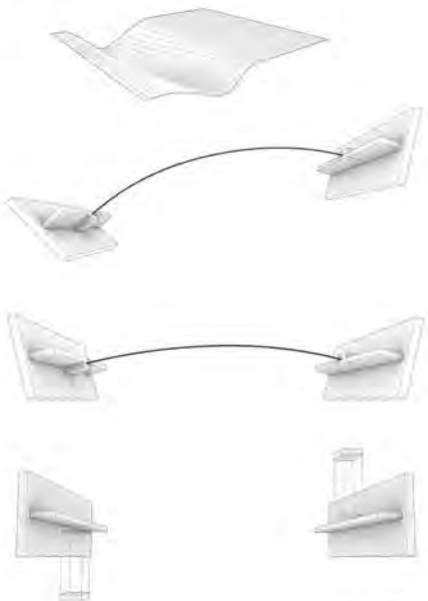
Hot-wire Bending Changes in Motion

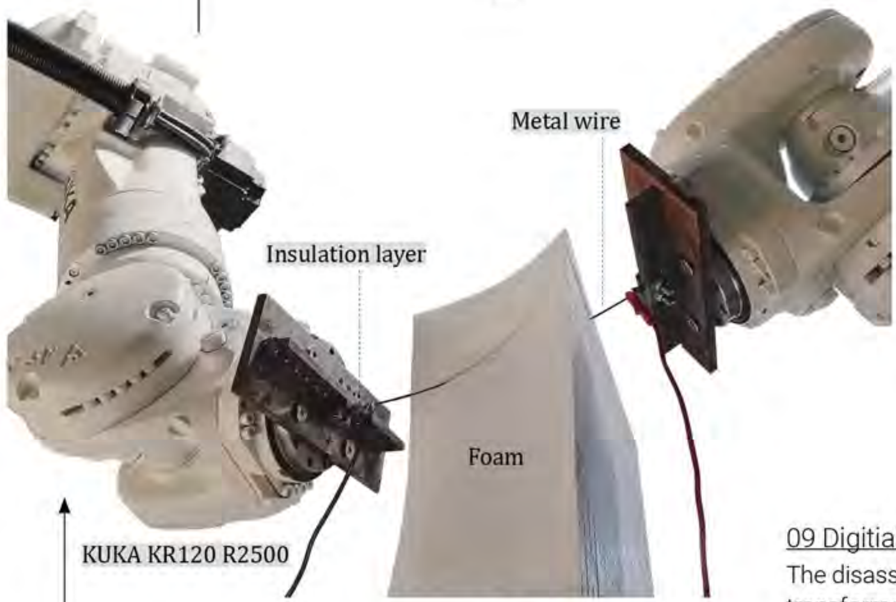
↑

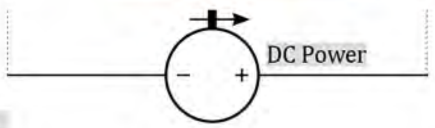
Bent Hot-wire

↑

Hot-wire Installation






KUKA Controller

1. Load Surface;
2. Extract cross-sectional lines and simulate the length of the hot wire;
3. Extract endpoints and their tangential directions;
4. Translate them to Top Center Points (TCP) that can be recognized by robotic arms;

Src file ← GH Programming

The robotic arms' motion positions are recorded in files, which are then uploaded to the control cabinet.

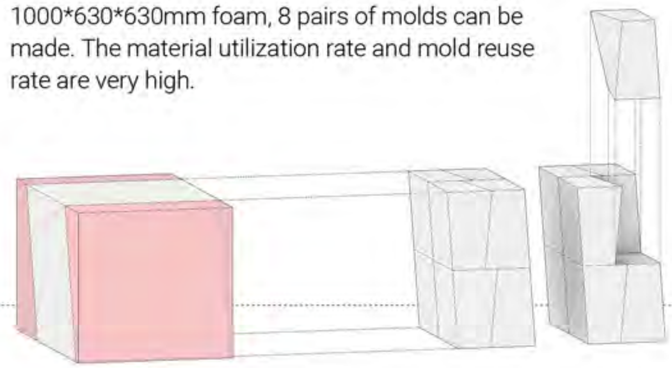
## 08 Formwork Size

**Size of [III] Emerging**

"Emerging" is 2400mm long and 800mm wide; it needs to be disassembled into 14 parts in order to be fitted by the motion path of a bent metal wire.

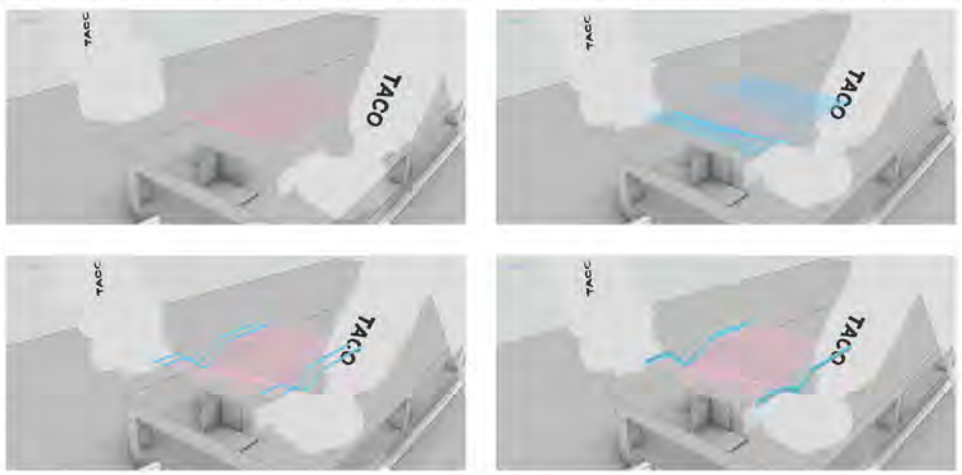
**Size of [IV] Hybrid**

The foam mold part of "Hybrid" is simple saddle surface, with a standard piece of factory 1000*630*630mm foam, 8 pairs of molds can be made. The material utilization rate and mold reuse rate are very high.



## 09 Digitialization/Robotic Workflow

The disassembled curved mold form was input into Rhino, and then was automatically transformed into motion paths of two robot arms through grasshopper graphical programming. This part of the code was originally written by Shuchuan Yao, and later improved by Zixun Huang and Zee Liang.




## 10 Another Relevant Experience

### A Carbonfiber Furniture Collection

The above was a workshop conducted in conjunction with the project: "Emerging", in which I served as a teaching assistant and guided the students in the operation of the robotic arm. Through a robotic approach similar to our "Emerging," the students created a variety of furniture forms, which helped us to demonstrate the potential of the approach in terms of geometric freedom.

**Computational Design & Digital Fabrication in Zhejiang University**

**Instructors:**
Hyde Meng; Zee Liang

**Teaching Assistant:**
Zixun Huang; Peiyi Huang

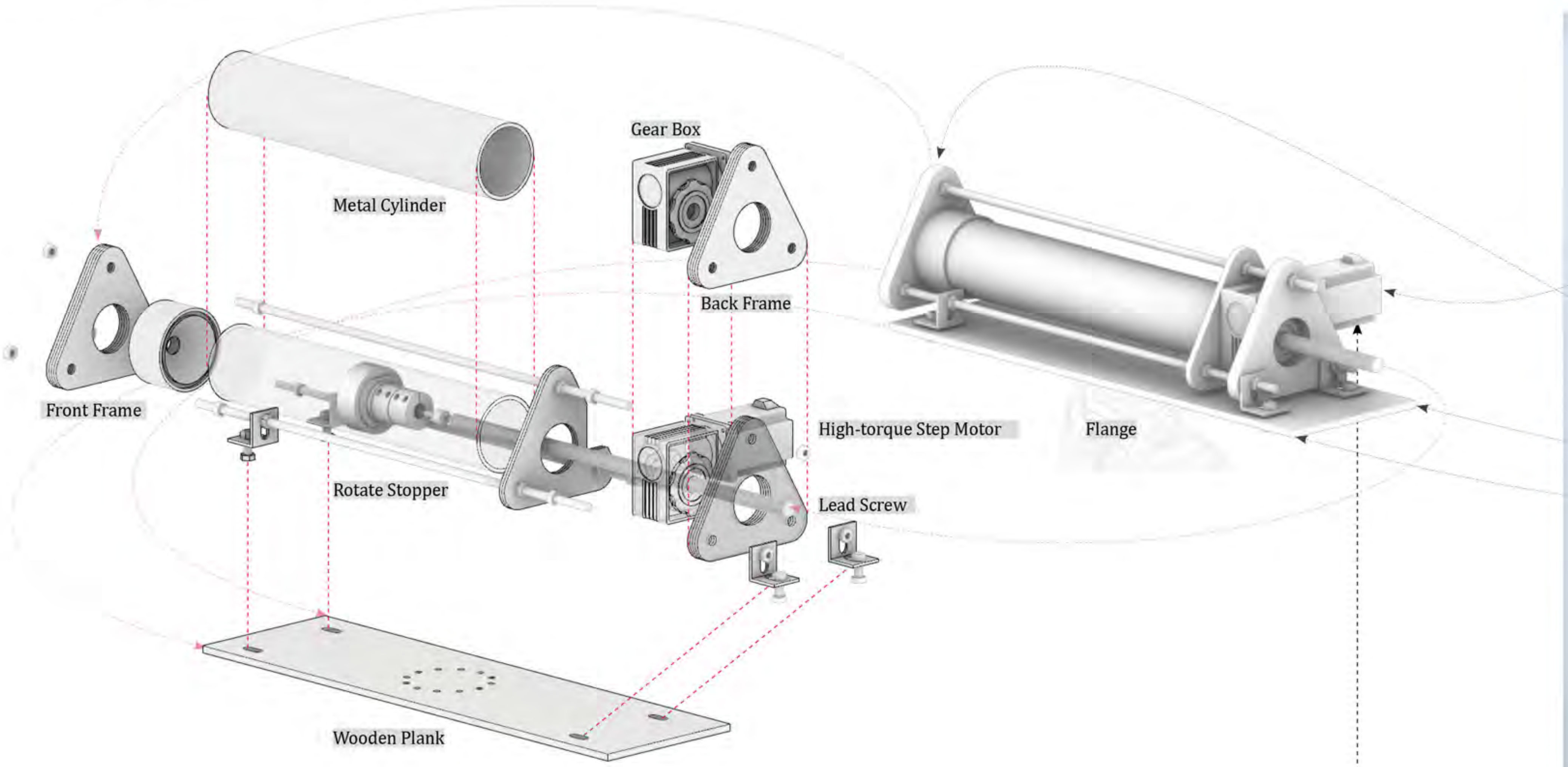
**Academic Year:**
2019 Spring

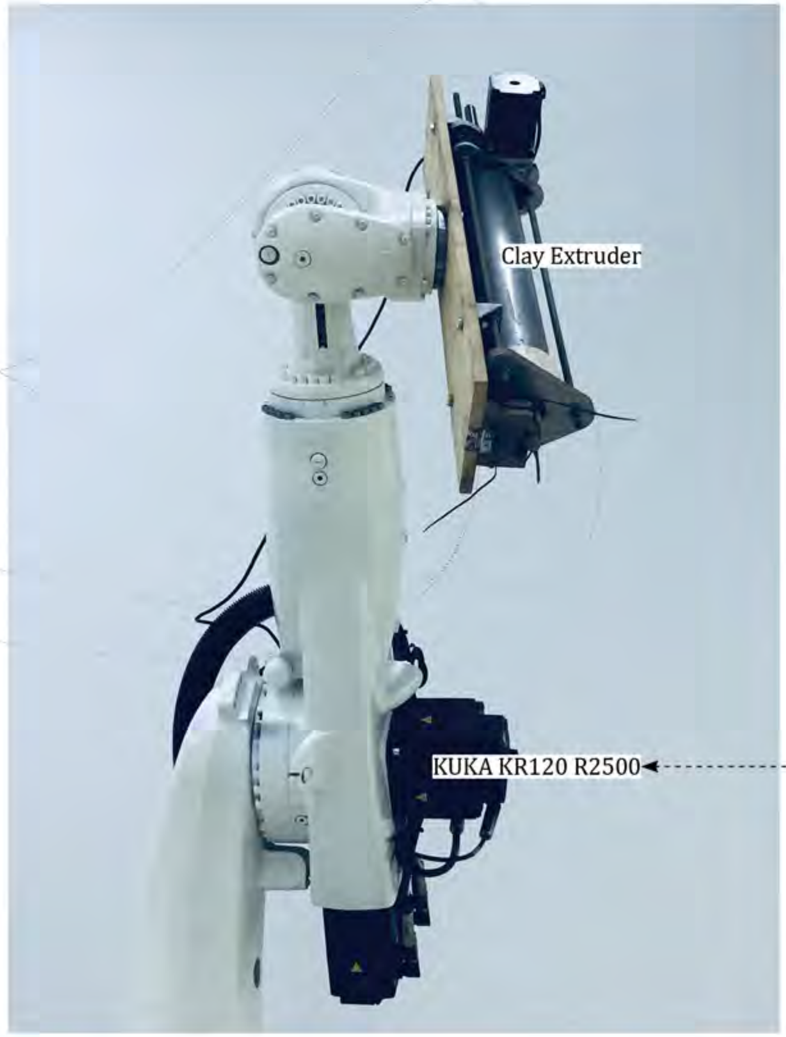
**Students:**
Kunsheng Huang, Ling Mao, Jiaqi Ye, Zhuocheng Doing, Zhiyuan Xu, Ni Ye, Zihao Jin, Yunpeng Wu, Han Yun, Kelei Wu, Haokang Xu, Xiaoyi Wang, Wei Zhang, Kaining Cui, Xinglong Liu, Xiangyao Tan, Nan Li, Chenghao Zhao, Yifan Tao, Yu Liu, Fangyuan Chen, Ye Zhou

**Tools:**
KUKA Robots, Hot-wire Cutting, Grasshopper_TACO, Carbon-fiber Composites

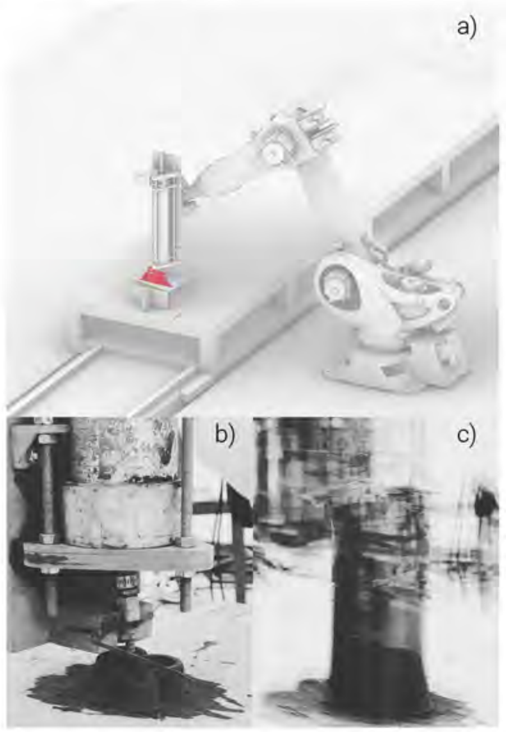
## MECHANICAL SYSTEM- 3DCP | *This section describes the mechanism and working process of the 3D clay printing device, and demonstrates its capabilities as a tool for manufacturing concrete casting.*

11 The Mechanism of 3DCP (Extrusion Speed Control)




12 Printing Process

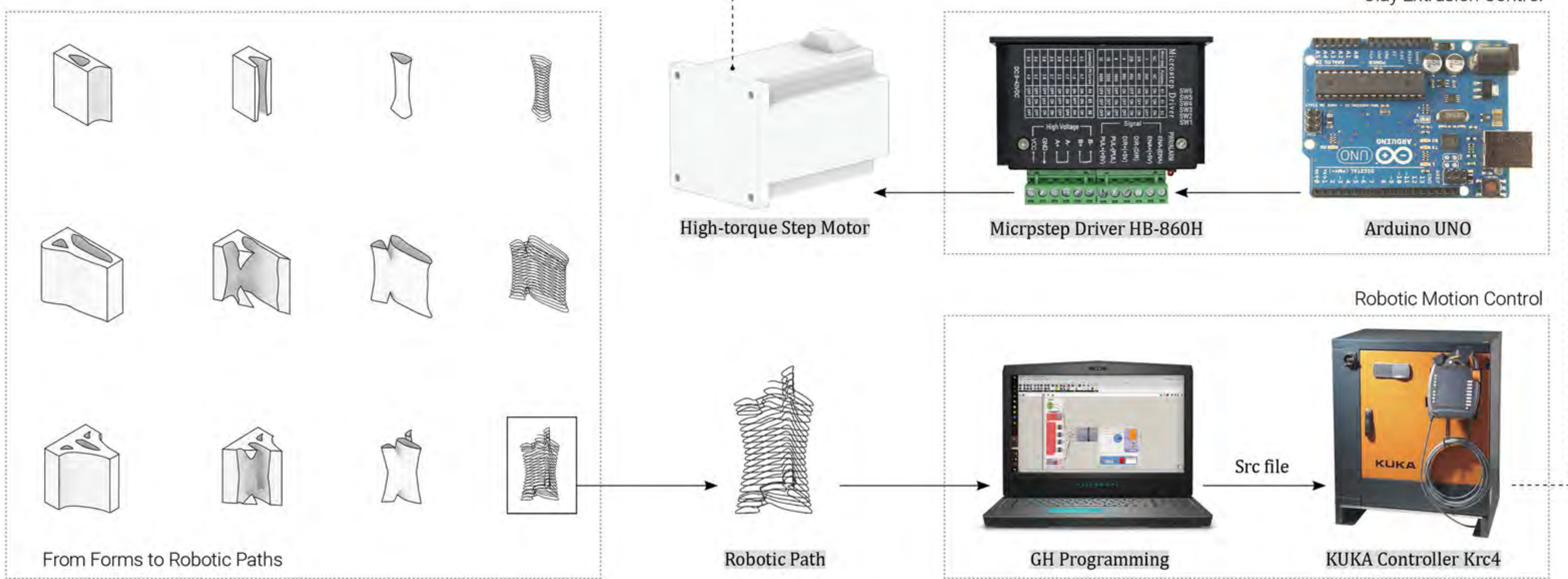



This clay extruder device was originally designed by Sihan Wang, and I reproduced it for the Hybrid Formwork Experiment in 2020. And based on this, I developed a method to print clay molds on curved surface.

The whole 3D printing device consists of two parts, the motion system which is executed by the Kuka robotic arm, and the extruder which is controlled by Arduino.

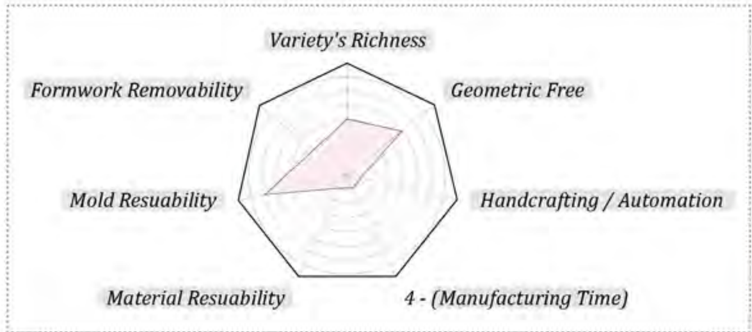
Fig. a is a schematic diagram of the robotic arm being printed on the printing table, and Figs. b and c are photographs of the extrusion unit printing process, representing the laminated printing process.

13 Printing Paths Generation & Robotic Motion Control



## RESULT EVALUATION

*This section evaluates where the four mold methods shown above can be improved in terms of accuracy, from which we can also see more visually the limitations of the different construction methods in terms of geometric freedom.*




### Rockery

The geometric freedom of the Rockery is limited in three ways. Firstly, the elastic fabric cured by the resin will still deform under the static pressure of the concrete, and this deformation will generate errors in the geometry. Subsequently, this deformation may also make it difficult to remove the mold, which may cause damage to the concrete block and make the mold irreversible. The other two geometrical constraints come from the geometrical constraints of the tensioning die itself and the removability of the formwork.


### Bush

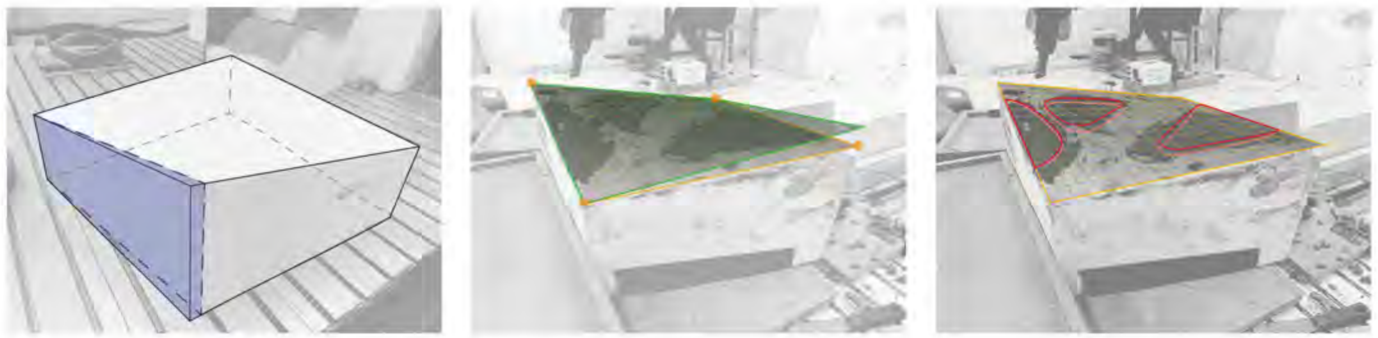
The precision and geometric limitations imposed on Bush are described in more detail in our paper:

1. The minimum width of the branch was set as 12mm which resulted in a crack after casting, 2. The sand as support was not condensed that caused the deformation on the longest side of the shelf, and 3. When printing with a sinuous path in a small area, the redundancy of material distribution might cause a displacement.


### Emerging

In the manufacture of furniture "Emerging", the RHWC method is not limited by material properties in the large span direction as the 3DCP method is.

In the manufacture of furniture "Emerging", the RHWC method is not as limited by the material properties in the large span direction as the 3DCP method. The surface shape of the product is limited by the variable interval of the wire, i.e., the cross section must be Quadratic bezier curve along the direction of motion, and the hot wire is affected by the resistance in the foam as it is bent by the robot arm, which is temporarily unpredictable.

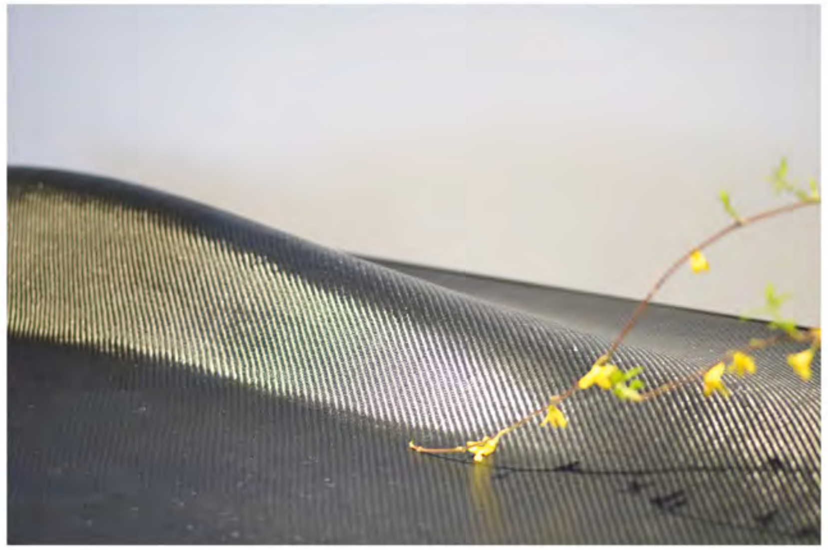
### Hybrid

The same errors and geometric limitations caused by the RHWC method are also present in the hybrid method in which it is involved.

Since error in the fabrication of RHWC foam is inevitable due to unpredictable friction between foam and wire, and that 3DCP requires accurate base surface data for tool path generation, it is important to re-model the formwork based on computational surfaces tailored to calibration procedures, which should re-generate the model based on measured data from the result of the RHWC foam. The best practice should be to model the RHWC foam surface as one or the combination of a limited number of computational geometries, and several feature points on the surface should be clearly identifiable to serve as input parameters for the computational model. 3DCP parts should be re-modeled as responsive geometries that can be re-generated based on the RHWC surface data.

## RESULT DEMONSTRATION


Left: The Project "Rockery" ; Right: The Project "Bush";
Next Page: "Emerging" & "Hybrid".



The project "Emerging" is shown in HD on the left.

The result of the project "Hybrid" is shown above.

The video in the QR code on the right shows the construction process of the project "Hybrid".