SELECTED WORKS

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CONTENTS

01

Non-Planar Sliced Robotic 3D Printing

Path Optimization For Non-Planar Sliced Single-Shell Surfaces Based On Minimum Path Coverage Algorithm

Year 5, Semester 1, Tongji University, 2023, Individual Work

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Please scan the QR code to watch the video

OVERVIEW

The application of robotic arms makes it possible to print non-planar paths. Non-planar slicing helps to break through the inherent limitations of planar 3D printing, reduce support and release new design potential.

Some research work has been done in related areas. Dai et al. introduced a method for printing models with complex topologies on a multi-axis robotic printing system, utilizing movable, rotating platforms. Additionally, the open-source Python-based framework COMPAS_SLICER develops non-planar slicing algorithms, enhancing accessibility for customers.

This project introduces **a non-planar path planning technique utilizing scalar field interpolation.** It involves identifying model boundaries and computing scalar fields through interpolation between these boundaries. The resulting paths guide printing by remeshing the mesh, leveraging geodesic distances, and establishing optimal print orientations.

Continuity in print paths significantly influences print quality and efficiency. This method treats each printing path order as a **directed acyclic graph (DAG)** and employs **a minimum path covering algorithm** to enhance continuity. This optimization reduces interruptions, improving printing efficiency notably.

Experimental validation using ceramic materials and PETG demonstrates the superiority of this approach over conventional planar slicing algorithms. Optimized print paths exhibit **increased strength, reduced print time, and smoother textures**, effectively addressing 3D printing limitations.

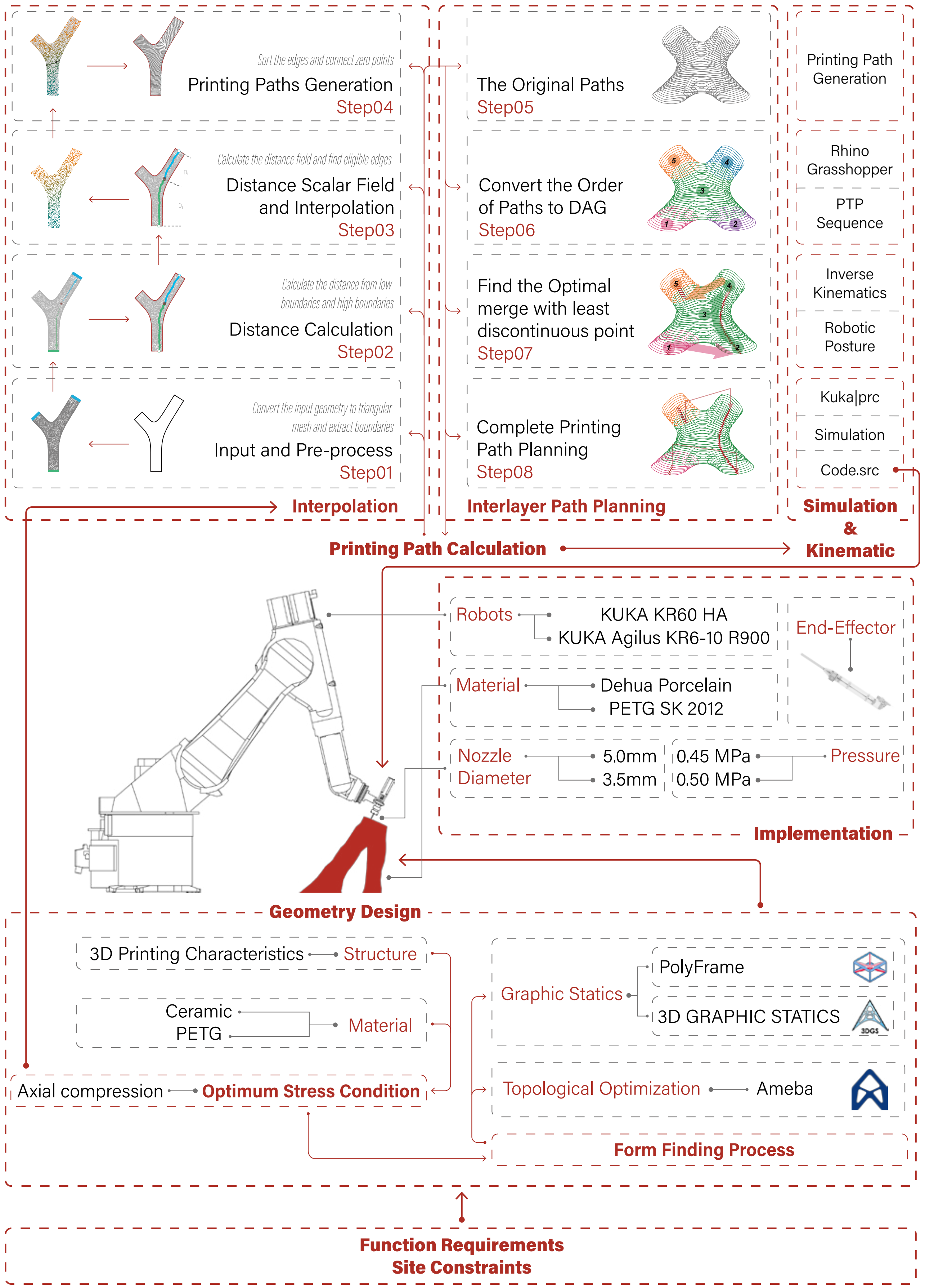
References:

[1] Ioanna Mitropoulou, Mathias Bernhard, and Benjamin Dillenburger. 2020. Print Paths Key-framing: Design for non-planar layered robotic FDM printing. In Proceedings of the 5th Annual ACM Symposium on Computational Fabrication (SCF '20). Association for Computing Machinery, New York, NY, USA, Article 6, 1–10. https://doi.org/10.1145/3424630.3425408

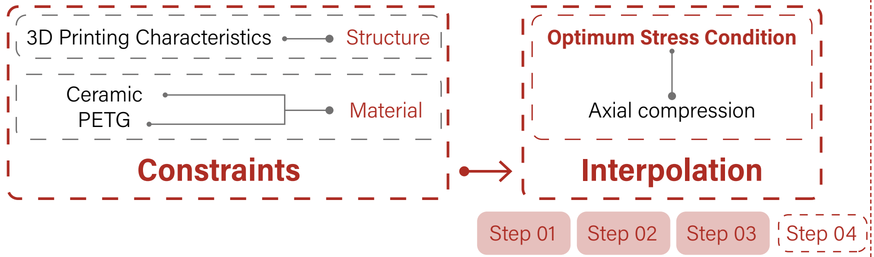
[2] Chengkai Dai, Charlie C. L. Wang, Chenming Wu, Sylvain Lefebvre, Guoxin Fang, and Yong-Jin Liu. 2018. Support-Free Volume Printing by Multi-Axis Motion. ACM Trans. Graph. 37, 4, Article 134 (July 2018), 14 pages. https://doi.org/10.1145/3197517.3201342

[3] Bhooshan, S., Ladinig, J., Van Mele, T., Block, P. (2019). Function Representation for Robotic 3D Printed Concrete. In: Willmann, J., Block, P., Hutter, M., Byrne, K., Schork, T. (eds) Robotic Fabrication in Architecture, Art and Design 2018. ROBARCH 2018. Springer, Cham. https://doi.org/10.1007/978-3-319-92294-2_8

WORKFLOW | DESIGN, CALCULATION, SIMULATION, KINEMATIC, IMPLEMENTATION



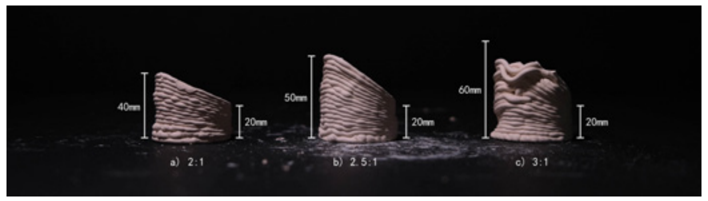
PRINTING PATH CALCULATION | INTERPOLATION



This section details the method we use to generate non-planar sliced printing paths. We calculate the distance scalar field and select eligible edges.

Step 01

- Remesh: To get accurate calculating results, the input mesh needs remeshing to mesh with uniform edge lengths. The length of the remeshed mesh edges should be constrained to a certain length range, similar to the average layer height of the 3D printing process.
- Ratio of the Maximum Height and Minimum Height: The limit of the ratio of the maximum height and minimum height must be tested due to the material characteristics. Otherwise, the quality of the 3D printing results can not be ensured. We have tested the limitations of ratio of the maximum height and minimum height for ceramic, finding that the maximum height can be up to 2.5 times the minimum height.
- Extract Boundaries: We need to extract the boundaries of the input geometry to generate distance scalar field, and then the printing tool paths. The boundaries are going to be separated into two groups.



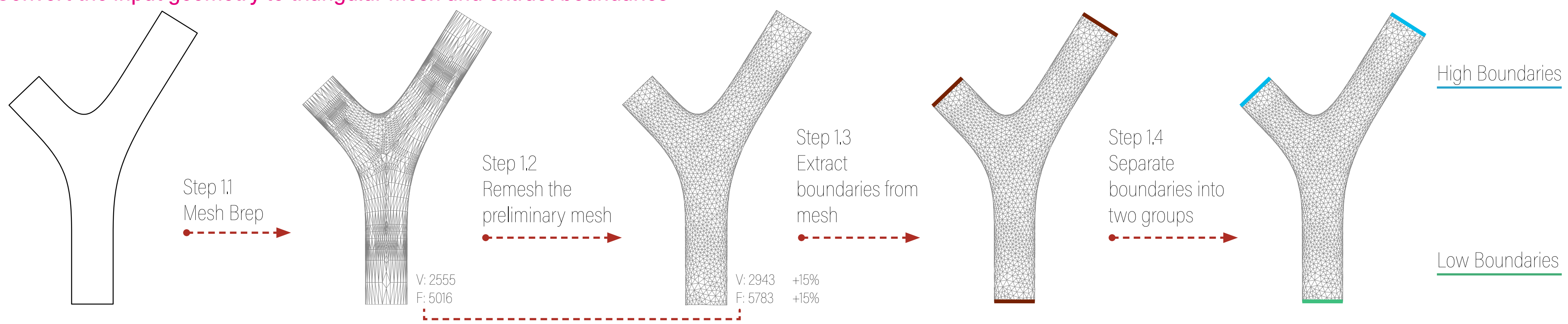
Step 02

- Distance Calculation: In this section, we calculate the geodesic distance from each vertex to its closest high and low boundaries, which is described by Figure 3, and the results are two lists of geodesic distance.

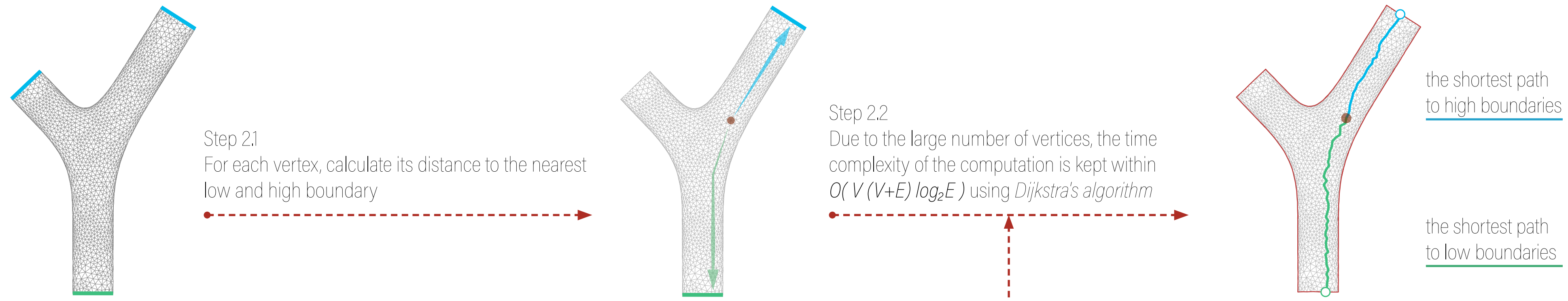
Step 03

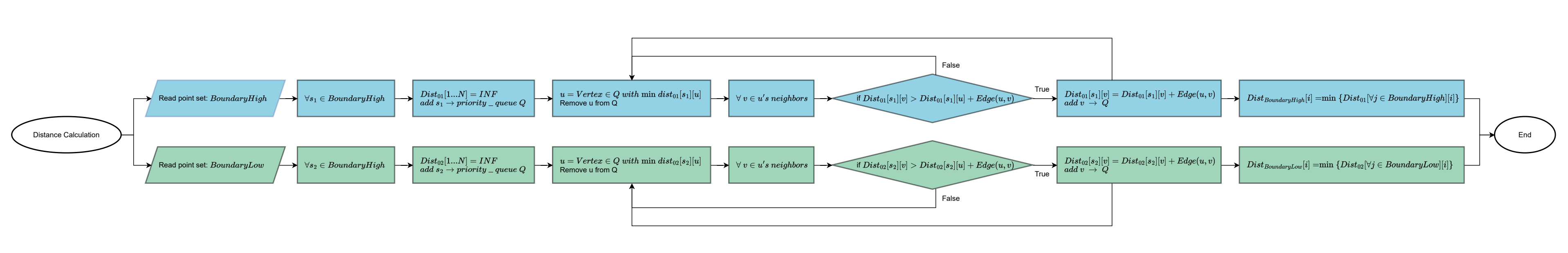
- Distance Scalar Field: This section utilizes the two geodesic distance lists to calculate distance scalar field. Every vertex has a scalar field value.
- Interpolation: The next step is to find the edges where the product of the distance scalar field value of the two endpoints is negative.

Step 01 Preceeding
Convert the input geometry to triangular mesh and extract boundaries

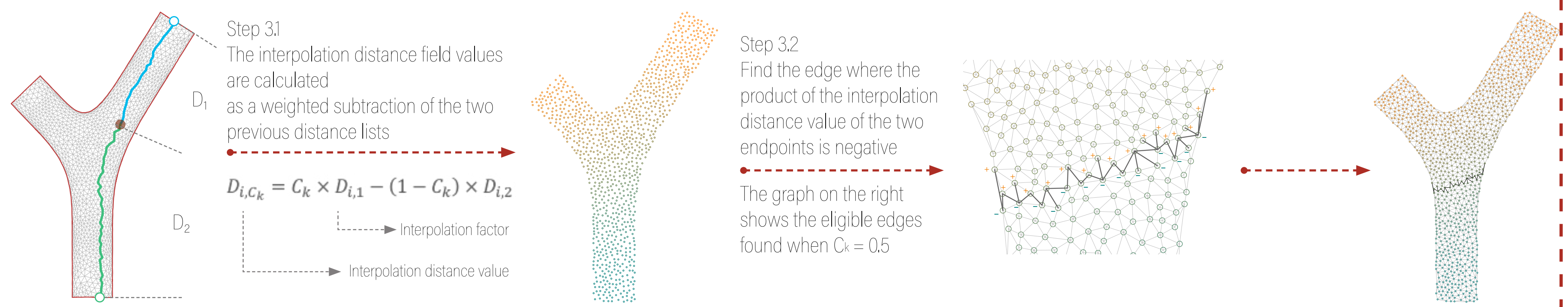


Step 02 Distance Calculating
Calculate the distance from low boundaries and high boundaries





Step 03 Interpolation field calculation
Calculate the distance field and find eligible edges



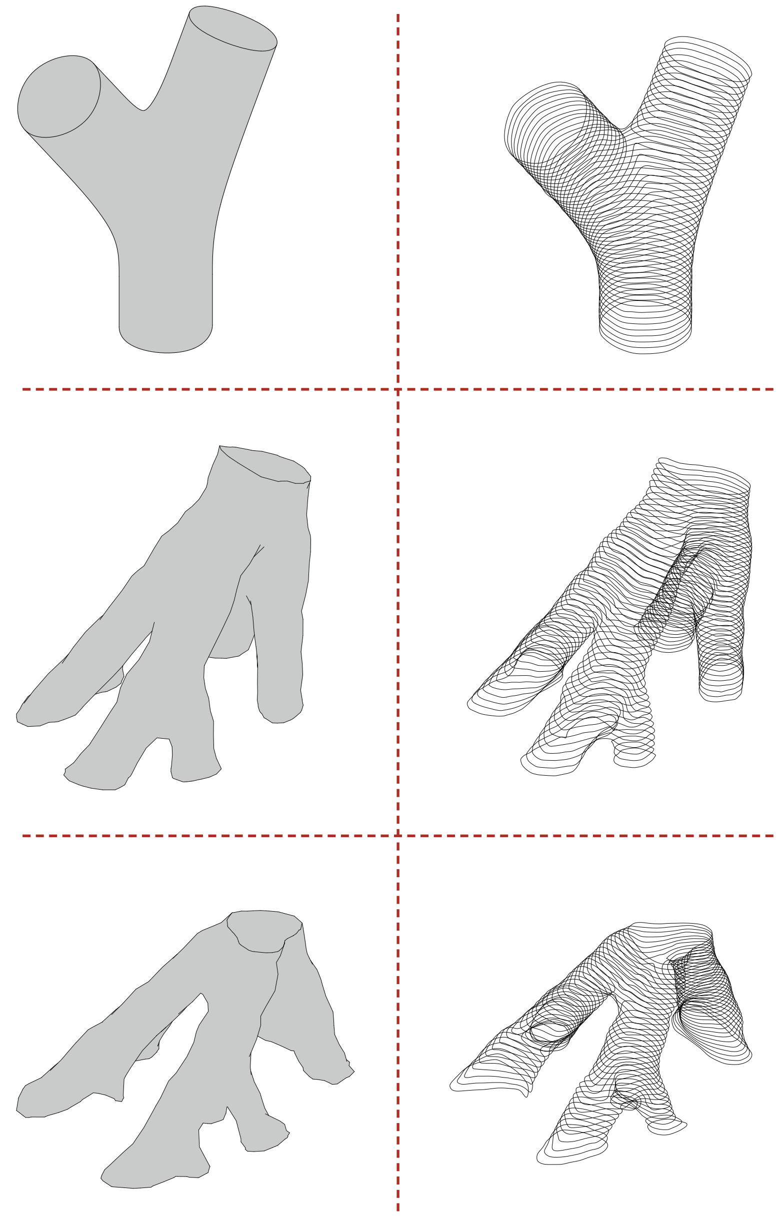
PRINTING PATH CALCULATION | INTERPOLATION

3D Printing Characteristics → Structure
Ceramic
PETG → Material
Constraints → **Interpolation**
Optimum Stress Condition
Axial compression

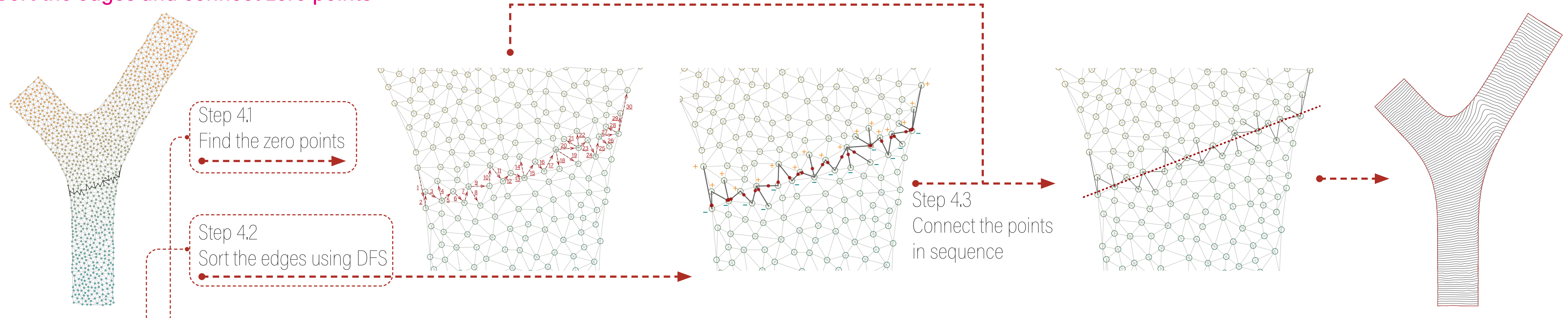
Step 01 | Step 02 | Step 03 | Step 04

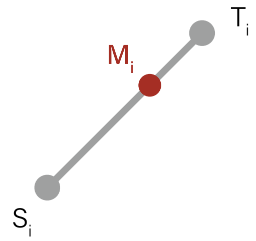
This section is going to generate the interpolation curves for each list of edges. To deal with that, the first process is to find the zero crossings of the edges.the second process is that the points need sorting to have the correct order.

Input Geometry | Interpolation Result



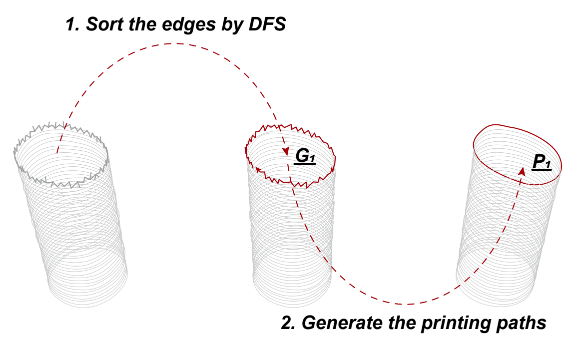
Step 04 Interpolation curves generation
Sort the edges and connect zero points





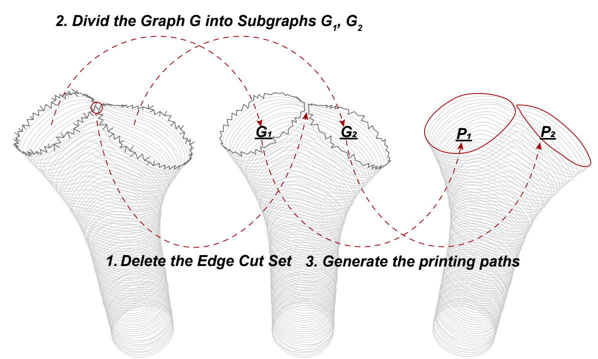
For each edge,
let S_i and T_i be the two endpoints of the edge,
and $V(S_i)$, $V(T_i)$ the scalar field value of the two endpoints.
Then the zero-crossing point M_i of the edge is:

$$M_i = S_i + (T_i - S_i) \cdot \frac{|V(S_i)|}{|V(S_i)| + |V(T_i)|}$$



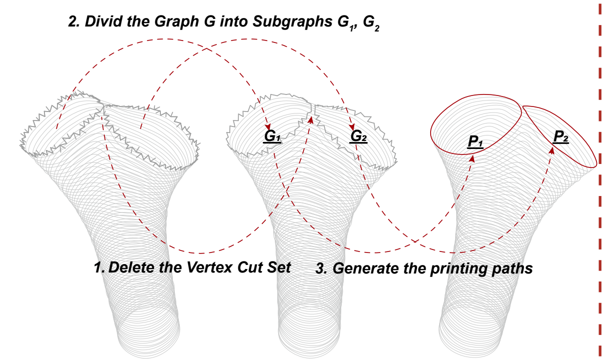
Sort the Edges by DFS

The simplest situation, the edges of each layer will be sorted by DFS. In other words, we use the DFS to calculate the longest simple path in the built graph.



Delete Edge Cut Set then DFS

Sometimes there will be edge cut set in the graph. The edges in the set will be deleted, which separates the graph into independent several subgraphs. And then sort edges in each subgraph.

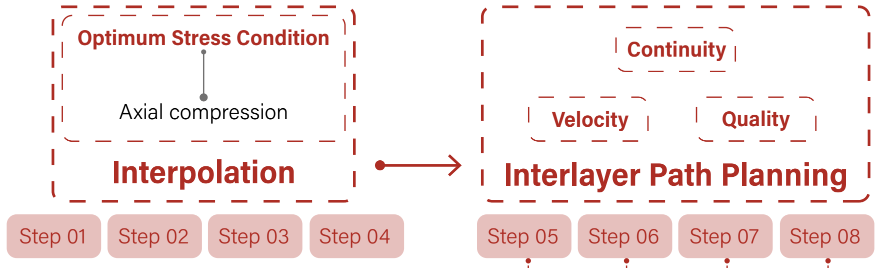


Delete Vertex Cut Set then DFS

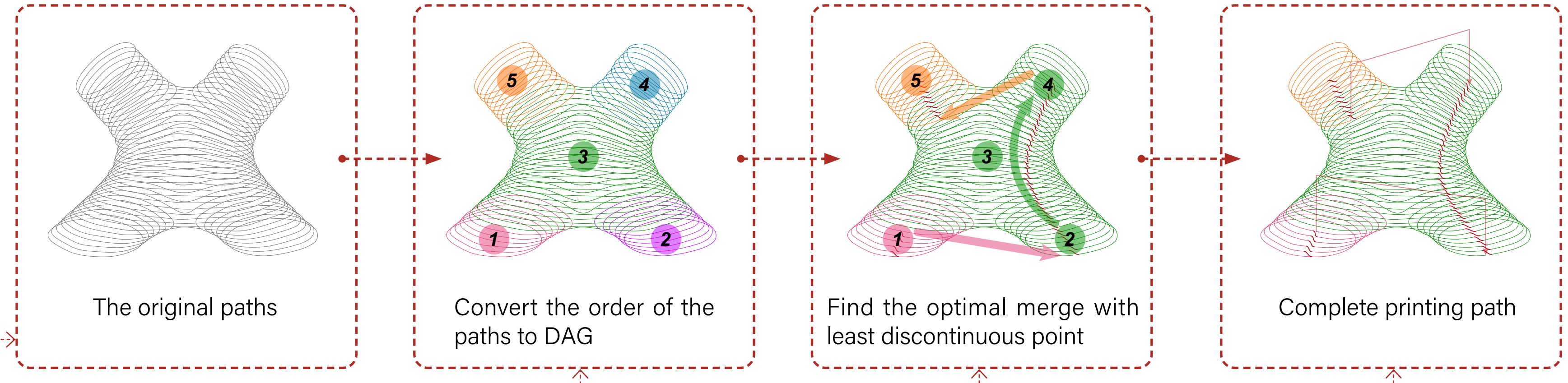
If there is vertex cut set in the graph, the graph will also be divided into several subgraphs by deleting the vertices in the cut set. And then sort edges in each subgraph.

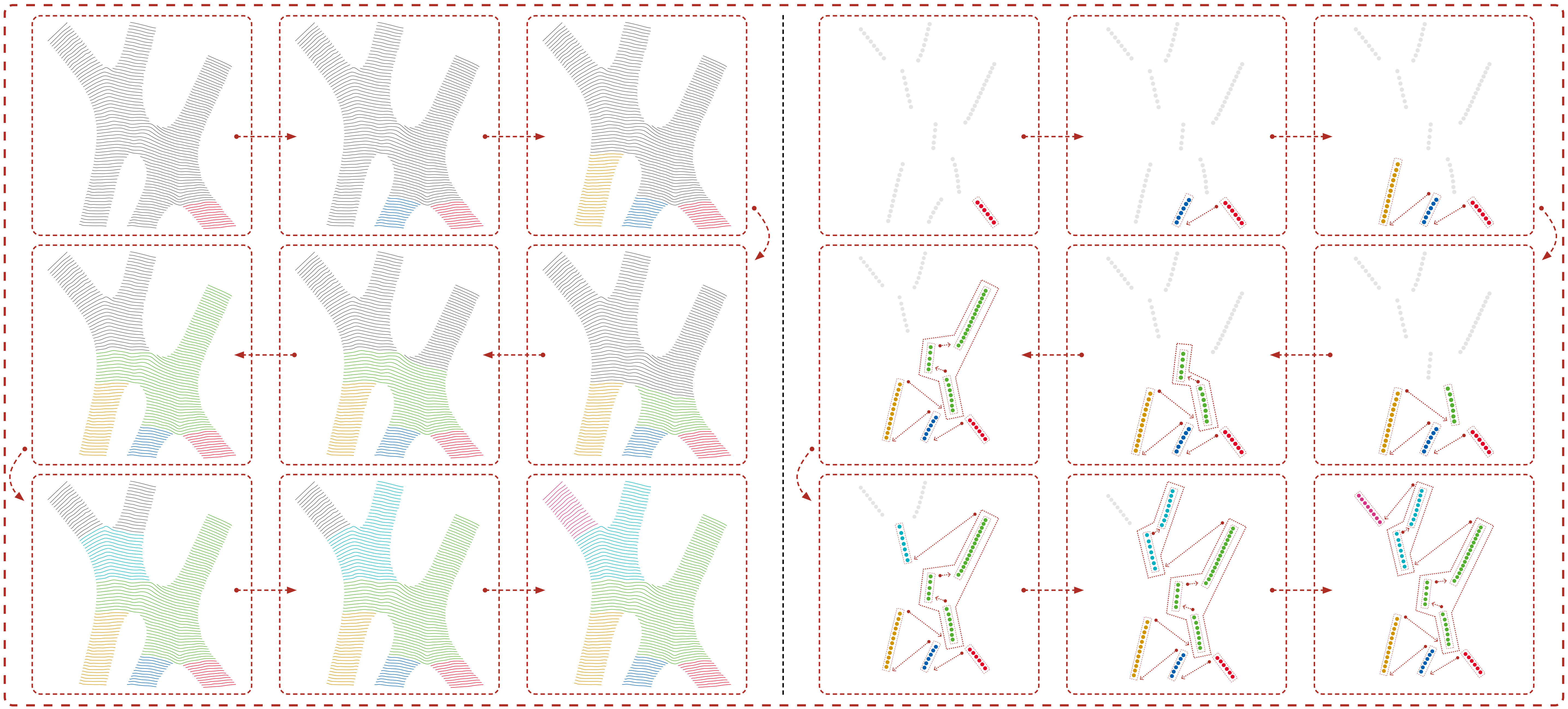
Please note that the longest path problem for undirected graph is NP-hard. So, there is a small chance that the calculation will take much time. However, since usually there is no circle or just one circle in the graph, most of the calculations will not take so much time.

PRINTING PATH CALCULATION | INTERLAYER PATH PLANNING



The method is that considering each layer path as a node and the printing orders as the directed edges linking different nodes. Then we can build a DAG and convert the original goal to a new one, finding the optimal merging strategy with least independent path left.





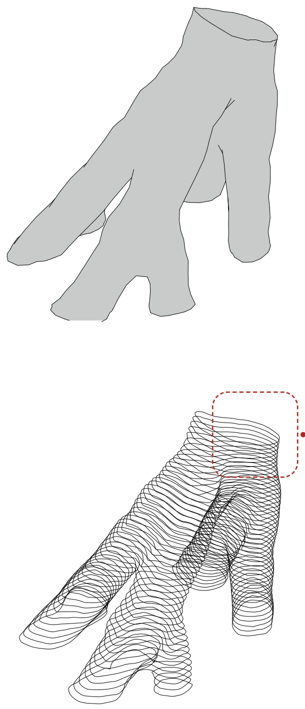
PRINTING PATH CALCULATION | SIMULATION & KINEMATIC

Interpolation

Interlayer Path Planning

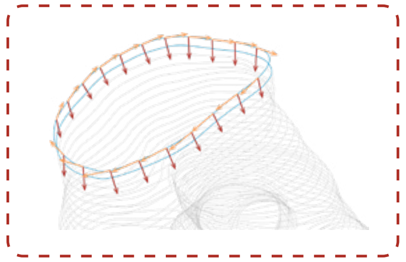
Printing Path Calculation

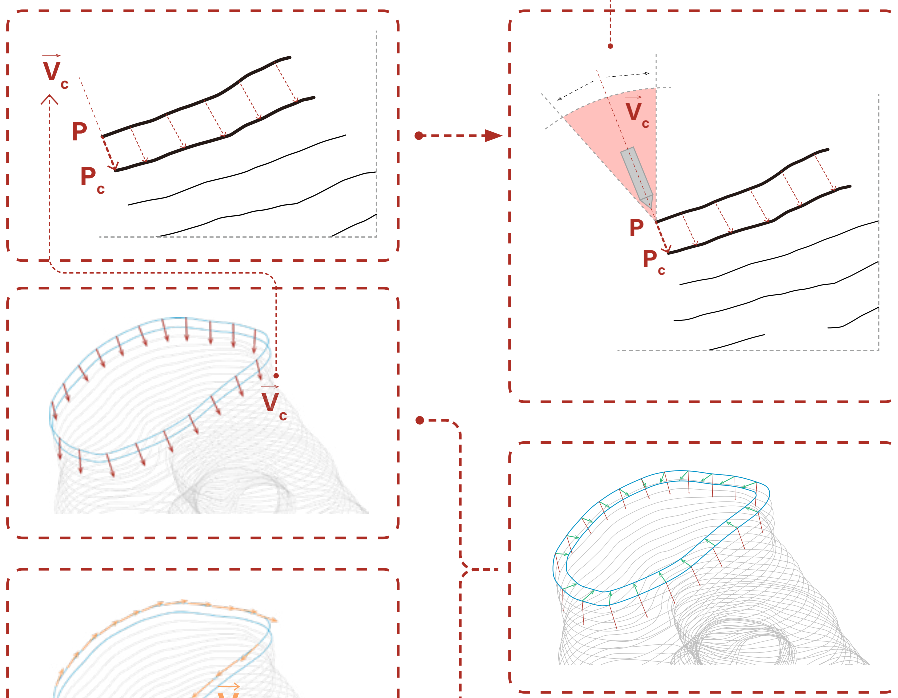
Printing Path Generation → Rhino Grasshopper / PTP Sequence → Inverse Kinematics / Robotic Posture → Kuka|prc / Simulation / Code.src



Orientation

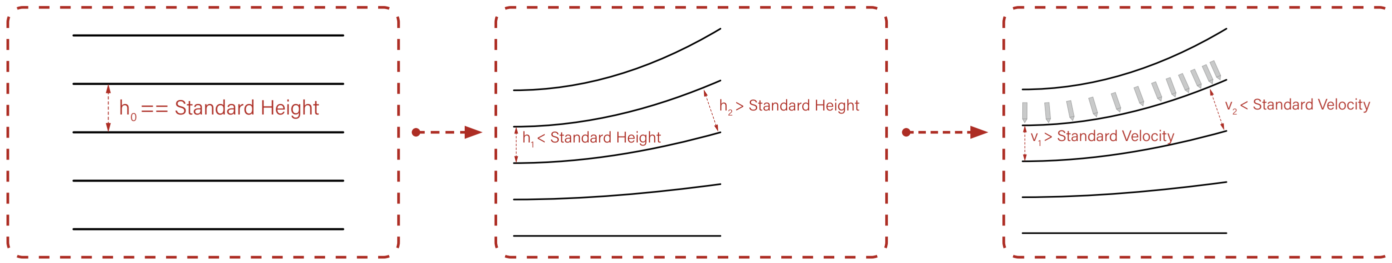
This section details the process of orientation calculation. To increase robustness of the print result, the nozzle was considered as a cone to be included as part of the path planning based on the test results of the prints, to increase the support of each layer and the friction between the neighboring layers.



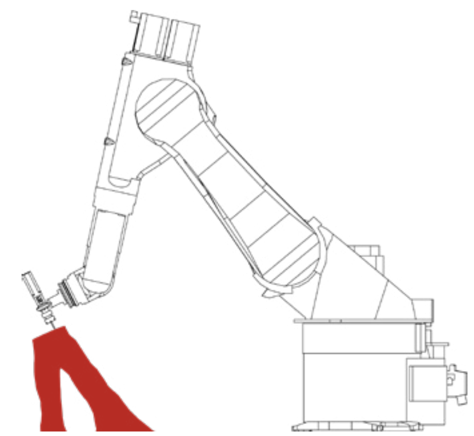


To increase the structural strength of printing, double walls can be generated

Velocity



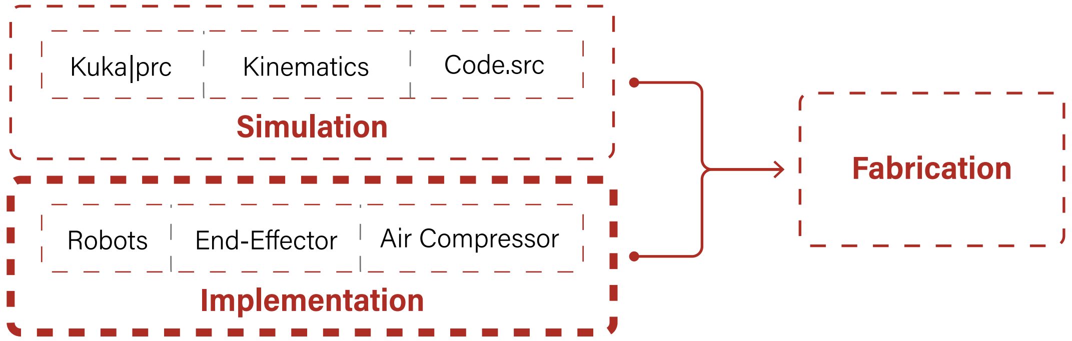
$$V' = (1 + (h_{std} - h') / h_{std}) * V_0$$



Simulation

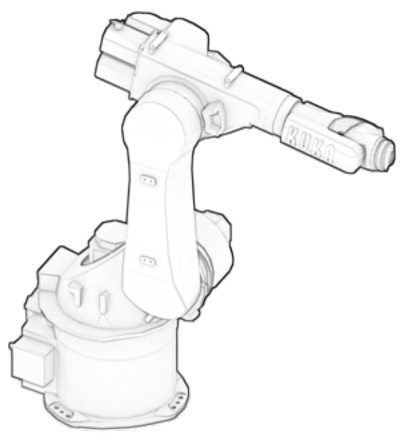
The simulation process will be completed base on kuka|prc before the fabrication to test the printing code and avoid collisions.

IMPLEMENTATION | ROBOTS, AIR COMPRESSOR, EXTRUDER



- The fabrication setup consists of a KUKA Agilus KR6 R900 Robot and KUKA KR60 HA Robot with 6 DOF.
- The end-effectors are with nozzle diameter D=5mm and D=3.5mm. The material we use is Dehua porcelain, one of the traditional ceramic materials in China, and PETG SK 2012.
- For nozzle diameter D=5mm, we set the average layer height to 2.5mm; For nozzle diameter D=3.5mm, the average layer height is 1.8mm.
- To squeeze the ceramic material to end-effector, an air compressor is used to generate the air pressure.

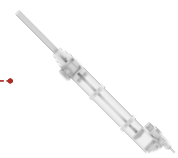
KUKA Agilus KR6 R900



KUKA KR60 HA

Air Compressor Parameters

Power: 800W
Rotate Speed: 1440 r/min
Voltage / Frequency: 220V / 50HZ
Air Displacement: 123L / min
Working Pressure: 0.8MPa



Ceramic Extruder

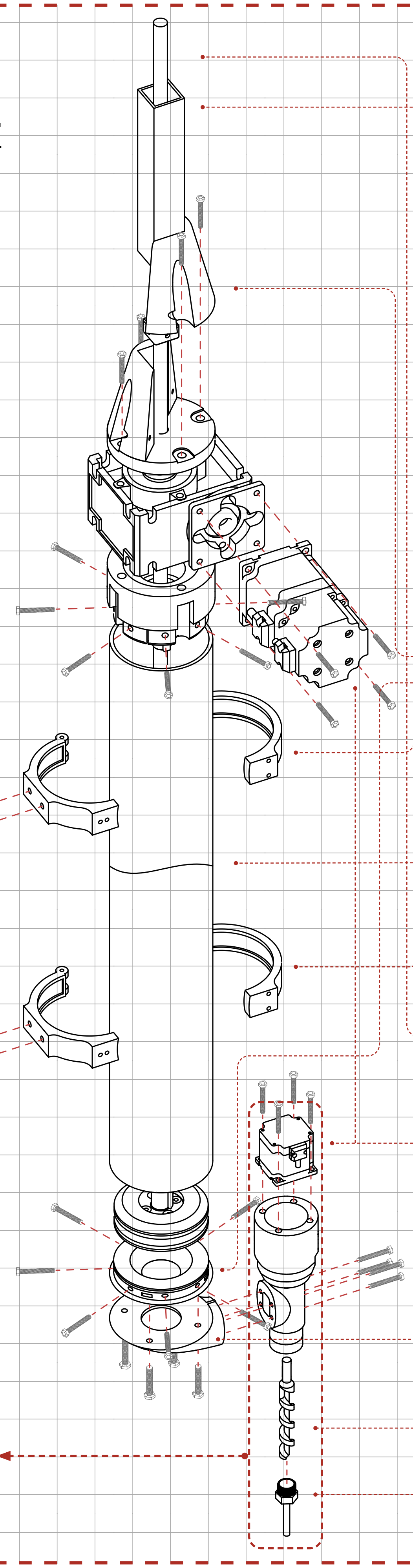
Screw Guide

Tube Base

Tube and Tube Holder

Plunger

Extrusion



Hardware and Fasteners

20x	Stainless Steel Machine Screws: M3
12x	Stainless Steel Machine Screws: M4
4x	Stainless Steel Machine Screws: M5
12x	Stainless Steel Nuts: M3
8x	Stainless Steel Nuts: M4
4x	Stainless Steel Nuts: M5

3D Printed Components

1x	Auger Housing
1x	Auger Screw
1x	Auger Stage
1x	Bearing Cover
1x	Tube Base
1x	Tube End
1x	Tube Holder1
1x	Tube Holder2
3x	Screw-Guide
1x	Plunger
2x	Gasket
2x	Tubeholder Grip

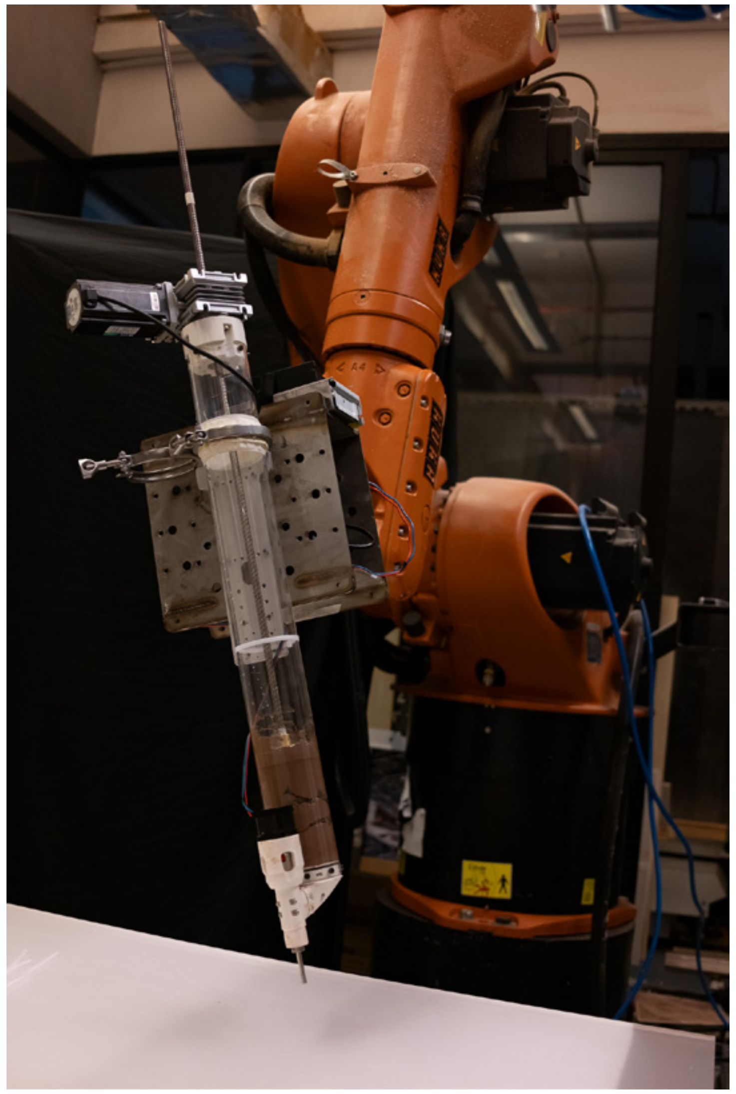
Mechanical Components

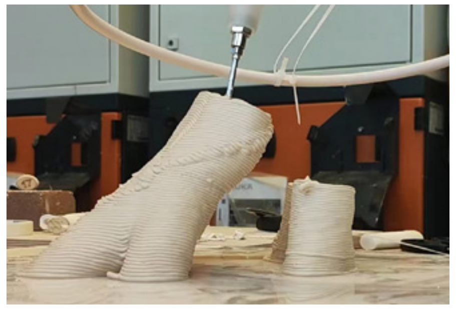
2x	Stainless Steel Ball Bearings
2x	Stainless Steel Washer
1x	Aluminum Square Tubing
2x	Motor Coupling
1x	Stainless Steel T10 Trapezoidal Lead Screw
1x	Acrylic Tubing

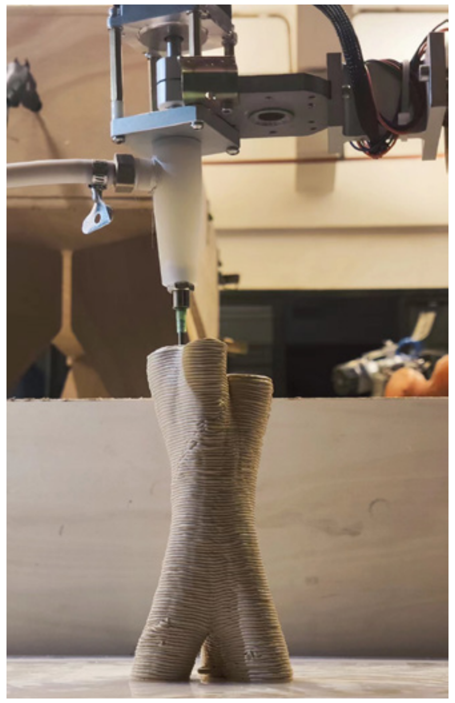
Motor

2x	Stepper Motor

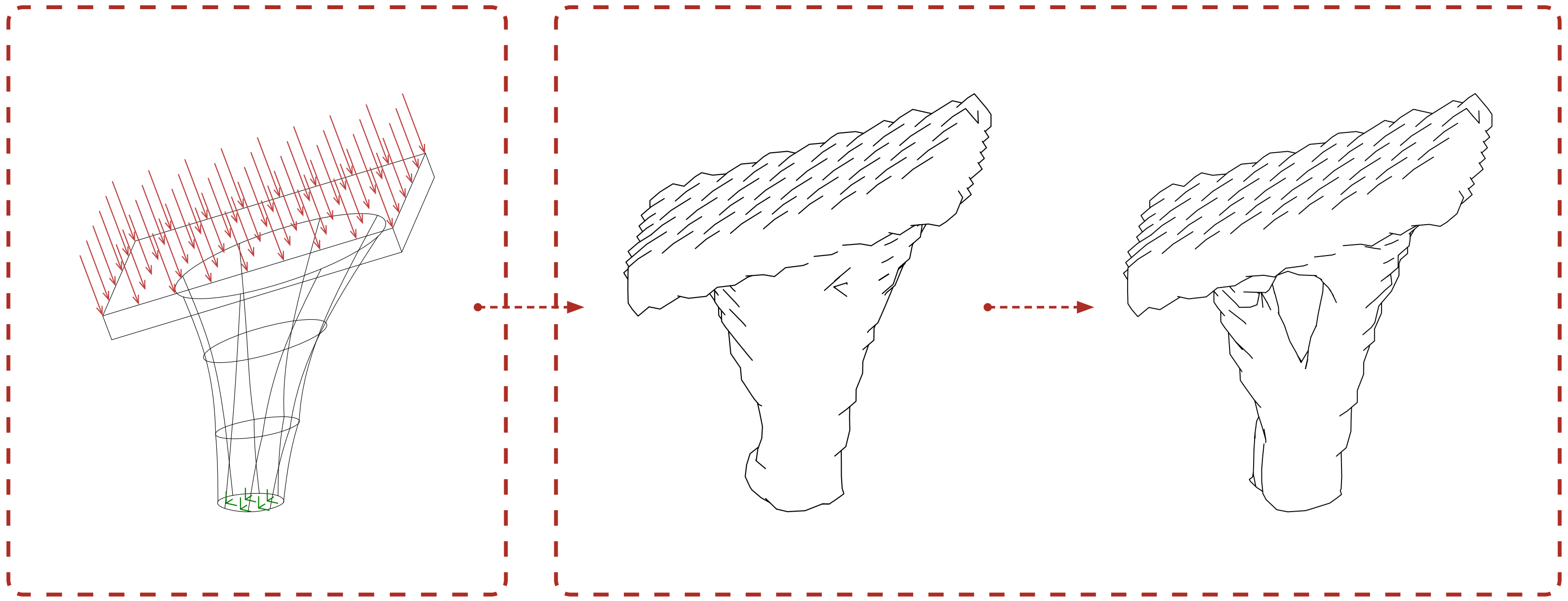
1x	Auger Screw Conveyor
1x	Nozzle







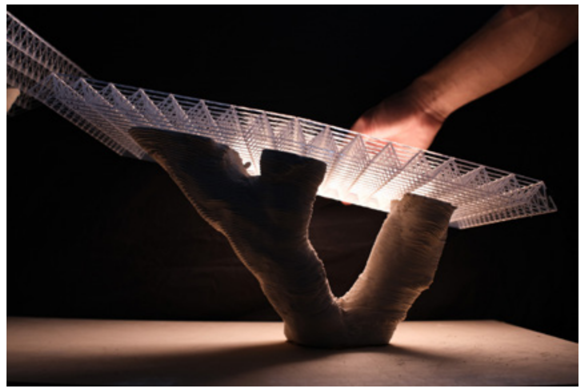
Topology Optimization

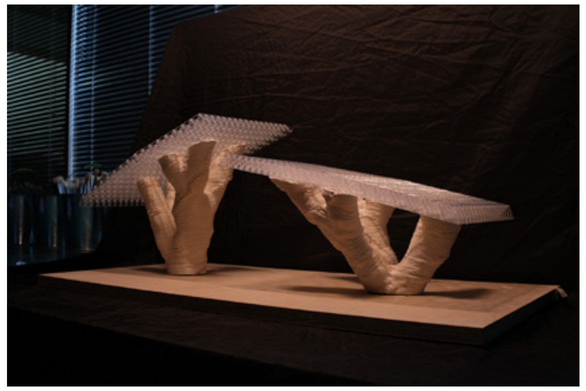


Set load and support conditions

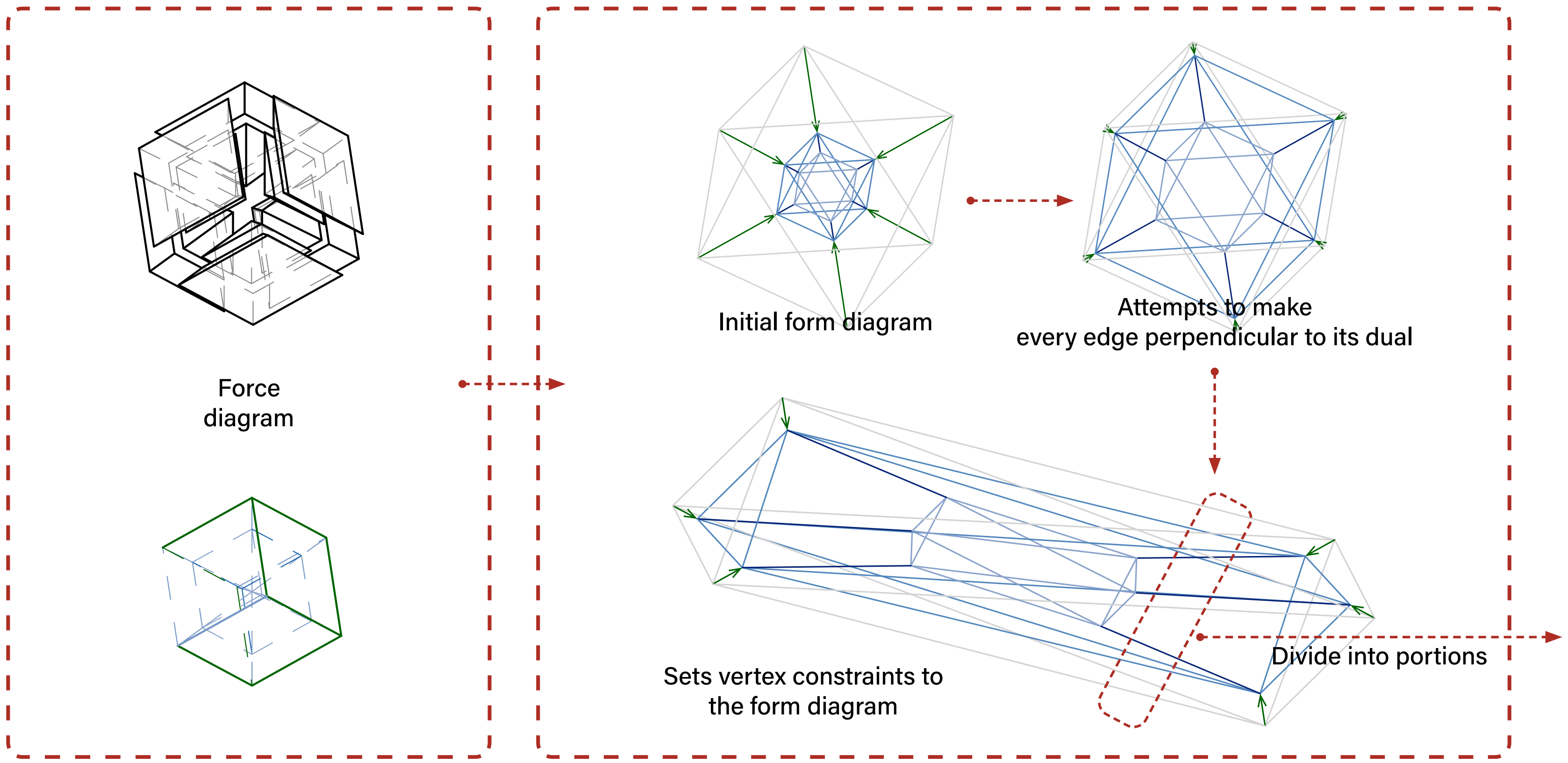
Topology optimization Iteration: 10

Topology optimization Iteration: 60

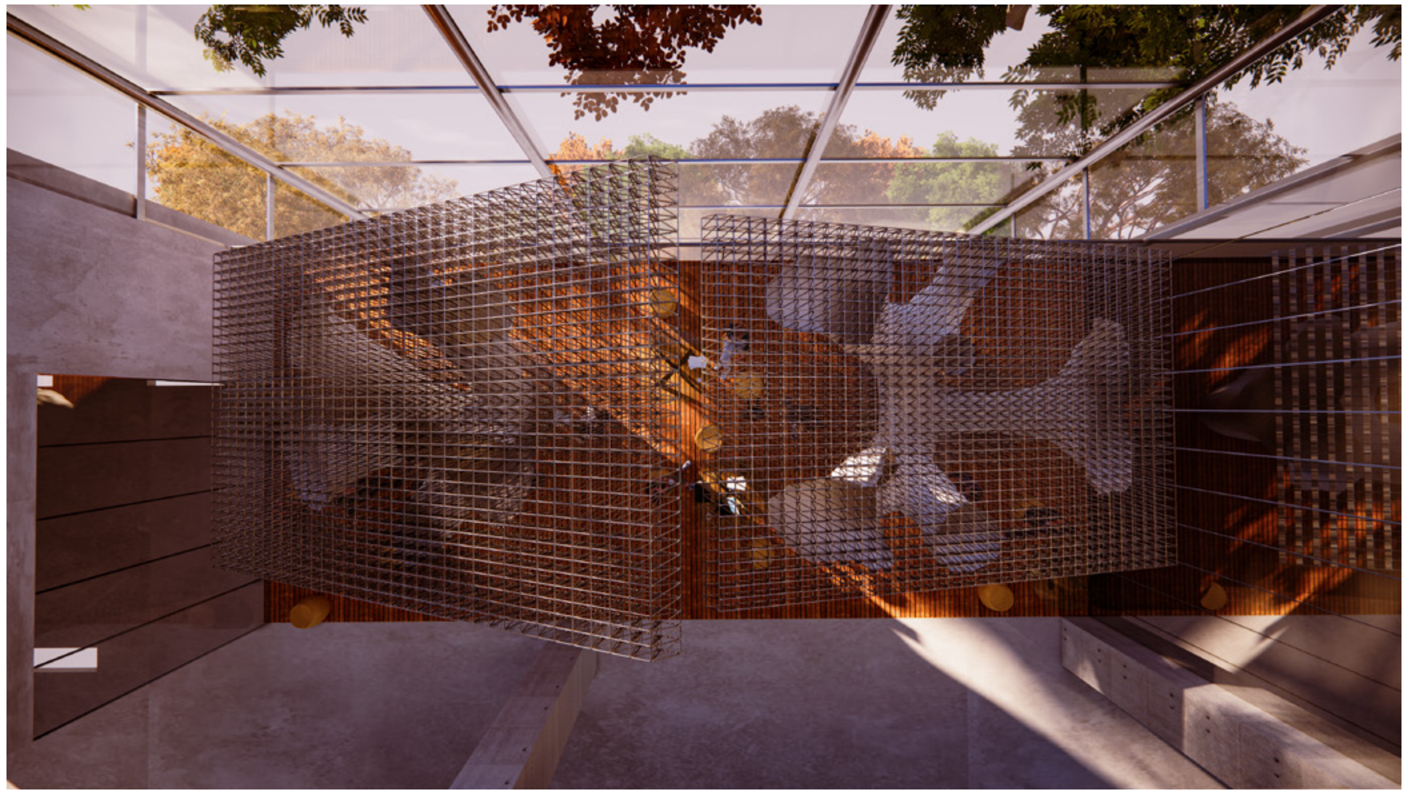


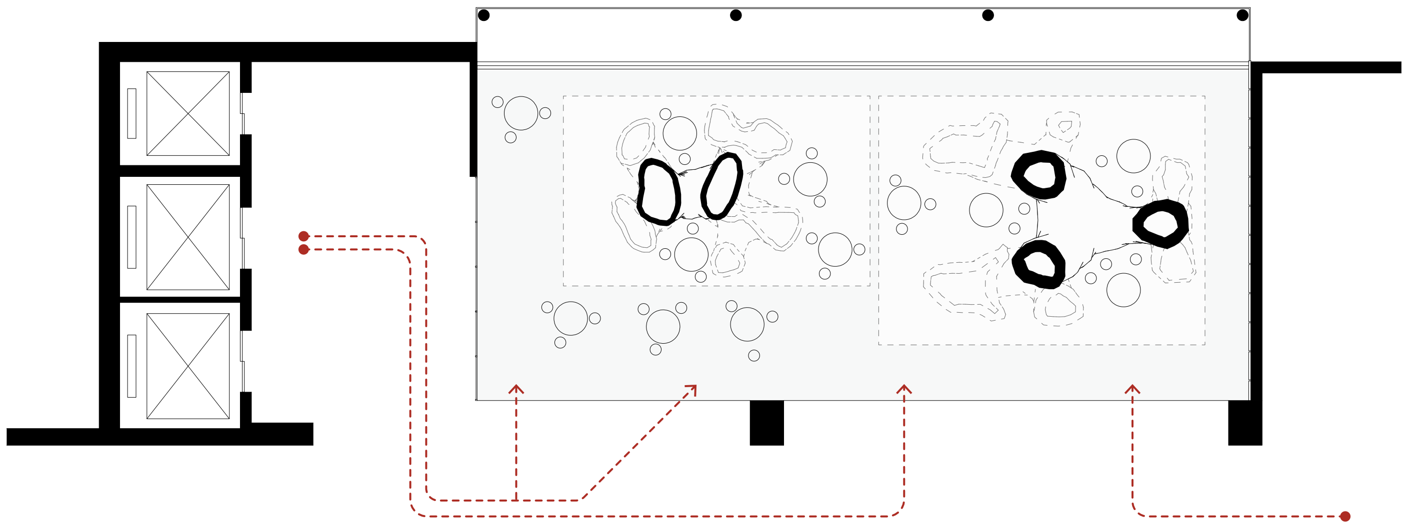


Graphic Statics

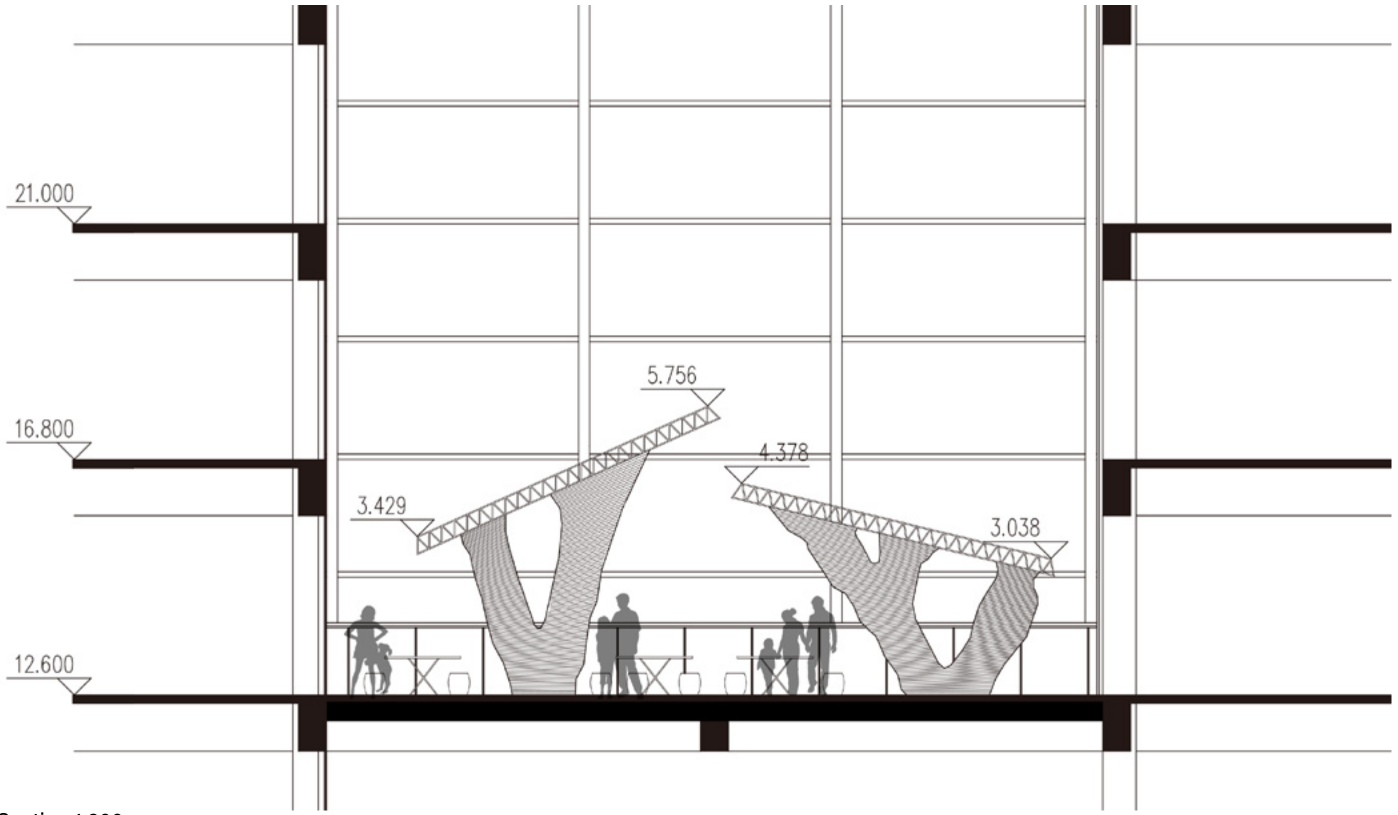


DESIGN AND FORM FINDING | PLAN, SECTION AND RENDERING

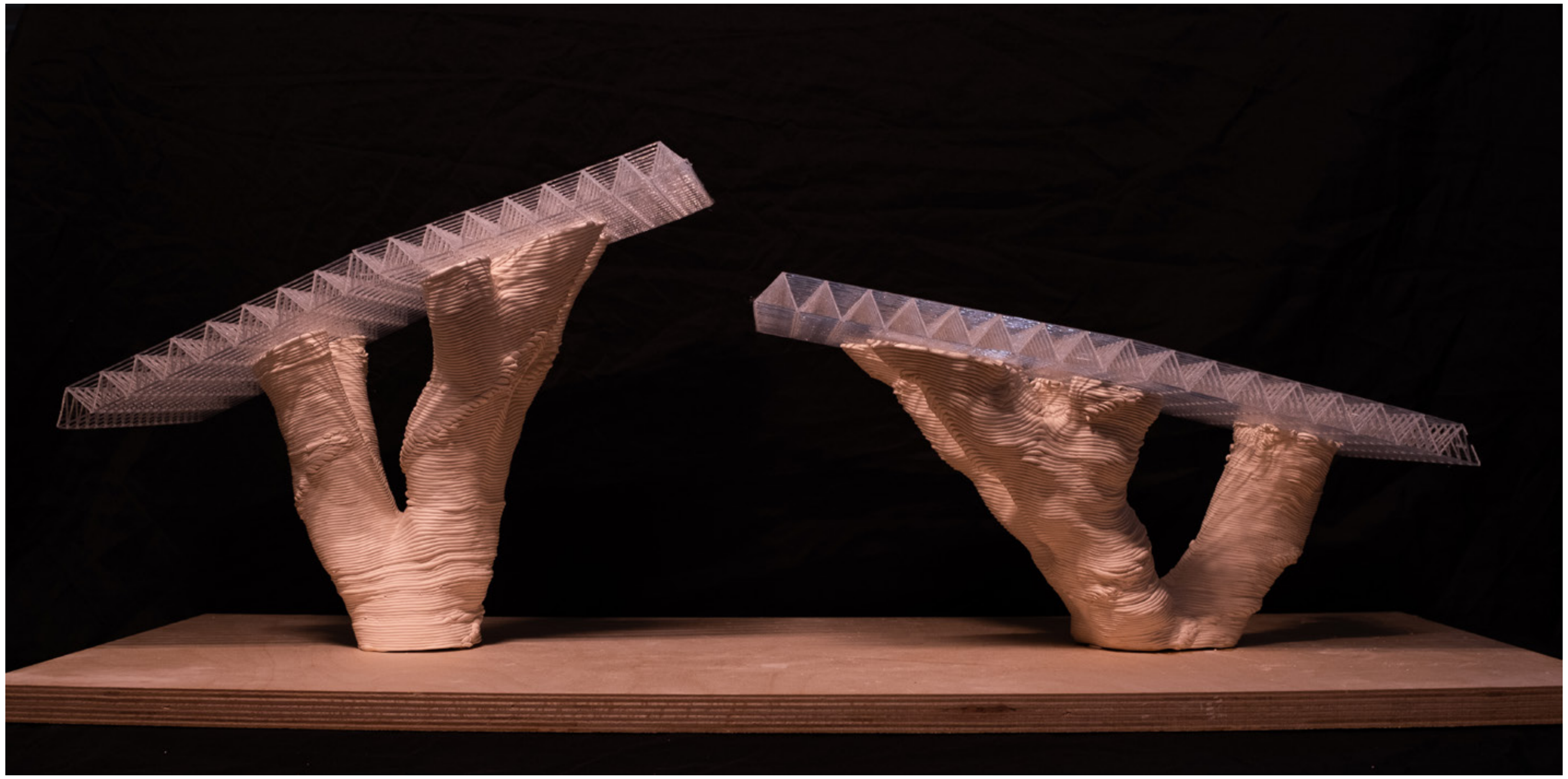




Plan 1:200



Section 1:200



02

Crafting Material Irregularity

Robotic Assembly with Heterogeneous Raw Wood

Contribution: Design / Programming / Fabrication / Drawing

Year 4, Semester 2, Tongji University, 2023, Gruop Work

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Group Work with Yujun Huang, Xiaofan Gao, Chuanwei Li, Mengxun Liu, Yunzhu Luo, Leo Wang, Zihan Xue, Qinhui Yang

OVERVIEW

The use of **natural materials** in construction has been gaining popularity in recent years due to their **sustainability, durability, and aesthetic appeal**.

However, building with natural materials such as logs presents unique challenges as each log is **irregular in shape, size, and texture**. This irregularity can make it difficult to assemble the logs together and to ensure structural integrity.

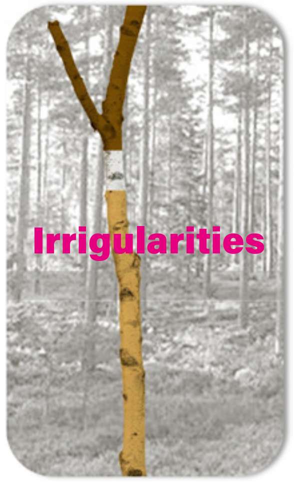
We have a great opportunity for this project that in Shanghai, there is a wood form being demolished. We collect some branches from there, **so all the branches used in the project are obtained for free as waste materials**.

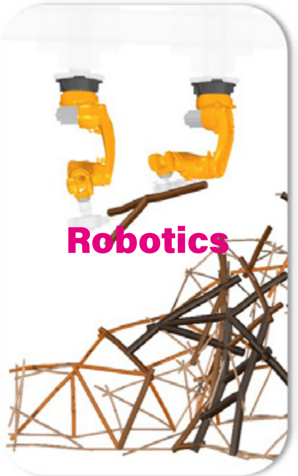
Then, **we scanned all the branches to obtain their 3D models**. After establishing such a **material library**, we attempted to design directly based on the materials we have. The design site is located next to an open café in our college. The structural design is generated based on **vector-based graphic statics**. We developed an algorithm to **match the collected branches to the structural design** based on their thickness, length, and branching angles.

The joint connections between the components is design to be precisely fabricated through **robotic cutting and drilling**. A RGB camera mounted on the robot's end-effector is used to **scan the branch to determine their positions within the robot's workspace**. During the fabrication process, one robot holds the branch in place while another robot is responsible for the cutting and drilling.

Once all the components are fabricated, they are transported to the site. Due to the use of **easily installable mortise and tenon joints**, the entire assembly process takes less than two days.

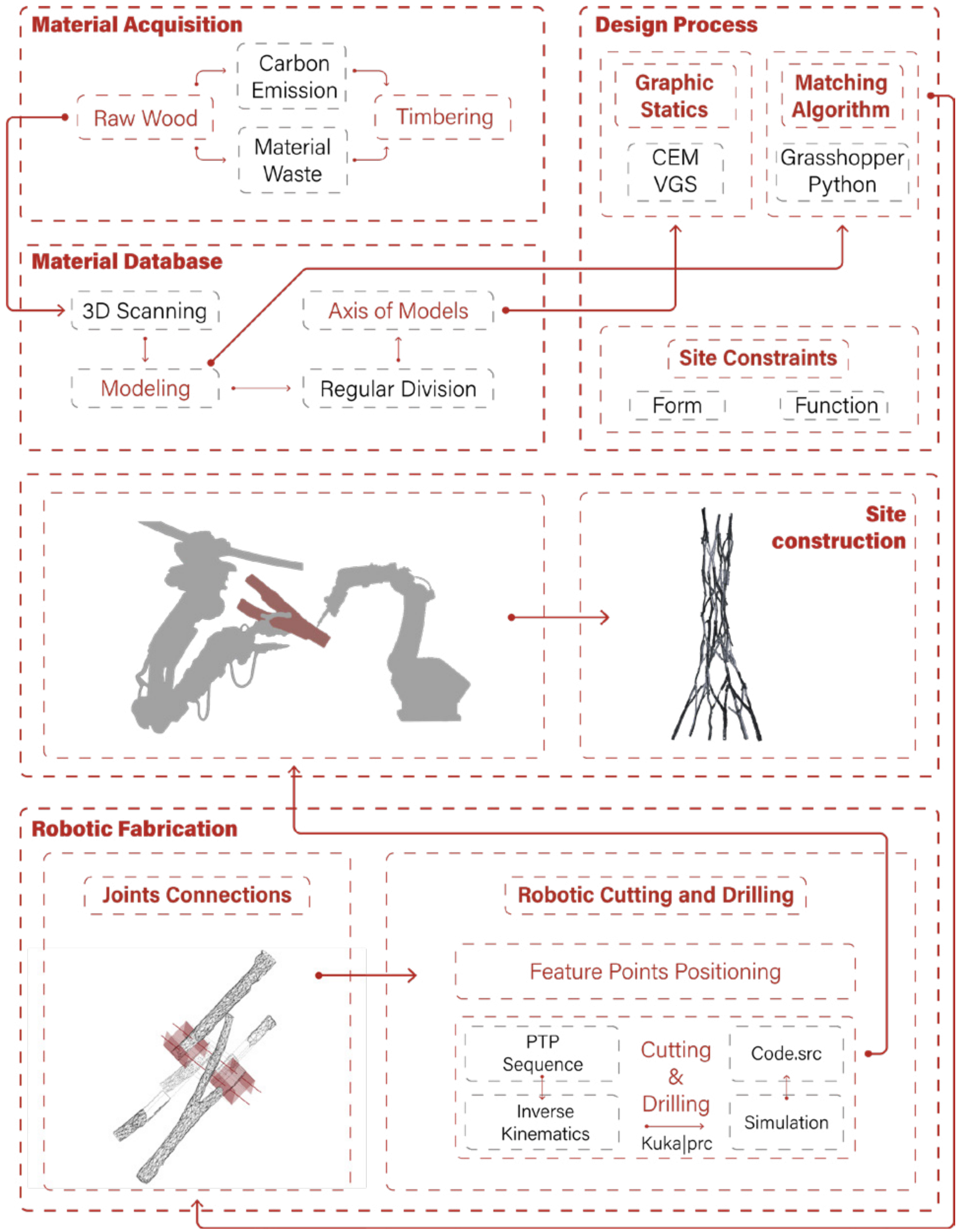
This project streamlines the design and construction process of irregular natural wood. We believe that, based on the possibilities of emerging technologies, we could explore **more co-friendly building paradigm building with natural wood**.



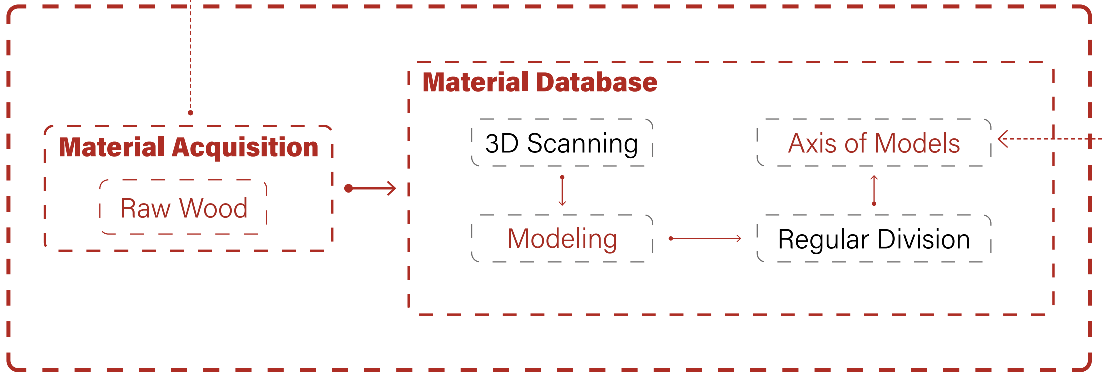


WORKFLOW

Material, Design, Robotic Fabrication, Site Construction



MATERIAL DATABASE | ACQUISITION & SCANNING

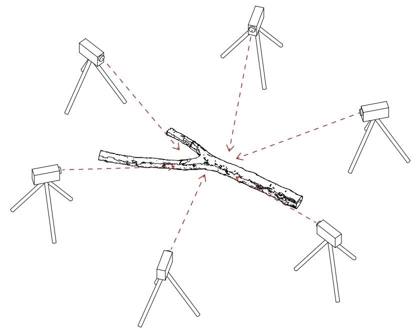


The use of natural materials in construction has been gaining popularity in recent years due to their sustainability, durability, and aesthetic appeal. However, building with natural materials such as logs presents unique challenges as each log is irregular in shape, size, and texture.

In this section, we build the material database through two steps. The first is collecting some raw woods. Then we scan them one by one and extract axis of each models, preparing for matching algorithm.

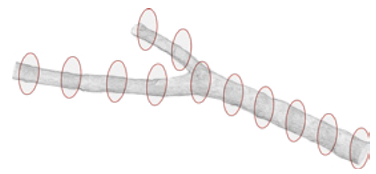
3D Scanning and Modeling

1. Branch

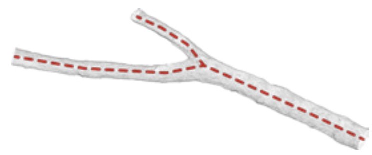


2. 3D Scanning

3. 3D Model (Mesh)



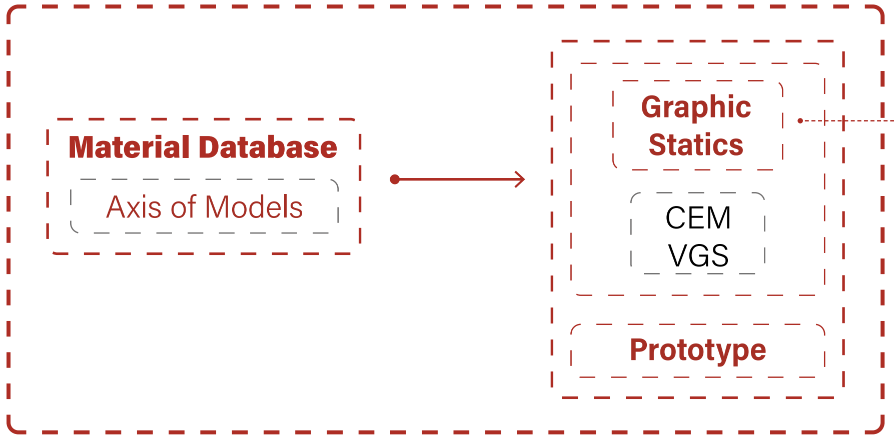
4. Regular Division of the Model

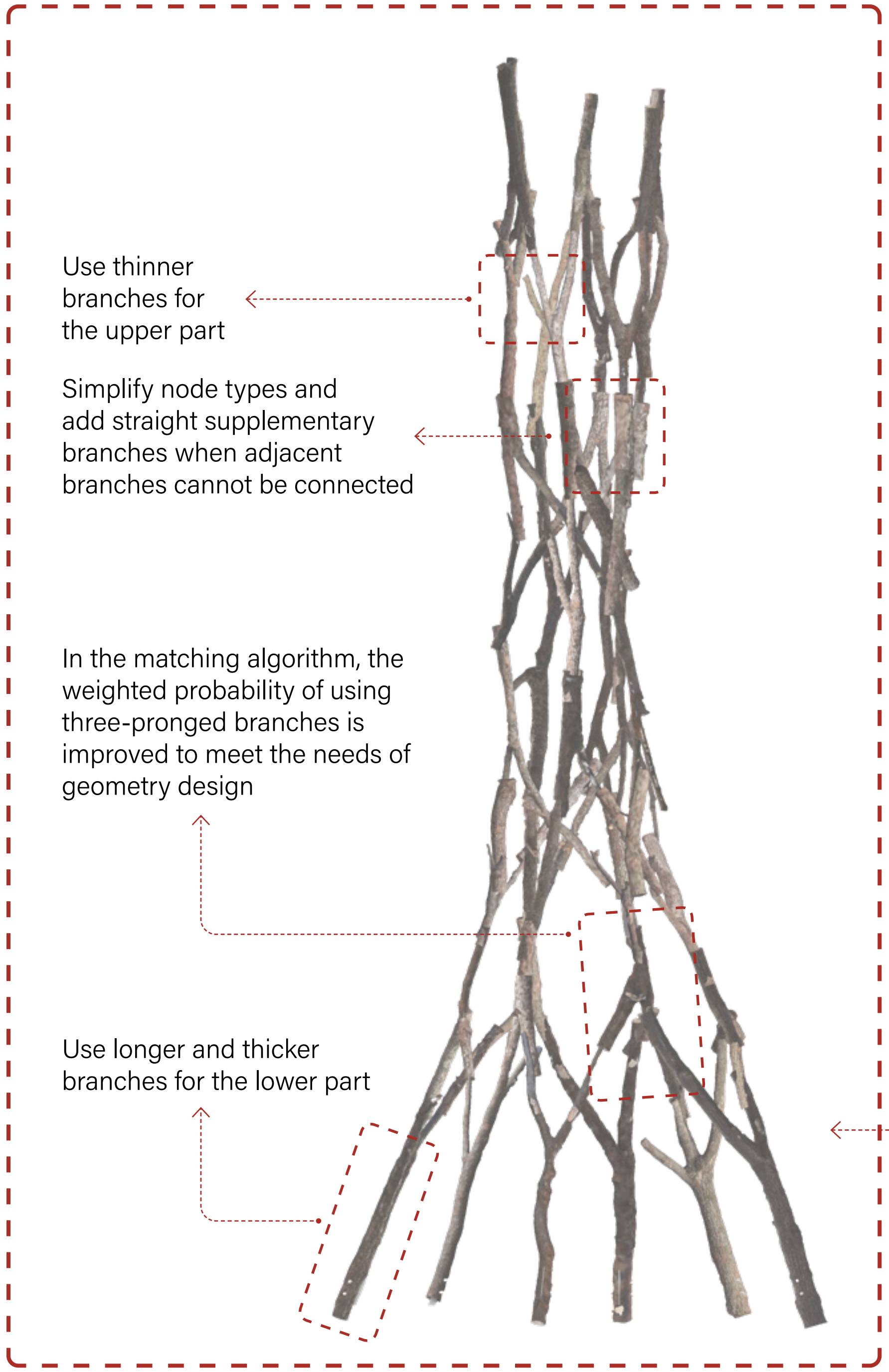


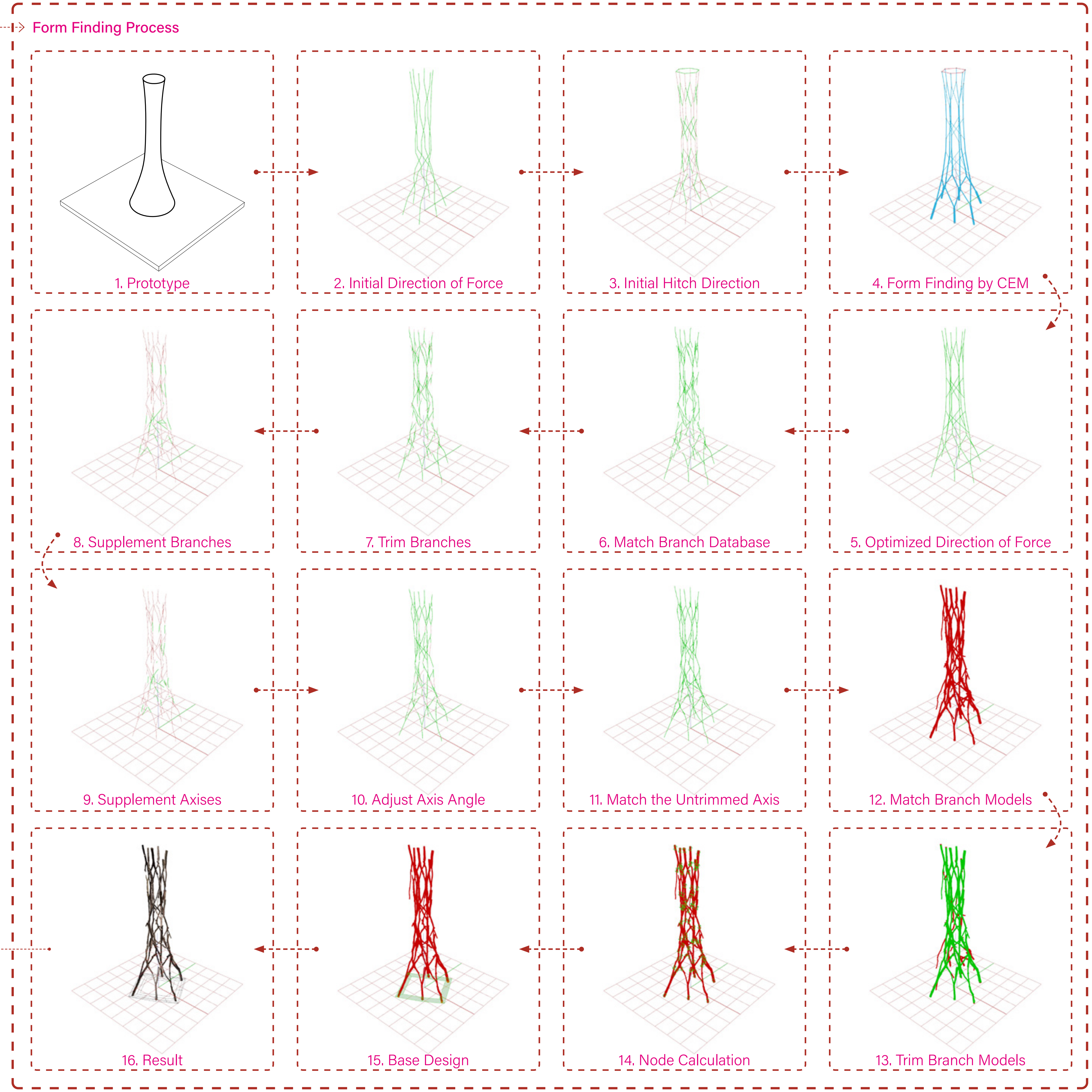
5. Centroidal Curve

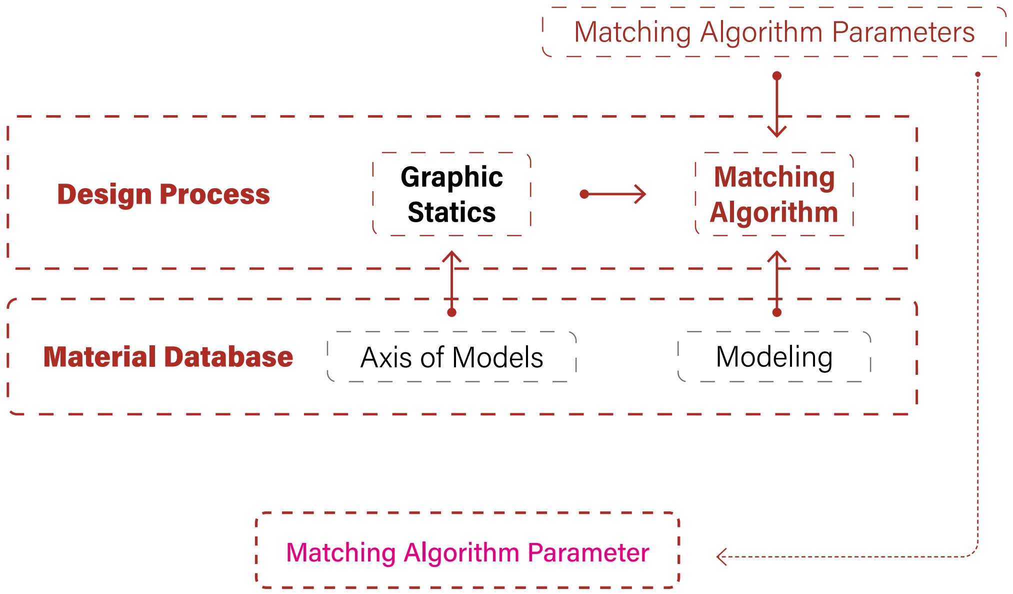
6. Axis of the Model

DESIGN PROCESS | GRAPHIC STATICS









Weight of First layer Angle
20.00

Weight of First layer Thickness
200.00

Weight of Non-First layer Length
6.00

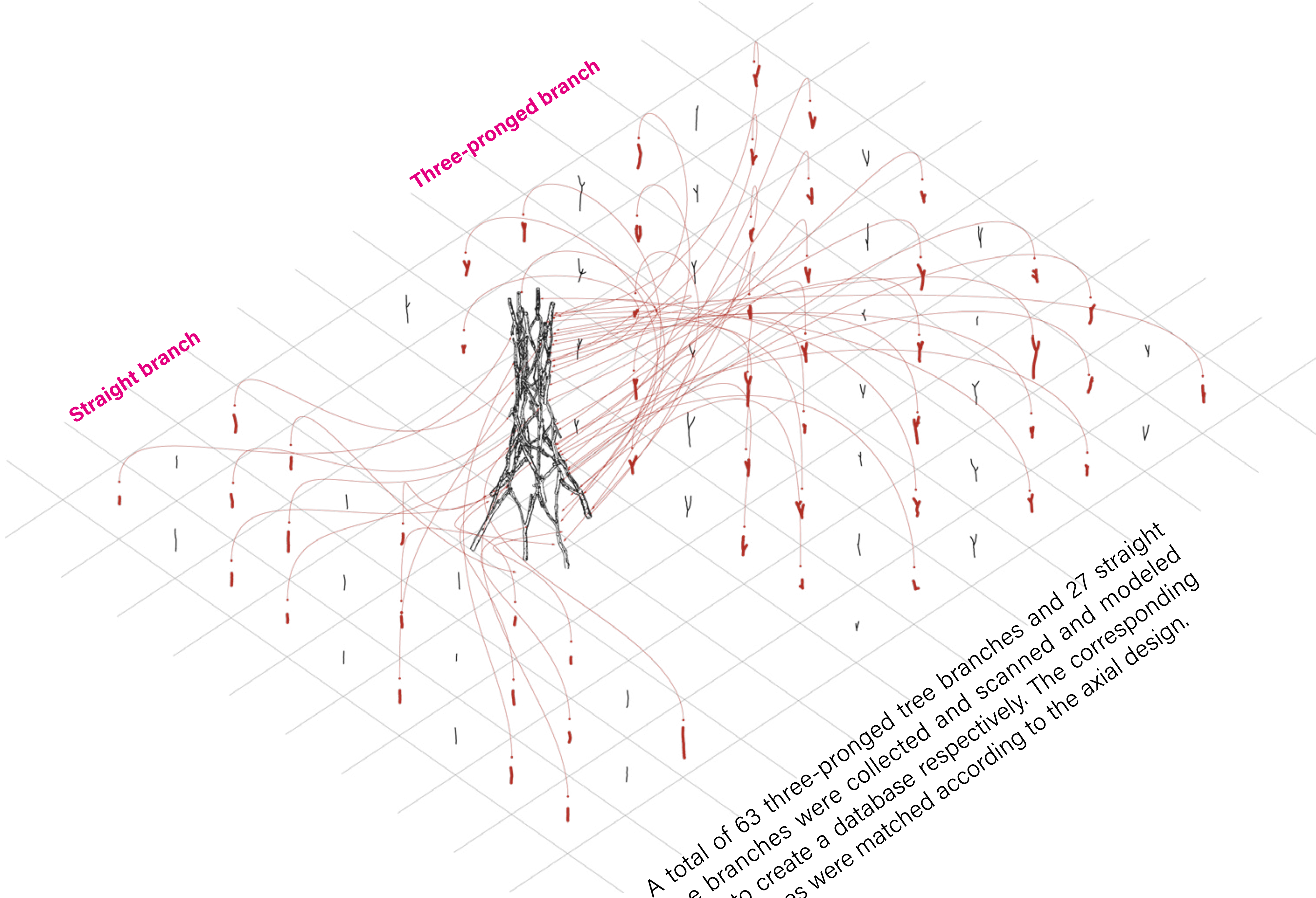
Weight of Non-First layer Angle
20.00

Weight of Non-First layer Thickness
200.00

Weight of Non-First layer Length
1.00

Length of Free Layer Cut off
1.60

Length of Overlap
0.12



A total of 63 three-pronged tree branches and 27 straight tree branches were collected and scanned and modeled in 3d to create a database respectively. The corresponding branches were matched according to the axial design.

ROBOTIC FABRICATION | POSITIONING, CUTTING AND DRILLING

Matching Algorithm → Joints Connections → **Robotic Cutting and Drilling**

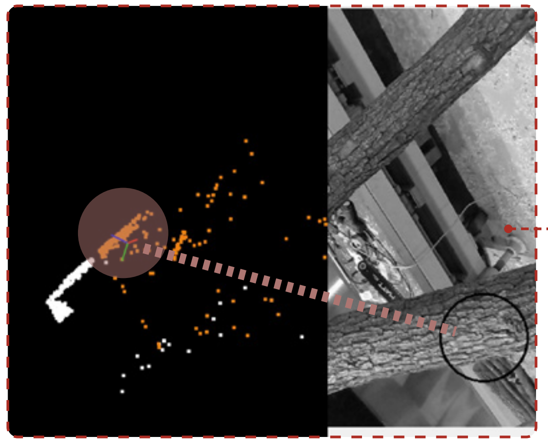
Feature Points Positioning

Cutting & Drilling

We design the joint connections based on the results of matching algorithm. The components are designed to be precisely fabricated through robotic cutting and drilling.

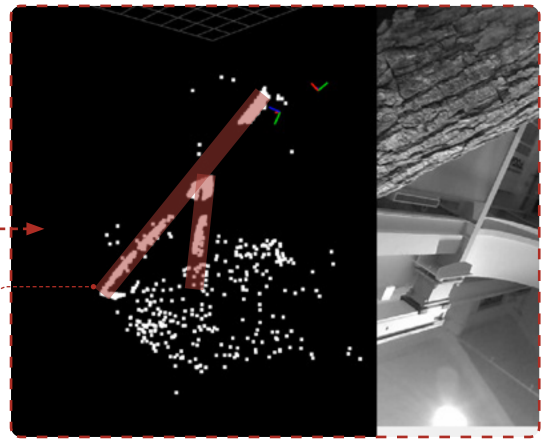
A RGB camera mounted on the robot's end-effector is used to scan the branch to determine their positions within the robot's workspace.

During the fabrication process, one robot holds the branch in place while another robot is responsible for the cutting and drilling.

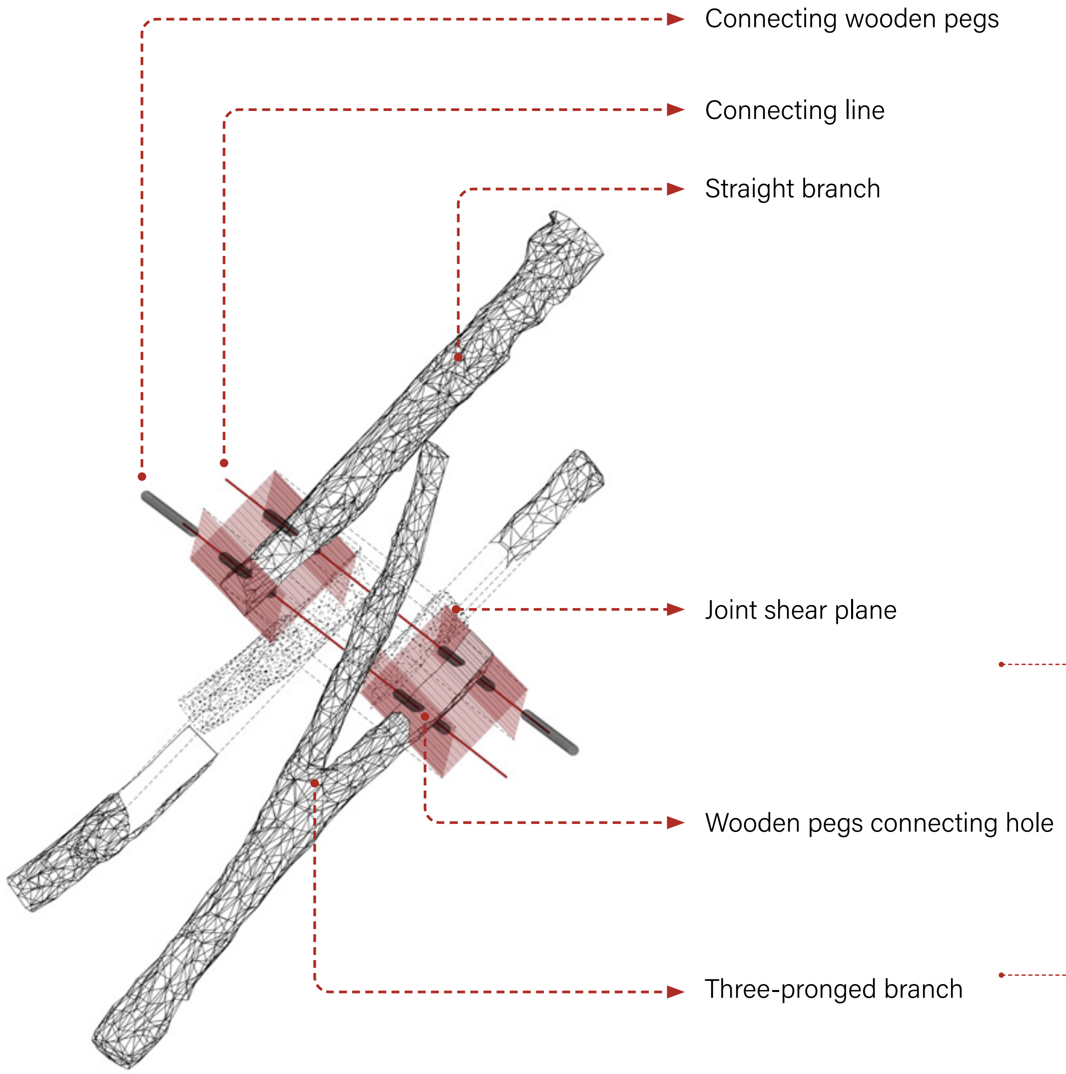


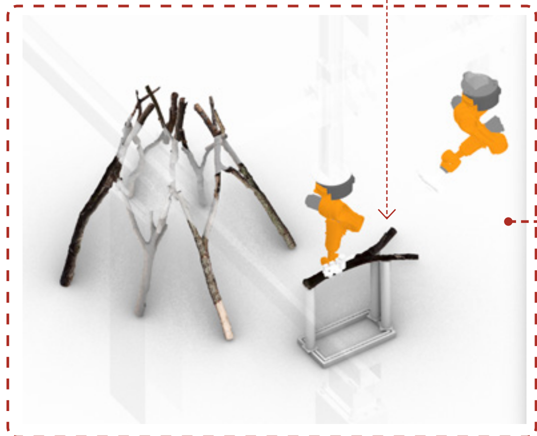
Feature Points Positioning 01

Feature Points Positioning 02

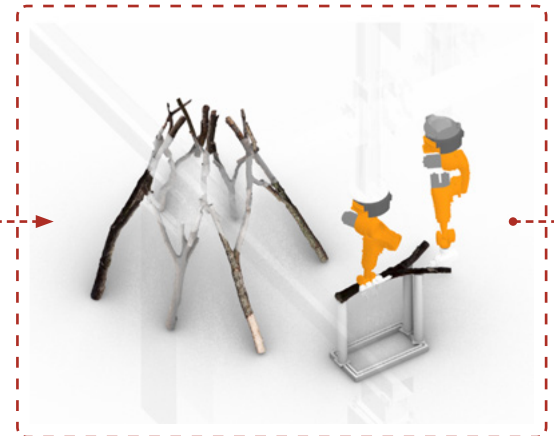


Feature Points Positioning Result



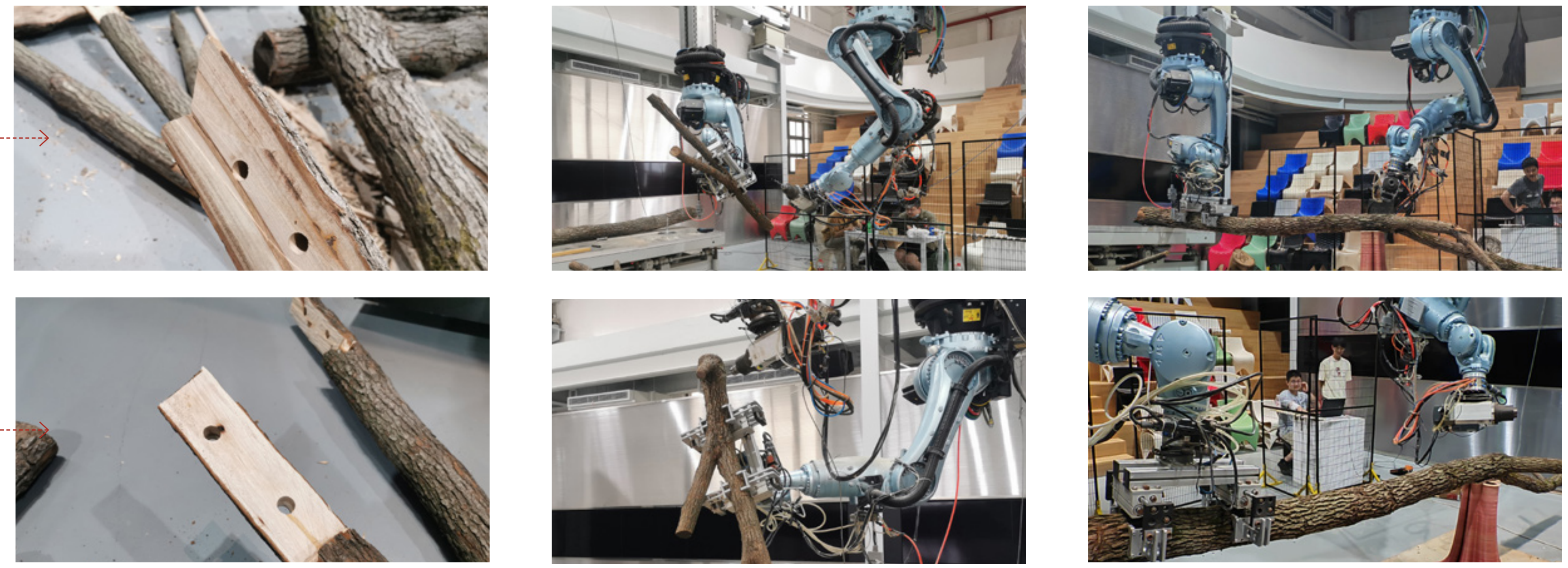


Robotic Positioning

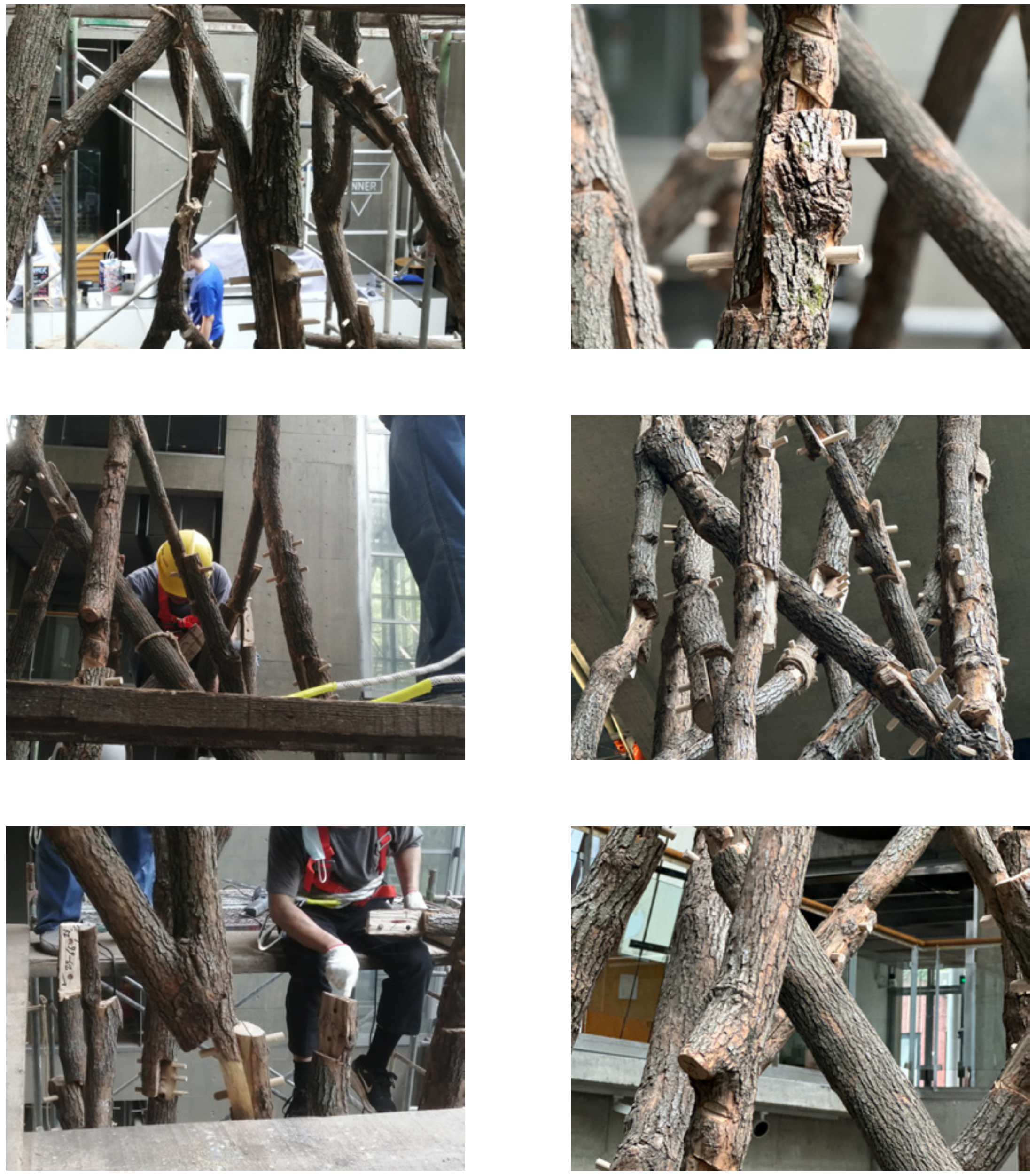


Robotic Cutting

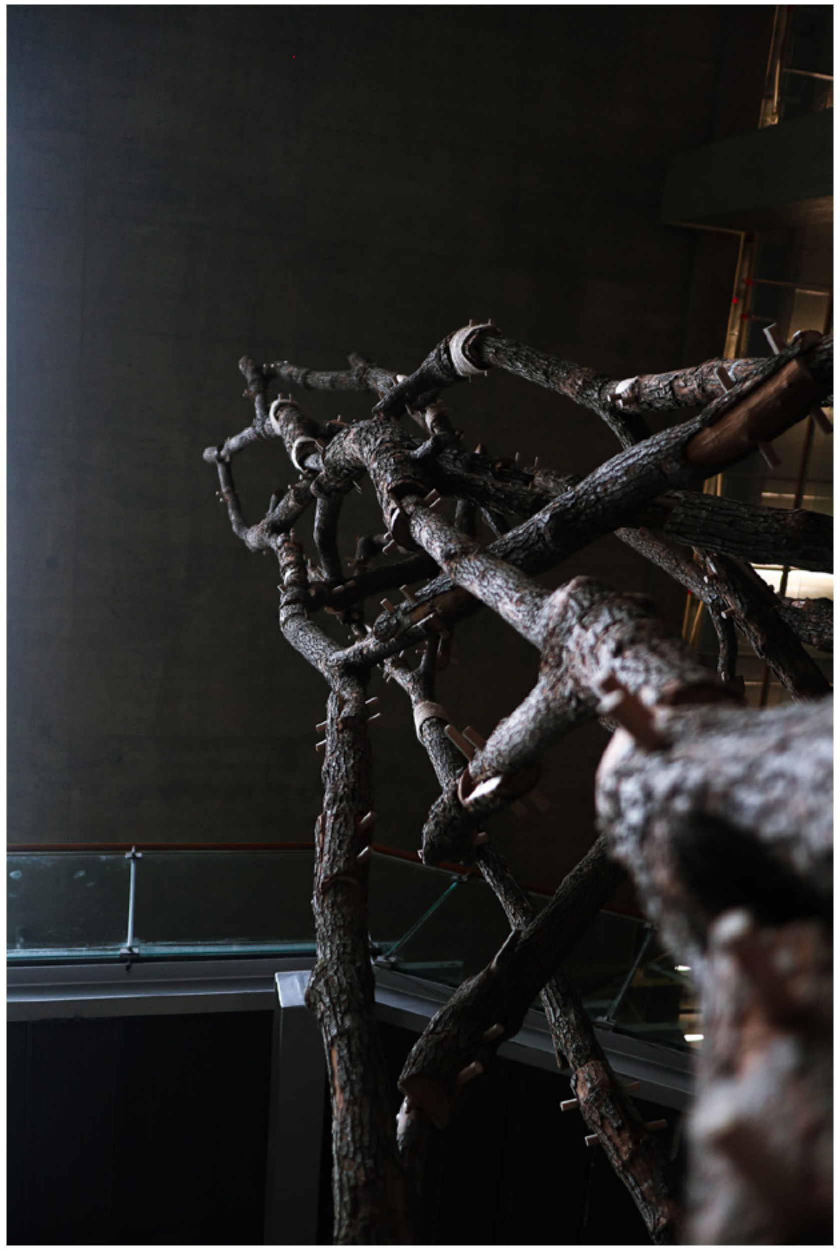
Robotic Drilling



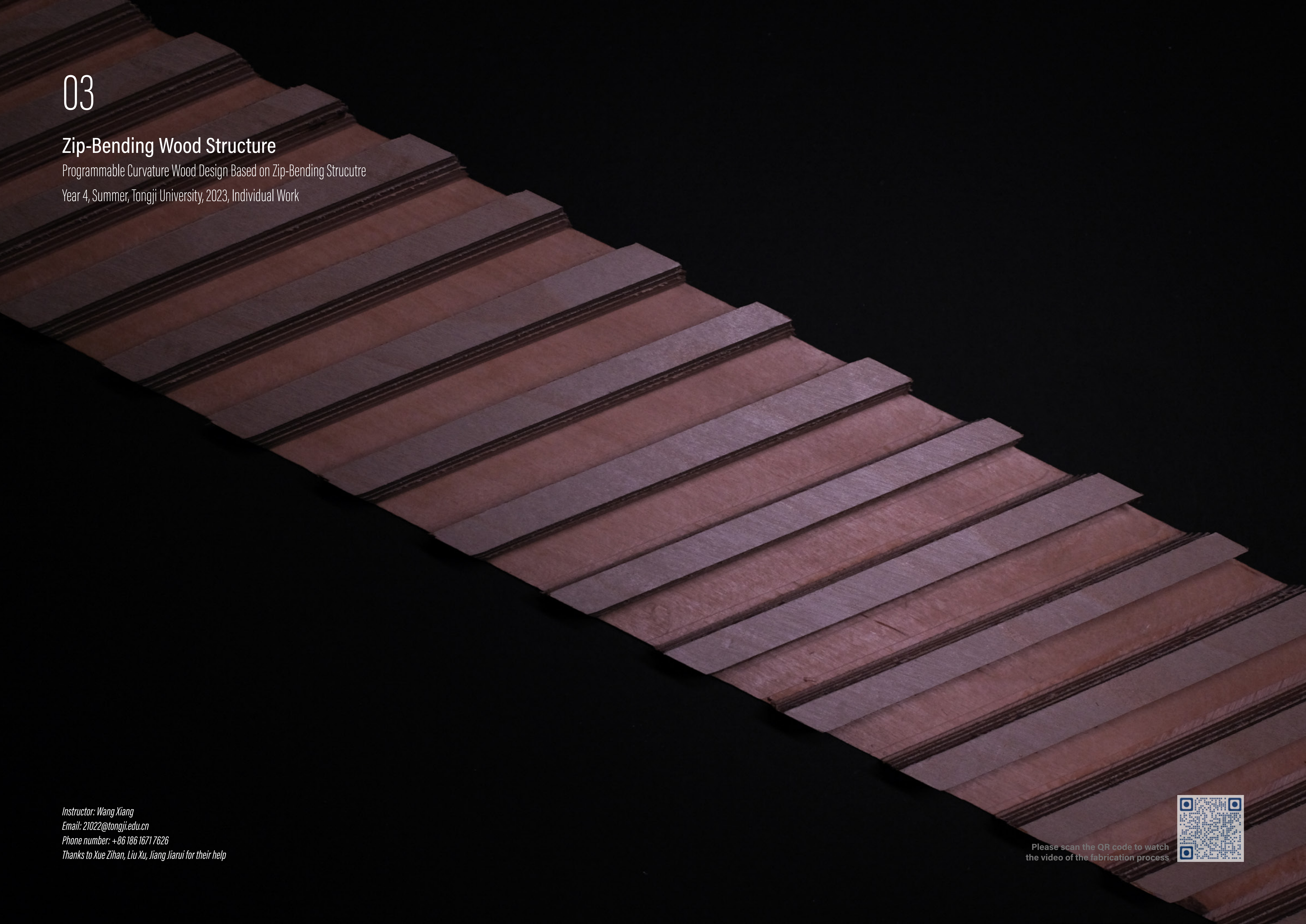
SITE CONSTRUCTION | PROCESS & RESULT



Construction Process



Final Result



03

Zip-Bending Wood Structure

Programmable Curvature Wood Design Based on Zip-Bending Strucutre

Year 4, Summer, Tongji University, 2023, Individual Work

Instructor: Wang Xiang
Email: 21022@tongji.edu.cn
Phone number: +86 186 1671 7626
Thanks to Xue Zihan, Liu Xu, Jiang Jiarui for their help

Please scan the QR code to watch
the video of the fabrication process

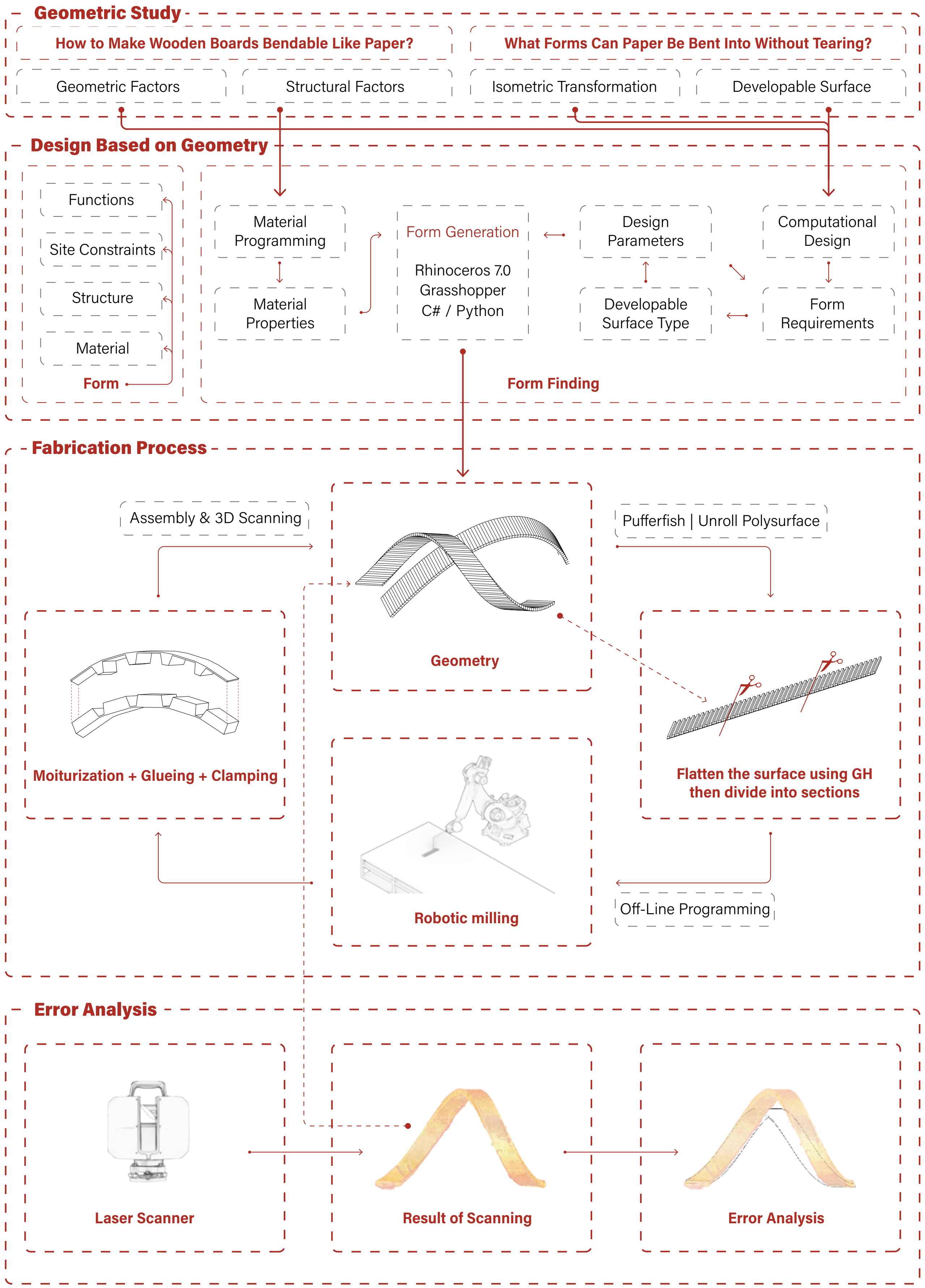
OVERVIEW

Recent years, with the development of the trend of carbon reduction, wood structures have been increasingly used in the field of architecture. At the same time, the rapid development of parametric technology makes a large number of **curved structures inevitably appear in buildings**.

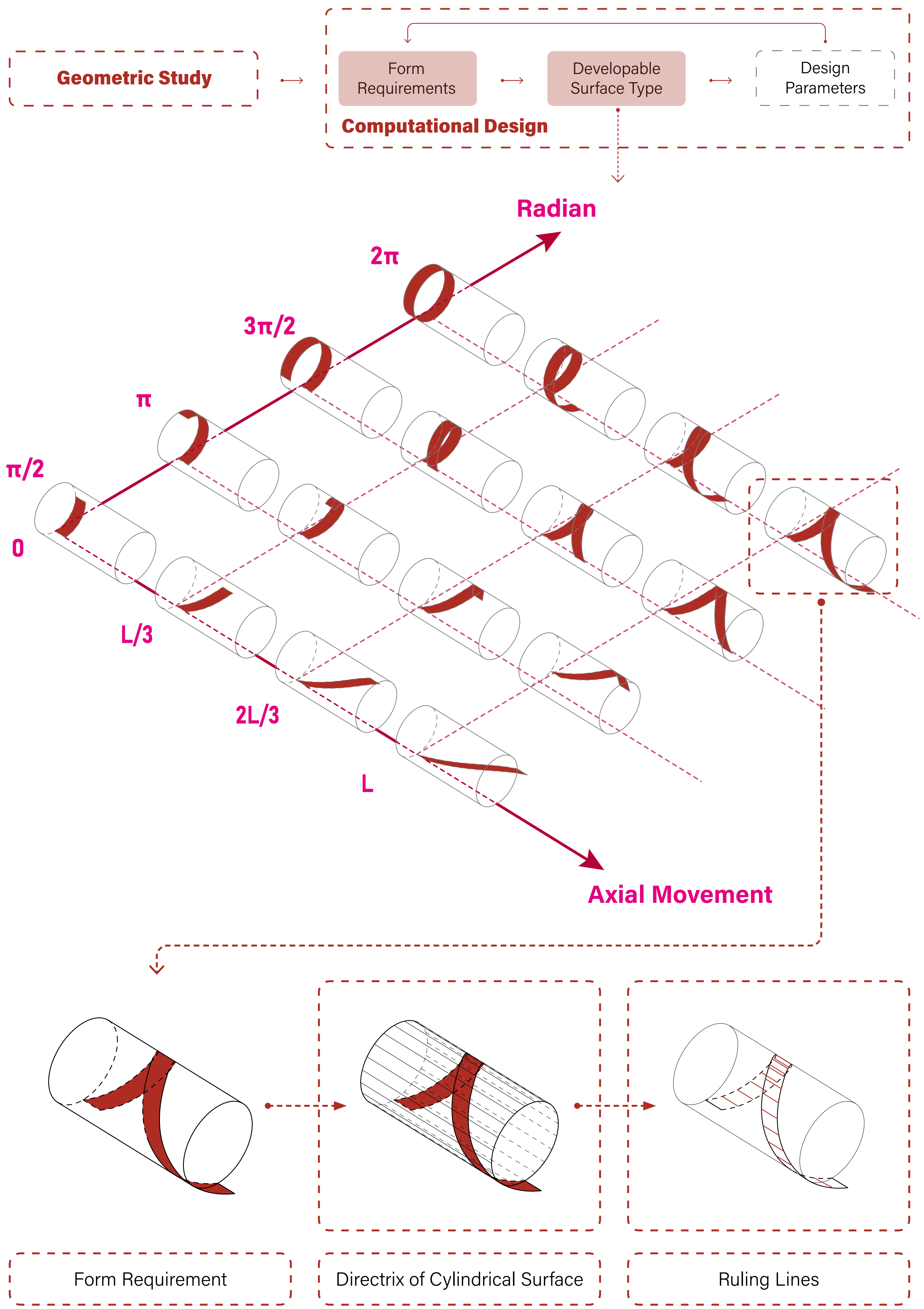
At present, the processing of curved wood is mainly to directly mill the wood in three dimensions to obtain the target curvature structure, which is **a large material waste** and complex technology.

Our research converts curved components into **zip components composed of two layers of plane wood** through self-programming to achieve pre-calculated curvature bending forms by biting each other, and completes the prefabrication of the components with the help of robotic arms by using digital processing. Firstly, the **geometric principle** of chain bending structure is studied; secondly, the core algorithm is written with the help of grasshopper platform based on the results of the study; then the **experiments with different materials and notch shapes** are completed with the support of the algorithm and the results are analyzed in terms of **error analysis**. Finally, the whole process of the work from experimentation to design and construction is completed once.

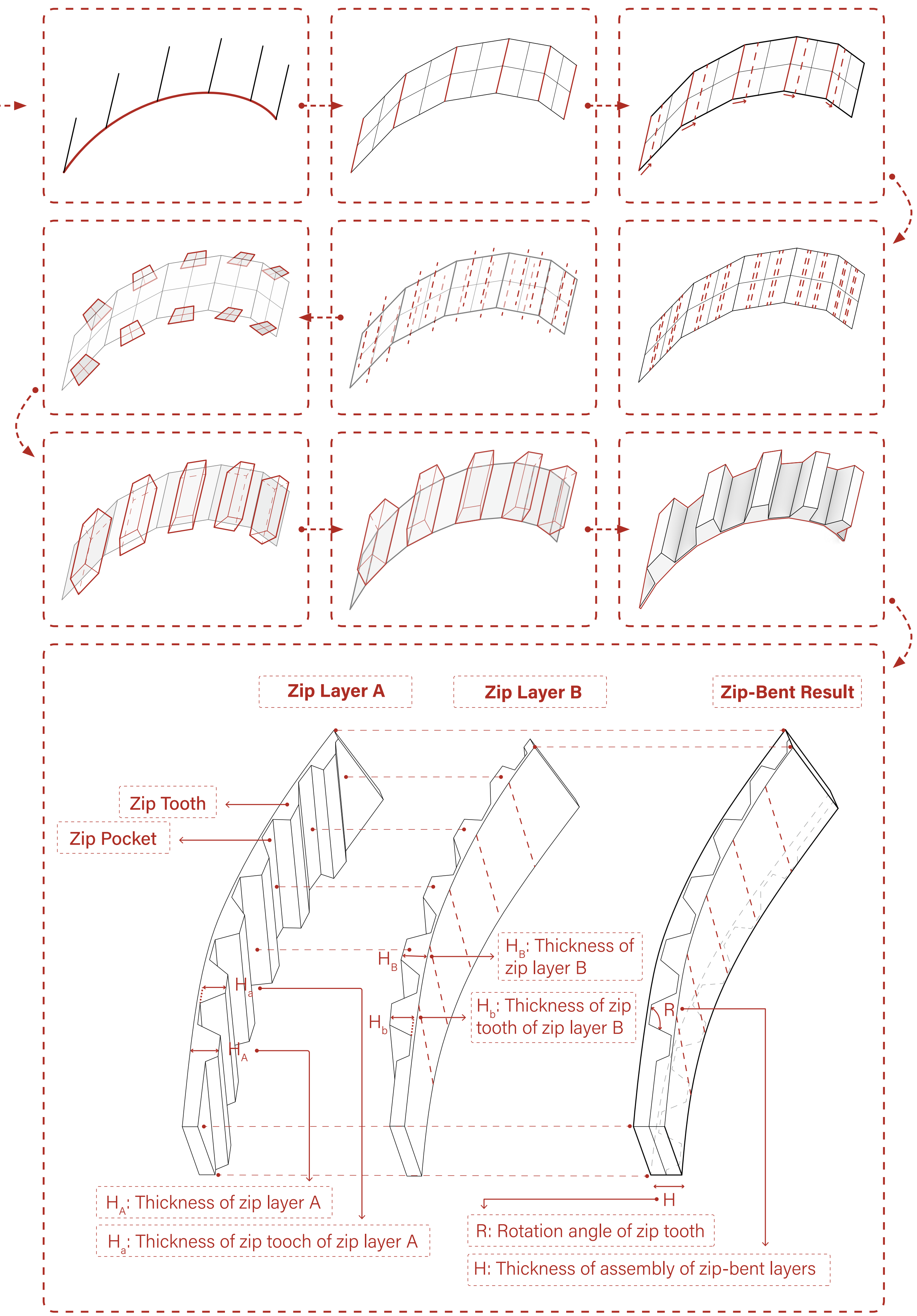
WORKFLOW | GEOMETRY, DESIGN, FABRICATION, ANALYSIS



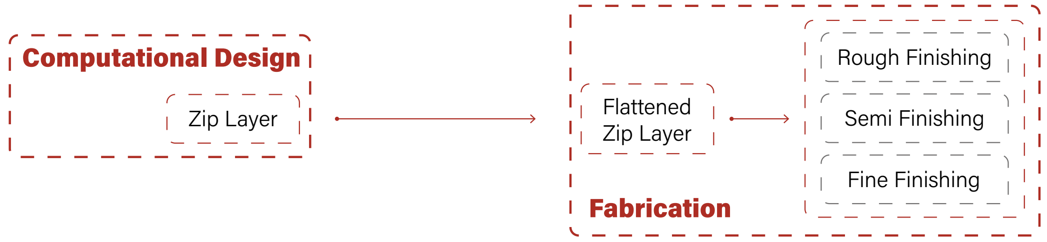
DESIGN BASED ON GEOMETRY | DEVELOPABLE SURFACE TYPE



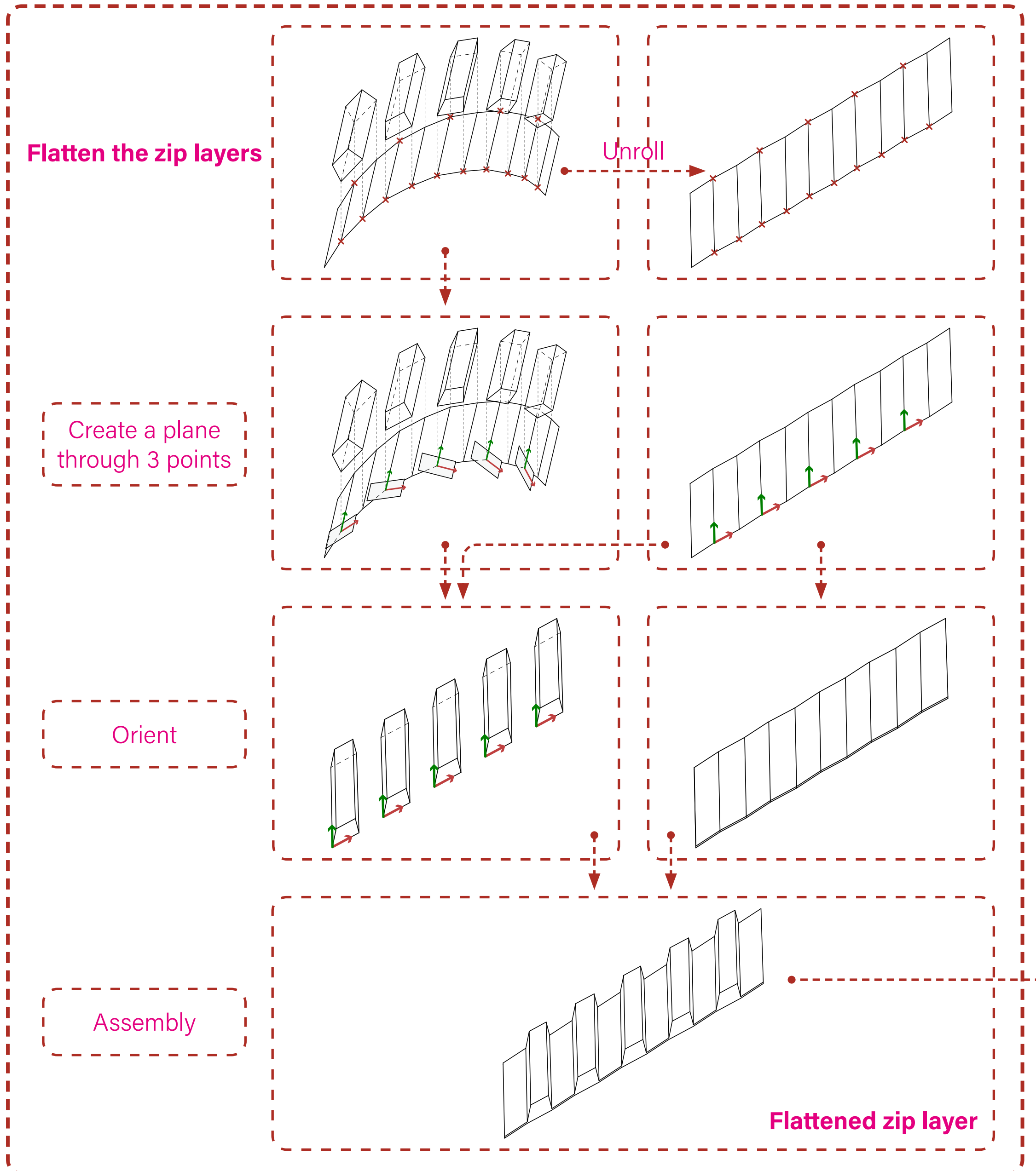
DESIGN BASED ON GEOMETRY | FORM GENERATION



FABRICATION PROCESS | UNROLLING & ROBOTIC MILLING



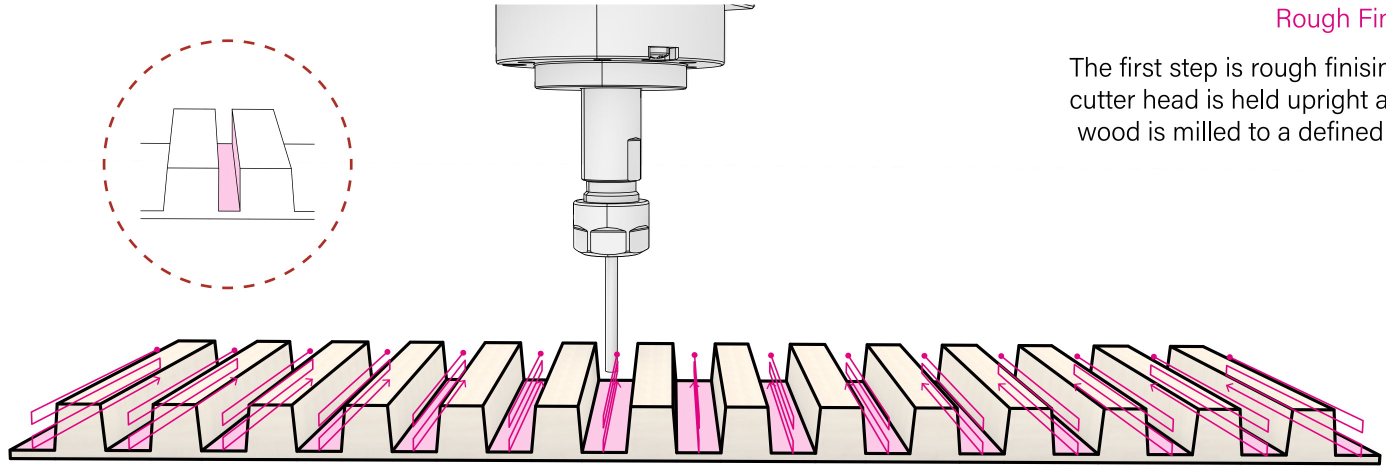
This section describes the main parts of fabrication process. The first step is unrolling the zip layer to flattened zip layer, preparing for mill. The second step is robotic milling. We generate three kinds of milling paths through grasshopper: rough finishing, semi finishing and fine finishing.



Robotic Milling

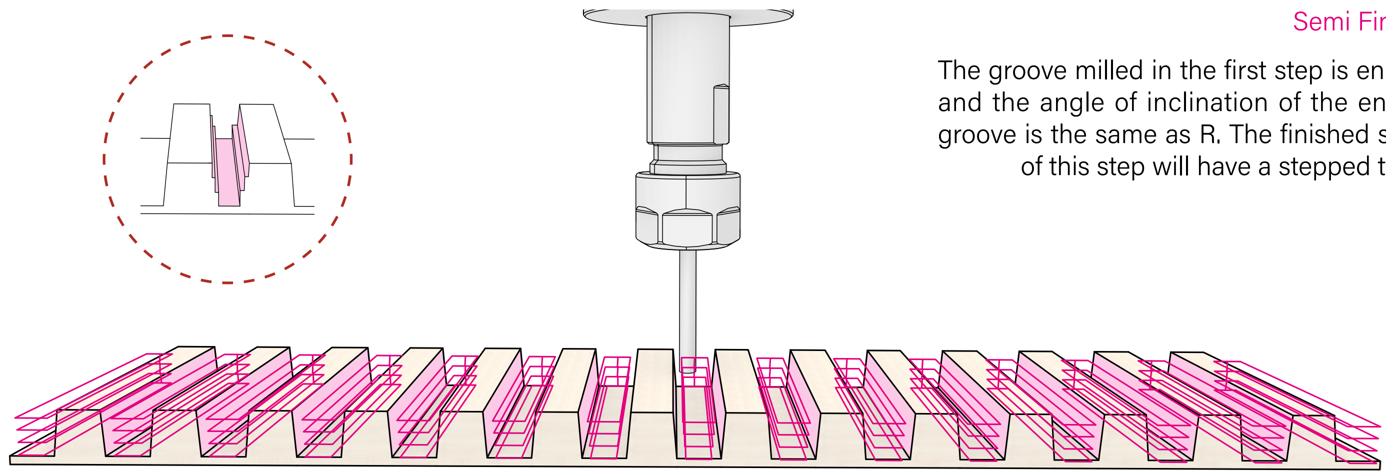
Rough Finishing

The first step is rough finising. The cutter head is held upright and the wood is milled to a defined depth.



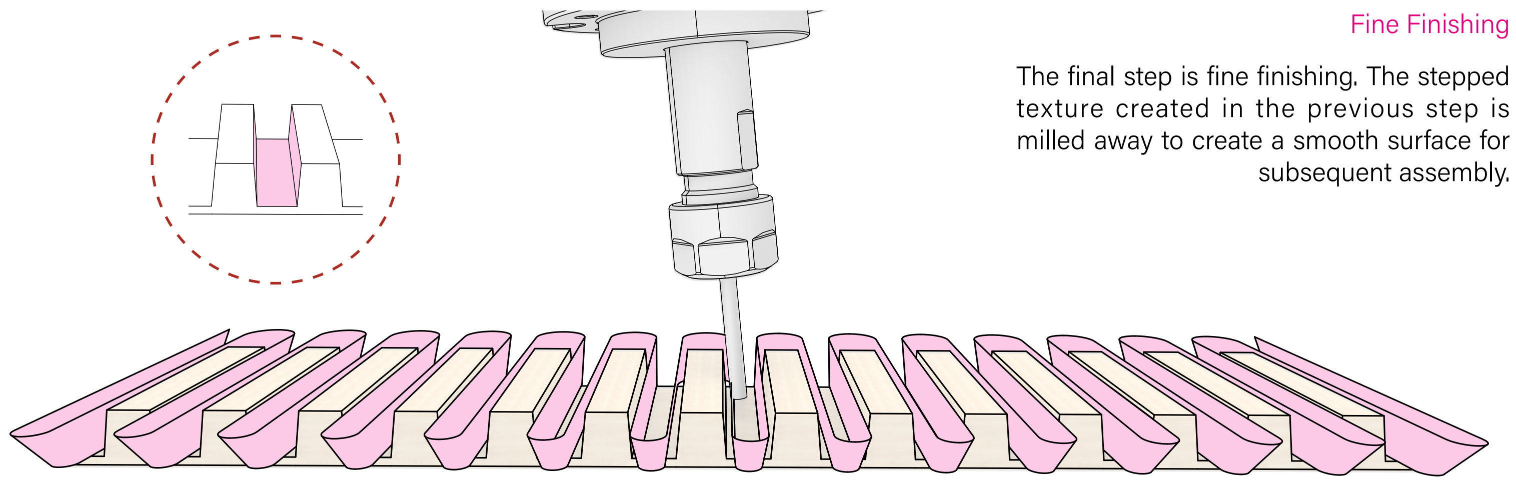
Semi Finishing

The groove milled in the first step is enlarged, and the angle of inclination of the enlarged groove is the same as R. The finished surface of this step will have a stepped texture.



Fine Finishing

The final step is fine finishing. The stepped texture created in the previous step is milled away to create a smooth surface for subsequent assembly.

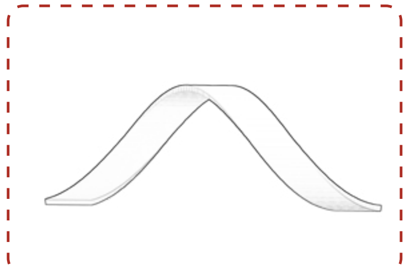


ERROR ANALYSIS

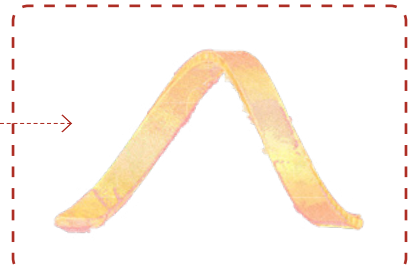
This section describes the process of error analysis. We scanned the assembled build as a point cloud model using a laser scanner and compared the point cloud model to the initial design model, which allows us to find the approximate value of the error.

We analyzed the possible reasons for the errors:

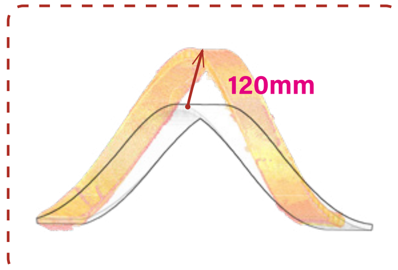
- The bending process produces a length difference between the inner and outer layers due to the thickness of the wood members, and the wood fibers prevent the bending to the correct curvature;
- The lack of references in the assembly process, and the presence of large human errors.



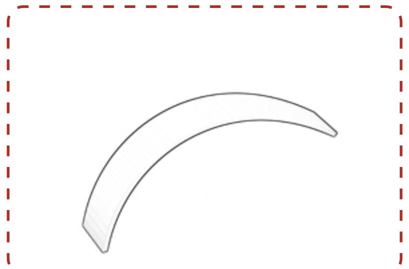
Initial model



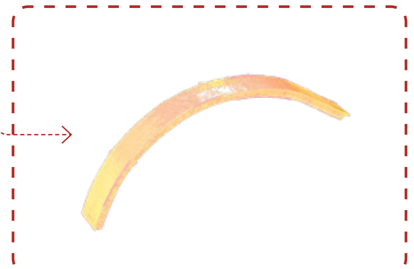
3d scanning modeling



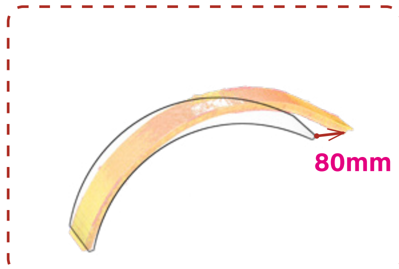
Error value



Initial model

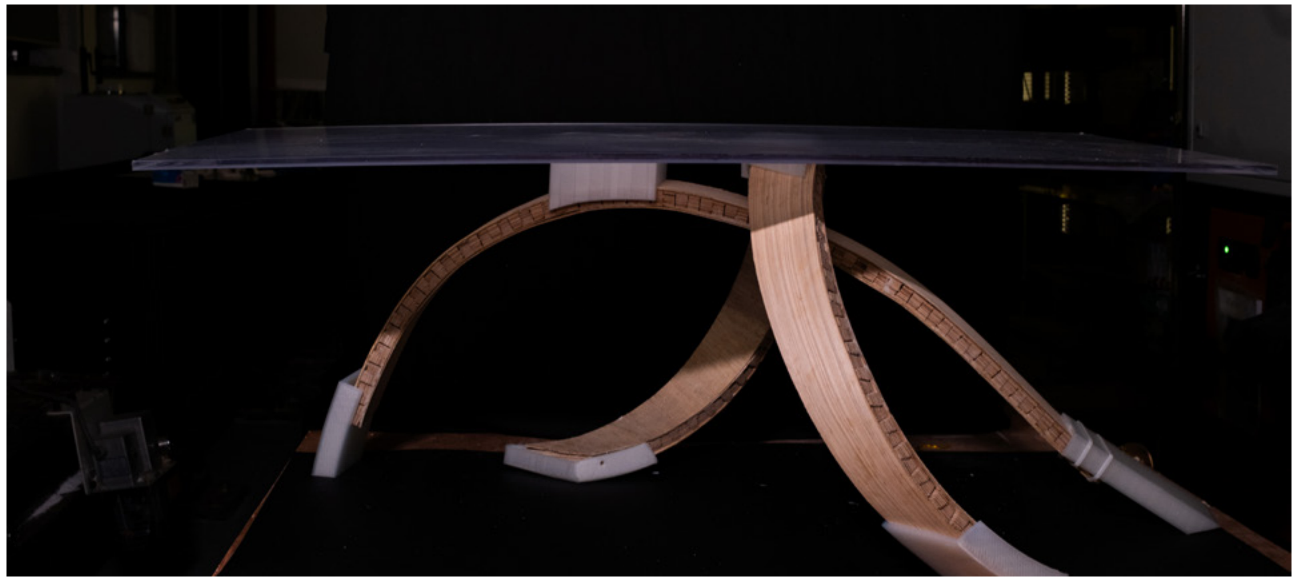


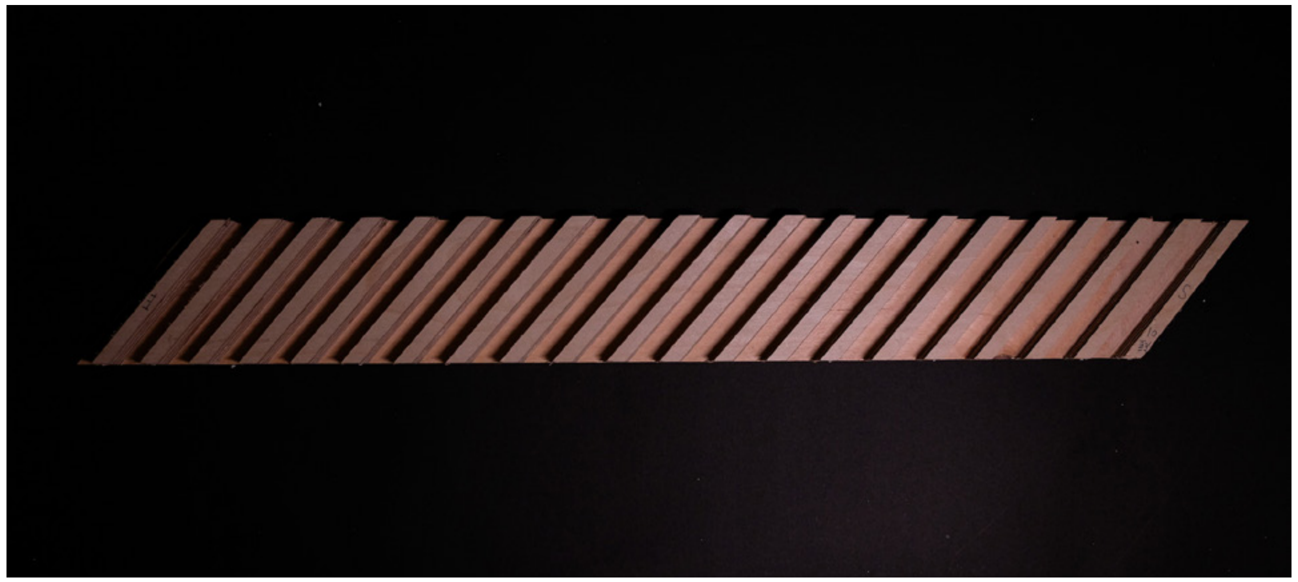
3d scanning modeling

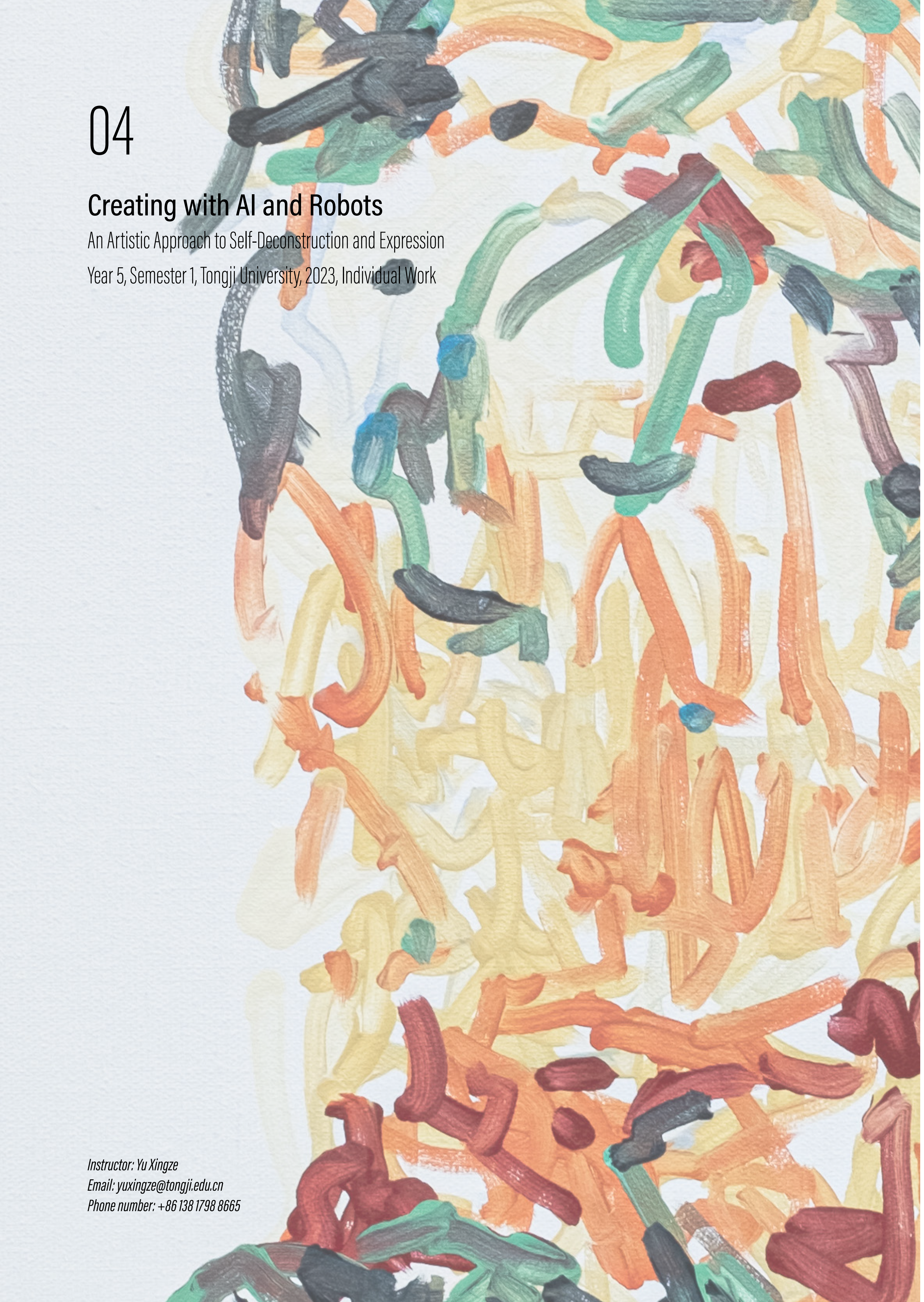


Error value

FINAL RESULT







04

Creating with AI and Robots

An Artistic Approach to Self-Deconstruction and Expression

Year 5, Semester 1, Tongji University, 2023, Individual Work

Instructor: Yu Xingze
Email: yuxingze@tongji.edu.cn
Phone number: +86 138 1798 8665

WORKFLOW | MOTIVATION, GENERATION AND CALCULATION

Marvin Minsky, an artifical intelligence scientise, mentioned that we cannot usually describe feelings, by can only do so by analogy, referring to things in our memories that cause such feelings.

Artists can achieve self-expression through a variety of artistic means, but for the average person, this is often difficult. Many artistic disciplines, including painting, require a great deal of training before they can become a means of personal expression.

We have developed a creative platform with artificial intelligence and robotics that aims to realize artistic self-deconstruction and expression in a more real-time manner, thereby lowering the threshold of personal artistic expression.

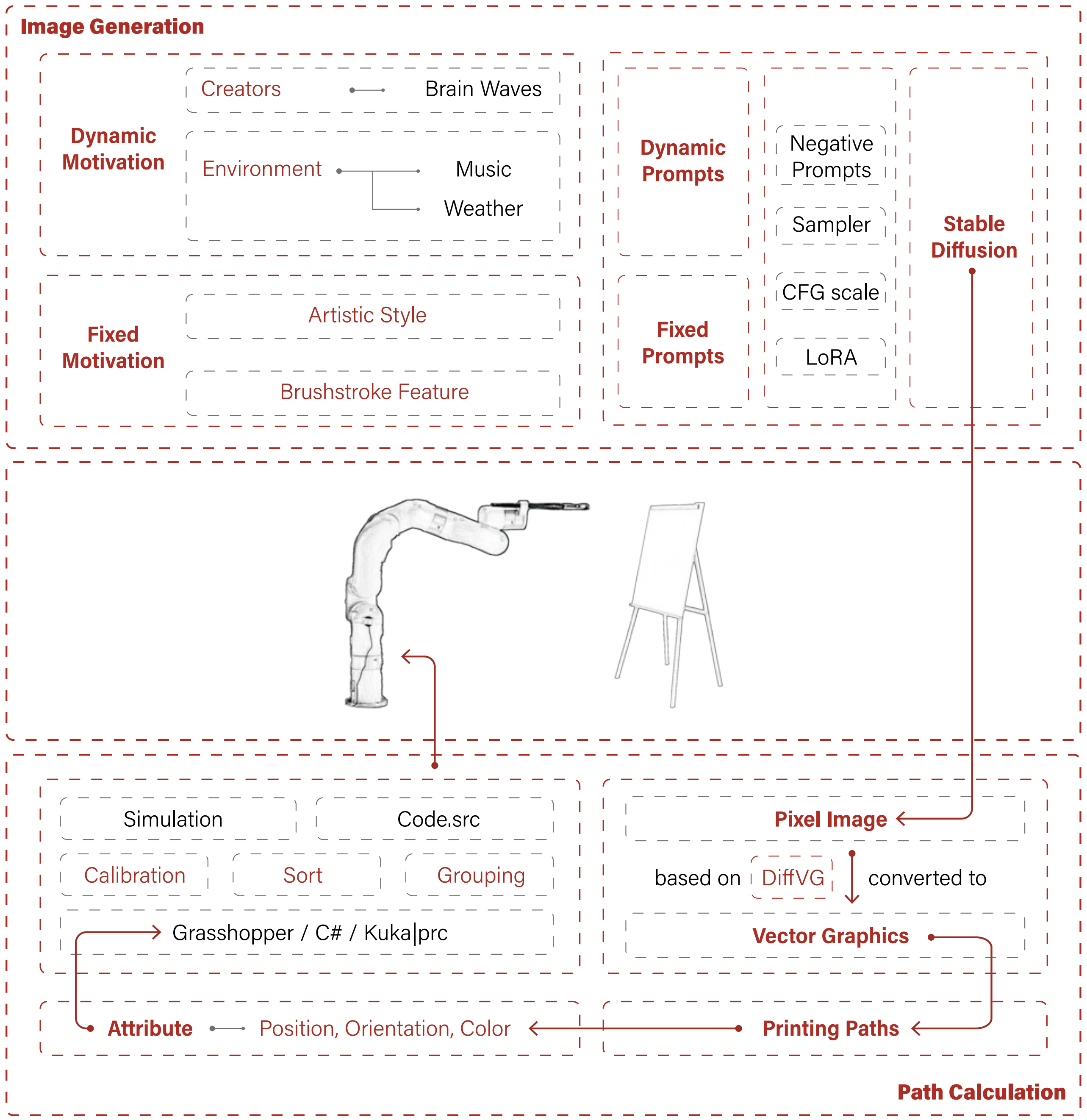


IMAGE GENERATION | FROM PROMPTS TO PIXEL IMAGES

Music
In order to elicit a more specific and intense emotional response, the creators will select a song that matches the emotional experience of the moment as the background music for the EEG test.

Weather
The weather conditions of the day will also be used as a key motivation.

EEG-Based Emotion Recognition

Dynamic Motivation
Inspired by the creator

Fixed Motivation
Determined through continuous testing

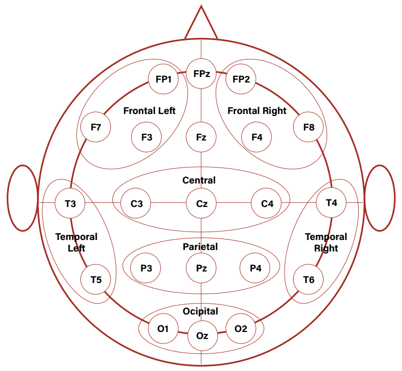
Dynamic Prompts
Representation of Self-Deconstruction

Fixed Prompts
Suitable for Robot Painting Features

+ Some Other Settings → **Stable Diffusion**

We consider music, weather and brain waves as three types of dynamic motivation. Electroencephalogram (EEG) signals respond in real time and are more sensitive to changes in affective states than peripheral neurophysiological signals. Thus, EEG signals can reveal important features of emotional states.

The EEG-based emotion distinct processes consist of signal acquisition, preprocessing, feature extraction, emotion classification, and evaluation. We used a convolutional neural network (RACNN) as a emotion classification method.



Independent Component Analysis (ICA)

- Apply ICA to EEG data
- Identify and delete artifact-related independent components
- Project EEG-related independent components back to electrodes to rebuild artifact-corrected EEG data

The major goal of feature extraction in the emotion recognition process using EEG data is to obtain information that can effectively reflect an individual's emotional state.

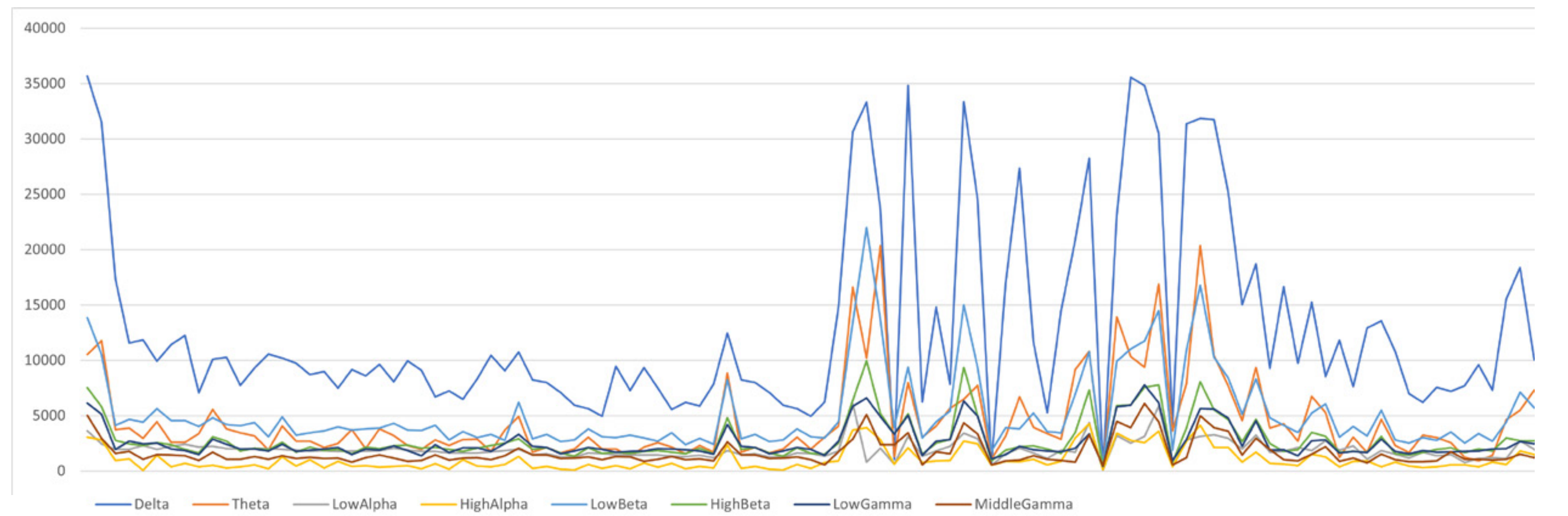
Subsequently, such information may be used in emotion classification algorithms. The accuracy of emotion identification is mostly determined by the extracted features.

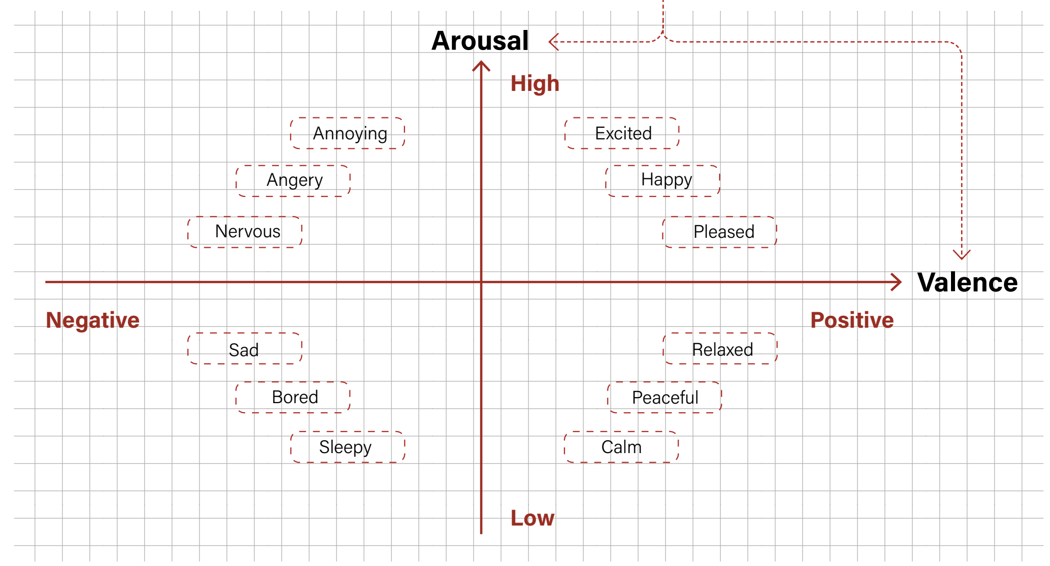
Deep Learning: RACNN

Dataset
DEAP
DREAMER

Reference:
https://doi.org/10.1016/j.knosys.2020.106243

EEG Signal Acquisition → EEG Signal Preprocessing → Feature Extraction → Classification → Evaluation





Prompts:
((abstract expression)), morden art, watercolor, <lora:impress:1>, low saturation
happy, comforting, relaxing
cure sky, warm sunset
best render, 4k

Negative Prompts:
Human, hands, legs, faces, realistic photo

Model:
anything-v5-PrtRE.safetensors [7f96a1a9ca]

Sampler:
DPM++ 2M SDE Karras

Steps:
30

CFG scale:
7.5

LoRA:
impress: 76f8f4791404

Seed:
3492128078

EEG-Based Emotion
Weather
Dynamic Prompts

Artistic Style
Fixed Prompts

Other Settings

Prompts:
((abstract expression)), morden art, watercolor,<lora:impress:1>, dark color
crazy, psychedelic, frustration, inner conflict
night sky, stars, sunset
best render, 4k

Negative Prompts:
Human, hands, legs, faces, realistic photo

Model:
anything-v5-PrtRE.safetensors [7f96a1a9ca]

Sampler:
DPM++ 2M SDE Karras

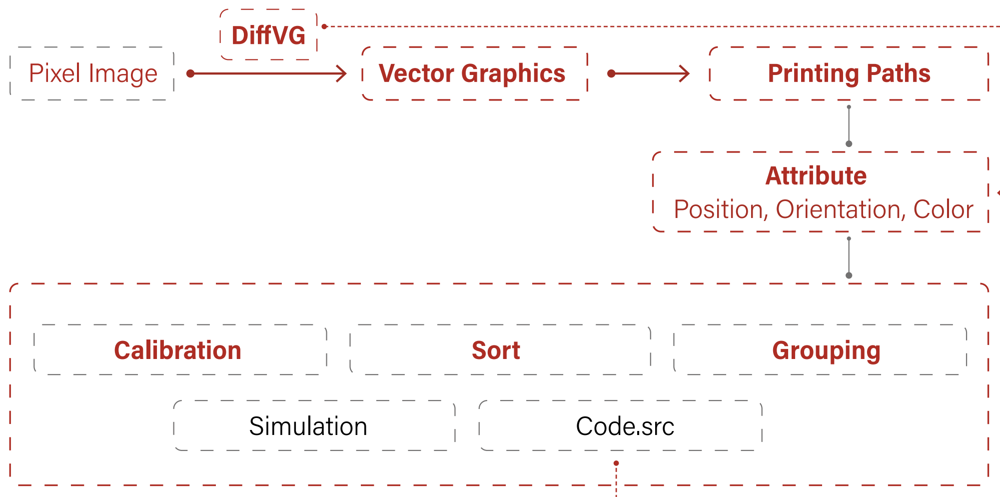
Steps:
30

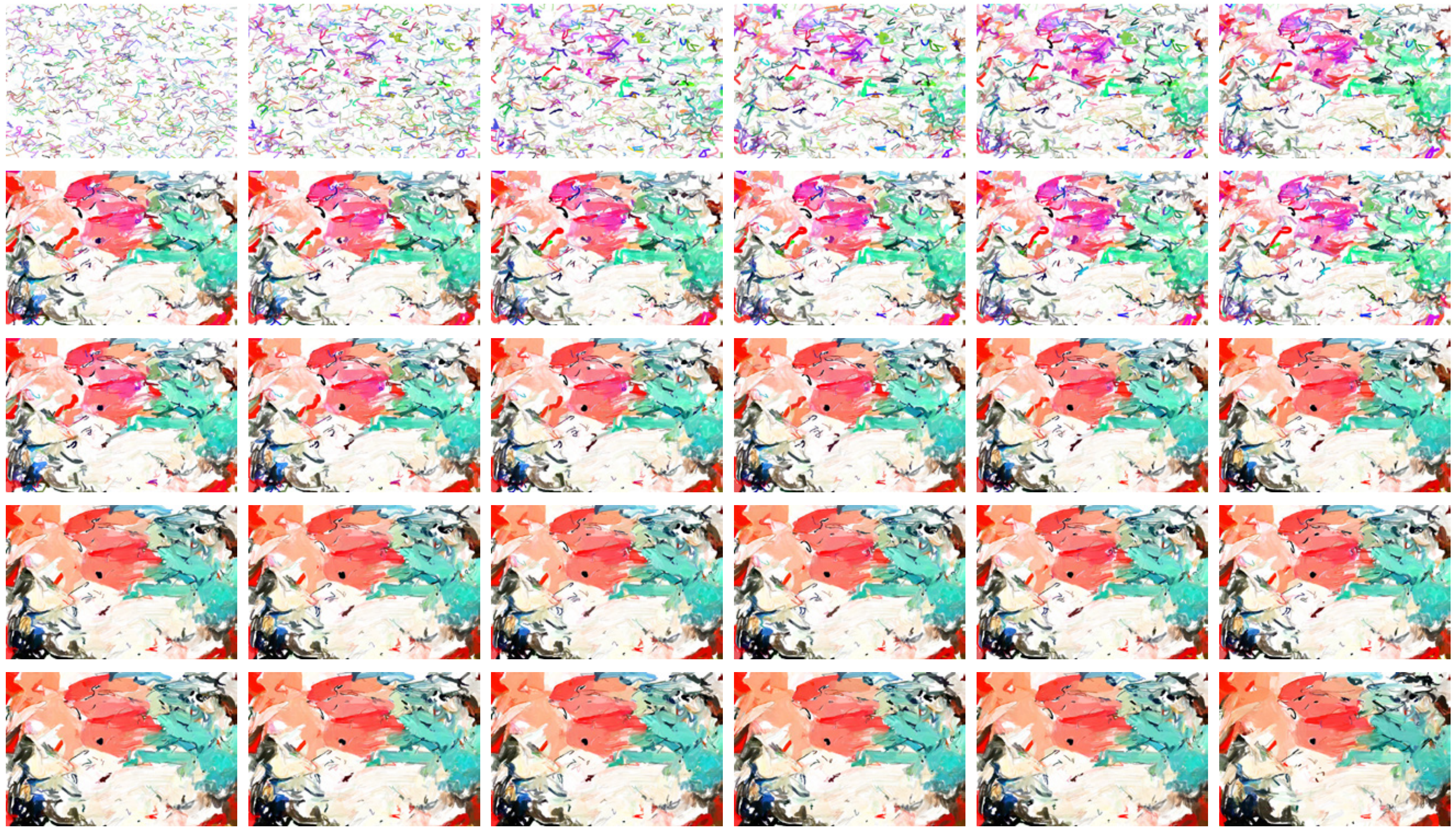
CFG scale:
7.5

LoRA:
impress: 76f8f4791404

Seed:
2729132475

path calculation | FROM PIXEL IMAGES TO VECTOR GRAPHICS



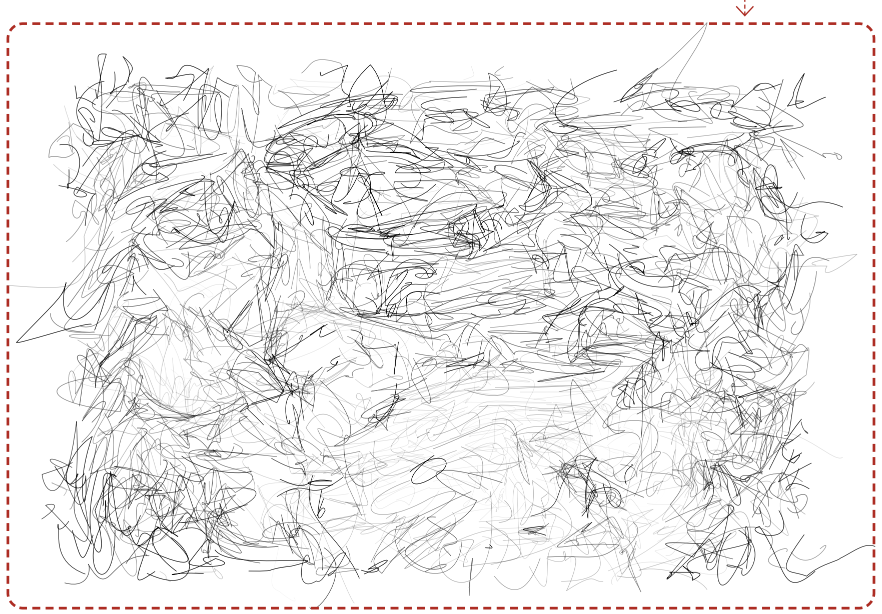


In this section, we use the open source platform DiffVG to convert pixel images generated by stable diffusion to vector graphics. DiffVG is method of differentiable vector graphics rasterization for editing and learning, by fitting random Bézier curves to a target image.

Then we retrieve information from the vector graphics to abtain the attributes of position, orientation and color of each path. We simplify the color information and sort the strokes by color. Strokes of the same color as a group to generate robot drawing paths. We also calibrate the position of the canvas and the palette.

In this demo, we're doing manual color grading for now. This will be improved in the future by introducing computer vision to assist the robot in automatically completing the color mixing for richer color expressiveness

Attribute:
Color



Attribute:
Position / Orientation

Reference:
https://people.csail.mit.edu/tzumao/diffvg/

Prompts:
((abstract expression)), morden art, watercolor,<lora:impress:1>, dark color
gloomy, frustration, inner conflict
cloudy sky, stars
best render, 4k

Negative Prompts:
Human, hands, legs, faces, realistic photo

Model:
anything-v5-PrtRE.safetensors [7f96a1a9ca]

Sampler:
DPM++ 2M SDE Karras

Steps:
30

CFG scale:
7.5

LoRA:
impress: 76f8f4791404

Seed:
2542135968

Robot:
KUKA KR10 R1420 Robot

Date:
December 1, 2023

DI Yizhuo
Selected works