Compliant Mechanism Moulding via NiChrome Wire Sintering Method

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This research proposed a unique process for the rapid manufacturing of large-scale compliant mechanism components. Using the characteristics of the NiChrome wire sintering method, it aims to rapidly fabricate a large-scale compliant mechanism model at low cost. NiChrome wire sintering is a method in which NiChrome wire is wound into a target pattern and then placed in a hot-melt material (TPU powder) to be energized and moulded. The low cost, high degree of freedom and one-piece characteristic of this new method bring new possibilities for the manufacturing process of compliant mechanism components. This research applies a new fabrication method to reduce the production cost and manufacturing difficulty of large kinetic installations. In benefitting from the non-mechanical wear characteristics of compliant mechanisms, the service life of manufactured installations can be greatly prolonged as well. The new fabrication method demonstrates an efficient way to produce a large scale of kinetic structure and provides a toolkit for designers.

Keywords: *Nichrome Wire Sintering, Rapid Prototyping, Elastic Material, Digital Fabrication, Compliant Mechanism.*

INTRODUCTION

This study aims to investigate the application of the new NiChrome wire sintering method (S.N.O.W.) in the manufacture of large-scale components of compliant mechanisms.

Conventionally, compliant mechanism components are manufactured using milling, moulding or vertical fused deposition modelling or stereo lithography printing methods. Each compliant mechanism fabrication method has its advantages and disadvantages, but all methods are subject to high requirements for the processing environment.

S.N.O.W was developed based on the concept of selective laser sintering (SLS), that is, the selective heating of hot-melt powder. Compared with SLS melting a material layer by layer with laser, the S.N.O.W method places the braided NiChrome wire into thermoplastic polyurethane (TPU) powder and sinters it with electricity. After exceeding the limitations of laser equipment, the fabricator can easily complete the sintering of 2D or 3D objects by winding wires. The sintered structure can be controlled to form in different strengths through regulating the sintering duration and temperature. The finished product will form strong elastic nodes where the wires intersect, which will directly affect the deformed state of the structure after being stressed.

To control the deformation of the fabricated parts into a more precise standard, a series of nodal sintering experiments was conducted to obtain basic data for controlling the deformation amount. These data were then applied to manufacture four common and one self-developed compliant mechanism components to inspect the feasibility of the new method. Based on the previous experiment results, a kinetic installation art was proposed to inspect the potential and organize the whole workflow of this new method.

The whole study is illustrated in three parts. Firstly, this study begins by examining existing works and papers that inspired this research. Secondly, it explains the sintering method and node sintering manipulation. Thirdly, the results of the current experiments are provided.

The following are the contributions of this paper.

1. Construction of the NiChrome wire sintering system for compliant mechanisms
2. Methods of flexible joint sintering
3. A summary of the current progress for further development

BACKGROUND RESEARCH AND PREVIOUS EXPERIMENT

The studies which inspired this research are illustrated in this chapter.

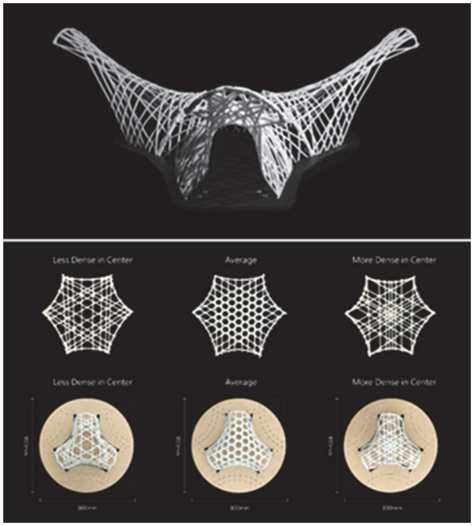


Figure 1
Fabrication results of S.N.O.W

Fabrication of Compliant Mechanisms

According to Lates et al. (2016) in their article 'Fabrication Methods of Compliant Mechanisms', the fabrication methods of compliant mechanisms are generally categorized as (1) milling, (2) 3D printing and (3) moulding. The integrally formed products fabricated by milling and moulding have excellent performance in load-bearing tests, while manufactured products formed via 3D printing have more delicate and complex components due to the method's high degree of fabrication freedom.

In terms of the disadvantages of these fabrication methods, milling results in the highest material waste rate due to the congenital limitations of subtractive manufacturing. Moreover, 3D printing is restricted by its relatively long processing time and the structural weakness of layer-by-layer printing. By contrast, moulding is capable of the most balanced performance among the three methods, but the initial mould manufacturing threshold has limited it from being used by the public.

The abovementioned compliant mechanism fabrication methods have their own advantages and disadvantages in terms of processing performance. However, the high requirements for the processing environment are common problems faced by these existing methods during the fabrication process.

Novel fabrication concept

S.N.O.W. (sintering TPU via NiChrome wire) (Tsung-Han et al., 2021) is an innovative fabrication method that can produce elastic structures rapidly using simple equipment and materials (Figure 1). In the last research project, the fabrication process was tested, and the finished product was proven to have high structural strength. The elasticity and integrally formed characteristic of the finished product were found to show the potential for fabricating compliant mechanisms. The S.N.O.W. construction method demonstrates the

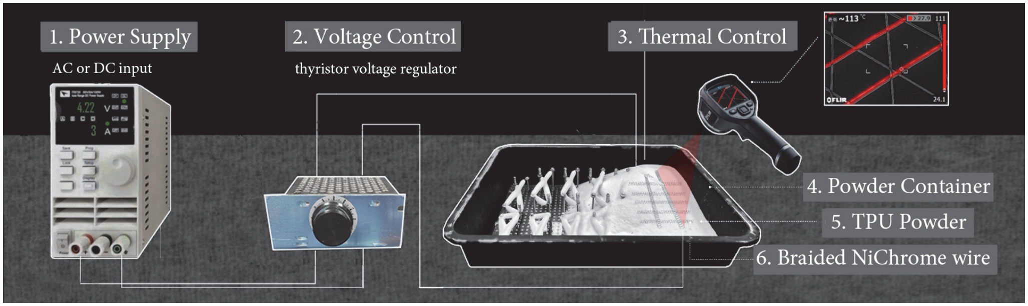
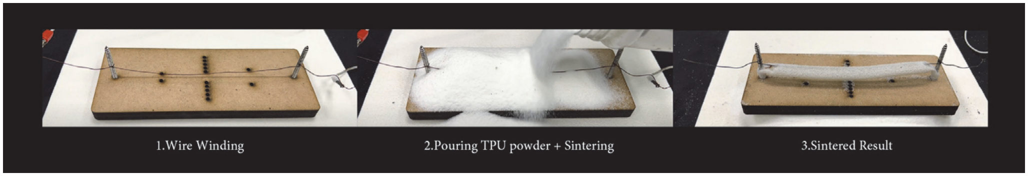


Figure 2
The overall sintering system



The sintering process demonstration (Bottom)

manufacturing advantages of rapid path processing of milling, complex 3D manufacturing of 3D printing and integral moulding and form shaping of moulding. A series of experiments are conducted to explain the operation details of this innovative method.

EXPERIMENT CONTENT

The development of the fabrication system is introduced in this chapter.

Sintering System

The sintering system of S.N.O.W will be examined in three parts (Figure 2).

Basic materials for sintering. To avoid the parallel connection of the intersecting wires when sintering, a special enamelled NiChrome wire covered with heat-resistant insulating material was introduced into the experiments. TPU was selected as the hot-melt powder material in the experiment in order to achieve the elasticity of the finished product.

Heating system that supplies power to the NiChrome wire to energize and generate heat. Both AC and DC power supplies can be used for sintering. Depending on the size of the sintered object (i.e. the total length of the NiChrome wire), the power needs to be controlled to match the reasonable temperature (120°C–140°C) during sintering process. A 220V thyristor AC voltage regulator was introduced as the output terminal so the voltage could be adjusted in time to restrict the maximum temperature.

External monitor system for adjusting the heating temperature of NiChrome wire. During the experiment, an infrared photothermal imager was used to monitor whether the sintering temperature fell within the desired range. Along with the voltage controller, the thermometer allows the fabricator to adjust the sintering temperature in time during the fabrication process.

Moulding System

Positioning and weaving control of the desired pattern. Screws are drilled into the wooden board according to the desired pattern as anchor points for weaving, and Nichrome wire is then wound on the screws in sequence. The NiChrome wire needs to be wound tightly on the screws to avoid dislocation due to the expansion of heated NiChrome wire.

Post-processing of the sintered component

Figure 3
Heat-treat process helps prevent the drop-off of unsintered powder remaining on the surface

The heat-treat process helps prevent the drop-off of the unsintered powder remaining on the surface. After sintering, the component is left to cool to semi-hardened status (~50°C) in the powder to avoid the deformation caused by losing the support of the remaining unsintered powder. After the temperature of the component is lowered, the powder can be shaken off and the excess sintered parts are trimmed to match the desired shape. The excess powder covering the component can be treated with a hot air blower to produce a smoother surface (Figure 3).

Basic Experiments - Shape Controlling and Sintering of Nodes and Members

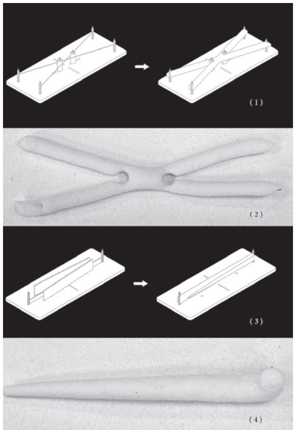


Figure 4
Diagram of the 'Joints' experiment (first and second images)

Diagram of the 'Thickness Control' experiment (third and fourth images)

- Joints
  To shape the joint for controllable deformation of the compliant mechanism, metal sleeves are deployed to the screws to absorb the heat generated from the energized NiChrome wire, leading to concave nodes (second image of Figure 4). When subjected to force, the concave nodes will deform in different degrees to achieve the purpose of action control of compliant mechanisms.

- Thickness Control
  In the same way, metal sheets are arranged to aid in controlling the shape and width of the sintered product (fourth image of Figure 4). The control of width allows designers to manipulate the bending degrees of the elastic member in order to further design components that can match the target trajectory.

Advanced application - Compliant mechanism fabrication attempt

The two shaping techniques (joint and thickness control) are then applied to fabricate four general kinds of existing compliant mechanisms and one self-developed mechanism (Figure 5). The goal is to examine the feasibility of the construction method and the restrictions that need to be considered when designing the components.

a. Gripper
The gripper experiment tested whether the elastic joints produced by S.N.O.W. could convert the applied force into shape deformation perpendicular to the direction of the applied force (top left image of Figure 6).

b. Cross-Axis Flexural Pivot
The Cross-axis flexural pivot experiment tests whether the elastic strength of the sintered object can withstand large bending forces (top right image of Figure 6).

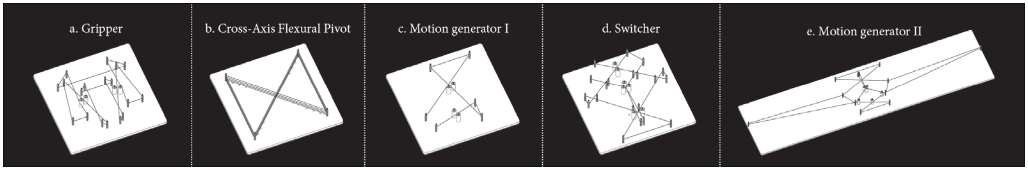


Figure 5
Winding setting of the five compliant mechanism experiments (from left to right: component a. to component e.)

c. Motion generator I

The motion trajectory of the sintered product can be edited by adjusting the position and type of nodes. The result shows the potential for fabricating locomotion generators (bottom left image of Figure 6).

d. Switcher

The switchable component produced by the S.N.O.W. can perform the ON-OFF mechanism. Although the results will sometimes fail due to the flexibility of TPU, which leads to the undesired deformation of rigid members, they revealed the potential for fabricating mechanical switches via S.N.O.W. (bottom right image of Figure 6).

e. Motion generator II

A prototype pattern is generated by using a mechanical device design assistant website to simulate conventional mechanisms (Motion Generator Website, n.d.) and to ready for fabrication. After the sintered component is connected to the drive shaft (servo MG995), it successfully converts the rotational force into the up and down swinging motion similar to the motion of seesaw (Figure 7).

The four experiments are tested and verified for the following characteristics of compliant mechanisms: (1) Conversion of force direction, (2) Material resilience, (3) Joint positioning and action controlling and (4) Switchable motion generating. The results show that the S.N.O.W. has the potential to create a compliant mechanism component with complexity. The fifth experiment (i.e. Motion generator II) shows the overall workflow of how this innovative approach can be used to design and manufacture compliant mechanisms.

The advanced application focused on the fabrication of components that can generate 2D trajectory motion is proven to be reliable for the purpose of motion generating. The deformation results of the (d) switcher indicate the possibility of achieving 3D trajectory motion. Combining these results with the results of the 3D constructing method using S.N.O.W. in the previous research (sintering TPU via NiChrome wire) (Tsung-Han et al., 2021) shows that the fabrication of 3D compliant mechanisms that can perform 3D trajectory motion is possible.

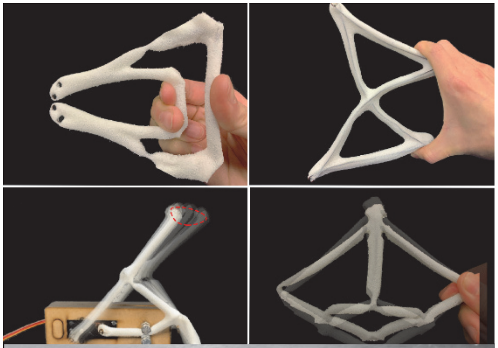


Figure 6
Operation effects of four general kinds of existing compliant mechanisms:
a. gripper (top left),
b. cross-axis flexural pivot (top right),
c. motion generator I (bottom left),
d. switcher (bottom right)

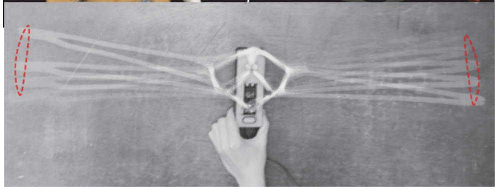


Figure 7
Overlay image of the operation of 'Motion generator II'

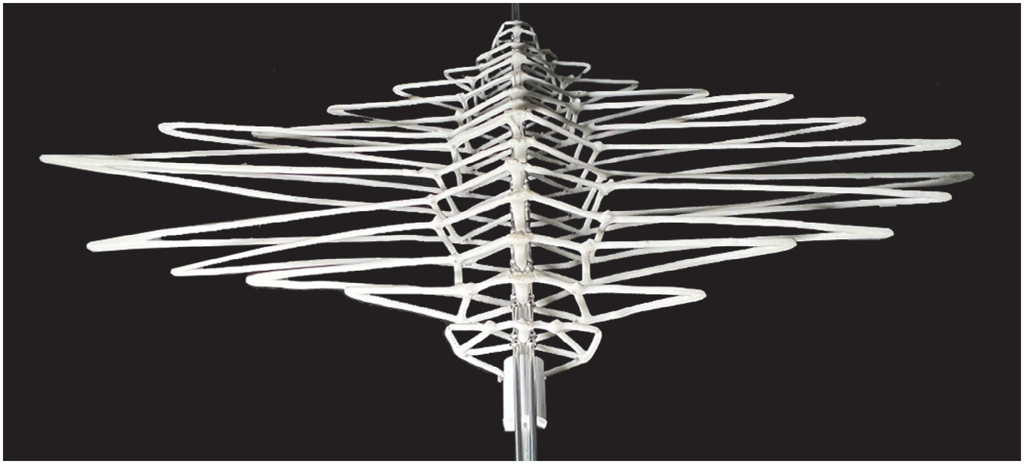


Figure 8
The last experiment is to complete an installation art composed of 15 compliant mechanism components fabricated by the S.N.O.W method

This device generates rhythmic waving motion when activating

DESIGN EXPERIMENTS

This study applies the new method to the design and fabrication of a kinetic installation art, which will demonstrate the efficiency and low cost of this novel method and showcase the fabrication workflow of sintering multiple components at the same time.

Digital Designing Method

The basic pattern of motion generator II is imported and simulated in the Rhino Grasshopper Kangaroo2 environment. The mechanisms can be operated with the combination of Kangaroo components shown in the picture (Figure 10). The desired trajectory path can be further tweaked by adjusting the input pattern of the mechanism. With a parameterized point adjustment, the sequential change components are designed and ready to be fabricated (Figure 9,left).

Fabrication

Separate 15 components into five sintering groups according to the fabrication size (total NiChrome wire length). These five groups of parts will be sintered under the same temperature range (135°C–150°C) 3–8 minutes. The wire diameter of the sintered components is measured from 10 mm to 22mm.

The usage of the voltage regulator greatly simplifies the tedious steps when the power supply for sintering different sizes of components is replaced. With the use of an infrared thermal imager, the voltage can be adjusted simultaneously according to the measured temperature. Moulds with a unit width of less than 1200 mm are processed by a laser-cut wooden board (1200 × 1200 mm).

For parts larger than 1200 mm, samples are first printed and pasted on a plywood board (2200 × 910 mm) as the reference (Figure 9, right).

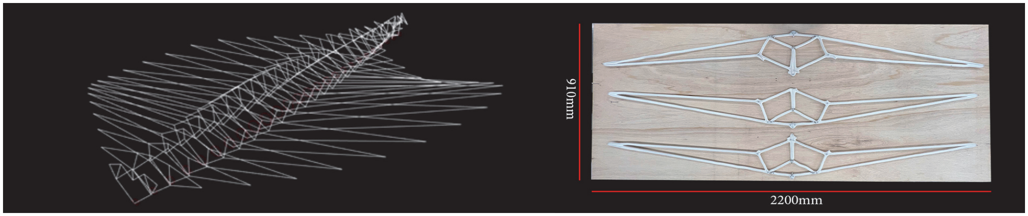


Figure 9
Desired motion is simulated and adjusted in the Rhino Grasshopper (left)

Components are separated into different sinter groups by size (right)

Anchor points are then set (drilling screws and applying metal sleeves to the board) according to the referenced pattern. Lastly, a long string of NiChrome wire is wound in sequence to match the desired pattern. The sintering process is rather simple because the parts of different sizes are separated in groups, and the components with the same diameter can be fabricated with one single connection to the power supply.

Lastly, components parallel to each other are connected and assembled with thin steel cable after the post-treatment of trimming and heat-treat. The aim is to avoid any undesired deformation of the elastic components when not being stressed.

Results

After the crankshaft is connected, the parts with different sizes and sintering patterns will be deformed correspondingly according to the rotation angle of the crankshaft, thereby producing a rhythmic motion (Figure 11).

The installation is very quiet during operation due to the frictionless trait of the compliant mechanism. Benefitting from the characteristic of the S.N.O.W., compliant mechanism components in large scale can be fabricated rapidly in an integral way.

CONCLUSIONS

The advantages of the S.N.O.W. fabrication method not only enable large-scale compliant mechanisms to be flexibly manipulated but also exhibit a more efficient way of fabricating. All the sintered components can be peeled off from the NiChrome wire after reheating, which can achieve the goal of material recycling.

In the advanced application of the basic experiment, the four components fabricated by S.N.O.W. successfully exhibited the following characteristics of the compliant mechanism: (1) Conversion of force direction, (2) Material resilience, (3) Joint positioning and action controlling and (4) Generation of switchable motion. The combination of these basic types of compliant mechanisms allows designers to create kinetic parts with more complex functions.

In the final experiment of design and fabrication, the possibility of manufacturing large-scale components and the operation process of sintering multiple components at the same time are proven feasible (Figure 12). The results show the possibility of fabricating large-scale decorative installations or functional facades, which enable designers to explore forms and kinetic structures in a manageable way by adjusting the pattern of the sintered parts. Compared to the conventional methods of fabricating compliant mechanisms, S.N.O.W. proposed a rapid, free-form geometric surface-generating method demonstrating a unique way of sintering powder to form wireframe structures without using supporting materials and in a fully powered state, the widget size is not limited.

Considering future aspects, this method has great potential to rapidly fabricate large-scale compliant mechanism components with more complex motion. Therefore, the system should be optimized for a more precise and reliable fabrication. Owing to the uniform hardness of the TPU powder, undesired deformation will sometimes appear on the parts that should remain rigid after being subjected to force. In addition, although the motion control of 2D sintered components is proven to be practicable, the generation of complex 3D trajectory still needs more research to examine. Finally, the power supply for the whole sintering system requires a more flexible solution to generate electricity from low to super-high voltage in order to complete components in different sizes.

Further research in this area will require the following: (1) In-depth study of the combination of sintering materials with different hardness, (2) Research on the fabrication of the 3D kinetic component and (3) Improvement to the current sintering system to extend the length limitation of NiChrome wire.

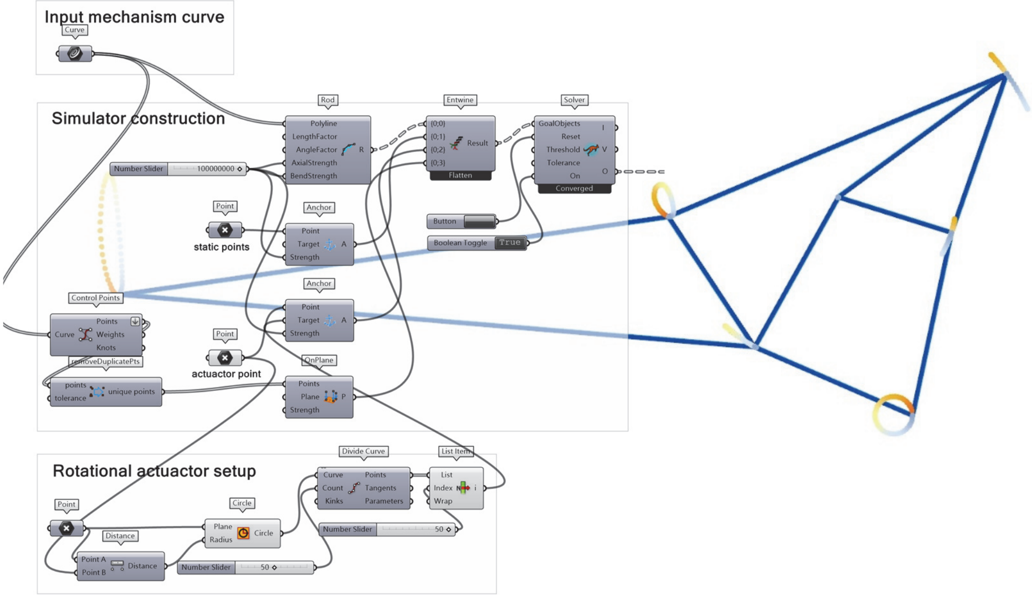


Figure10
Details of the
Kangaroo
simulation process

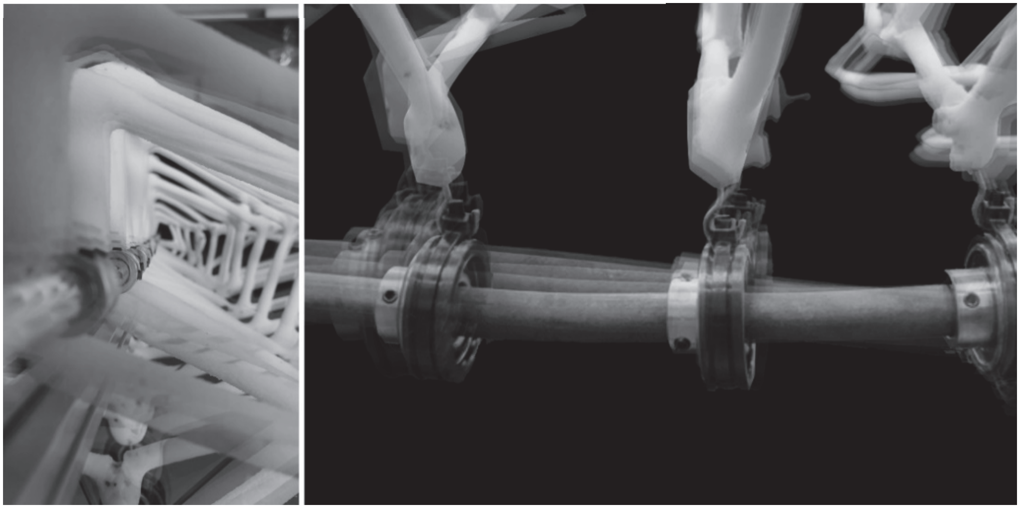
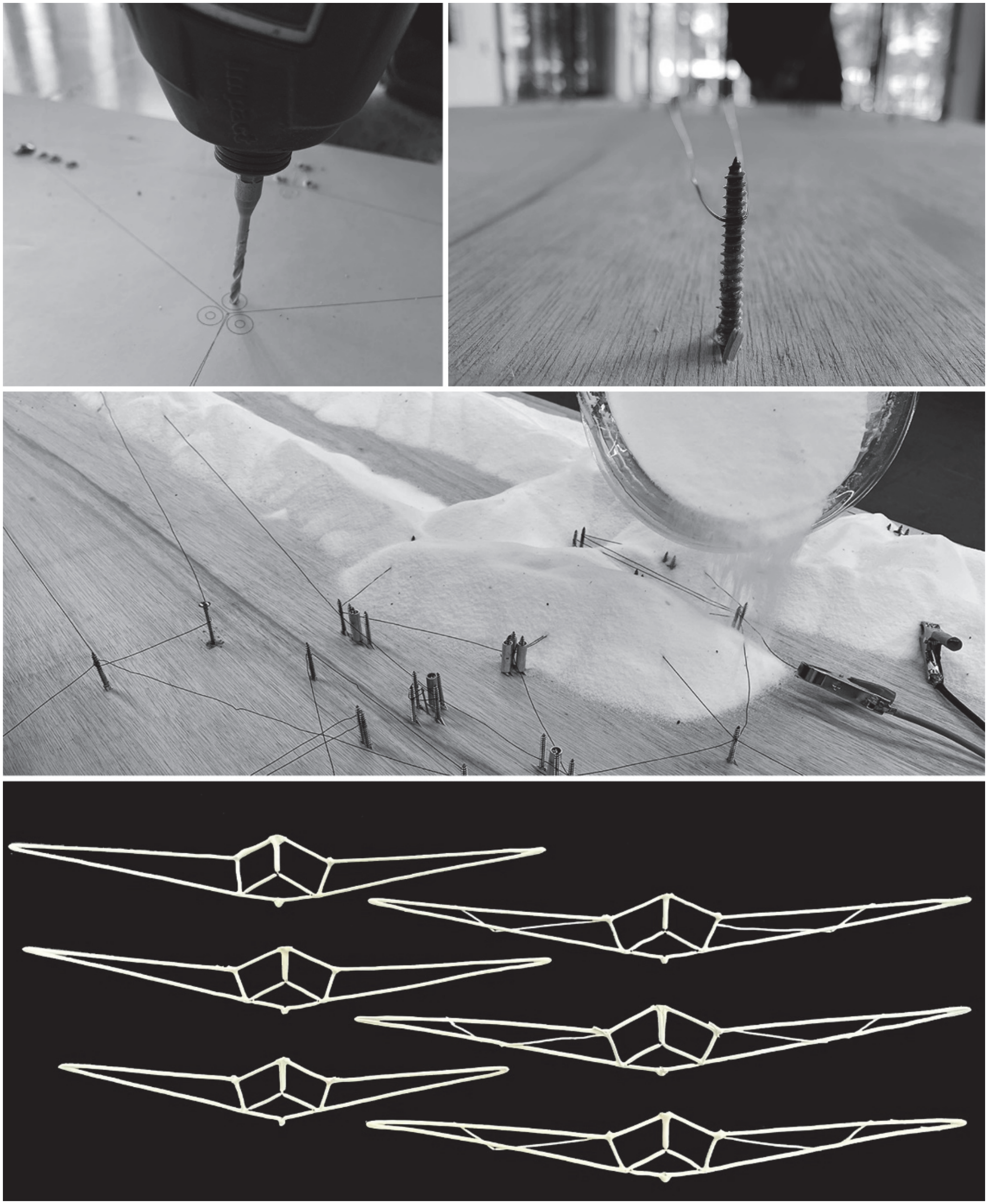


Figure11
Details of the final
model

Figure 12
Fabricating process
of the final model



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