Pneumatic Auxetics:

Inverse design and 3D printing of auxetic pattern for pneumatic morphing

Soya Eguchi
Keio University, Kanagawa, Japan
eguchi-soya@keio.jp

Claire Okabe
Keio University, Kanagawa, Japan
o_claire@keio.jp

Mai Ohira
Keio University, Kanagawa, Japan
mai.ohira@keio.jp

Hiroya Tanaka
Keio University, Kanagawa, Japan
htanaka@sfc.keio.ac.jp

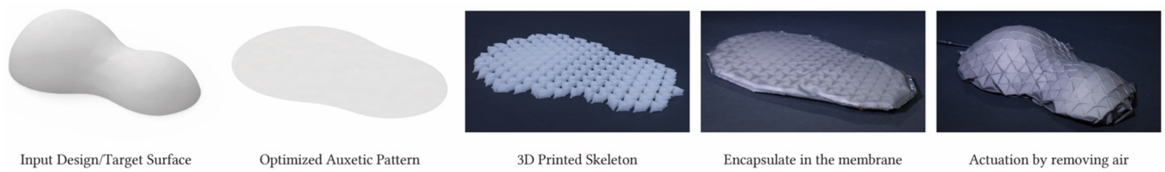

Figure 1: Pneumatic Auxetics is composed of a flexible but non-extendable three-dimensional skeleton and a pneumatic enclosing membrane. Our method optimizes the size and thickness of the patterns so that the folded structure best approximates the desired input surface.

ABSTRACT

This paper presents Pneumatic Auxetics, an inverse optimization method for designing and fabricating morphing three-dimensional shapes out of patterns laid out flat. In origami/kirigami research, optimization of patterns that can be transformed into the target surface by inverse design has been attempted. On the other hand, in the research area of pneumatically actuated geometries, the control of the transformation using skeletons and membranes has been attempted. In the study of the inverse design of the auxetic pattern based on kirigami, it cannot actuate deformation by removing air because the design does not consider the thickness. Therefore, we simulate the pneumatic transition with the thick shell structure that is generated by offsetting the input surface (Figure 1). The designed skeleton is optimized for FGF (Fused Granular Fabrication) 3D printing, and it is 3D printed using soft elastomeric materials. These allow for both a deformable hinge and a rigid pattern. Thus, a skeleton made of a single material can be deformed to approximate the shape of the target-input surface by placing it in a membrane and removing the air. In this paper, we introduce related works and research contexts, challenges, inverse design simulator and its fabrication by 3D printing, and potential future applications.

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CCS CONCEPTS

• Applied computing; **• Physical sciences and engineering**; **• Engineering**; **• Computer-aided design**;

KEYWORDS

Inverse Design, 3D printing, Auxetic Pattern, smart materials

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1 INTRODUCTION

Structures with negative Poisson's ratio, mainly origami/kirigami structures, have been widely used from products that enter the human body, such as stent grafts [1], to large-scale products, such as architecture and space structures [2, 3]. Origami can be folded from a flat surface into a compact state and create a target shape. Kirigami can expand into various shapes and sizes by applying graded cuts (Figure 2). It is also well known as the Auxetic Pattern. In the field of inverse design, origami folds from a flat surface to create the target curved surface and structure [4-6]. Kirigami can deform target curved surface by spreading them out from a flat surface [7-11]. However, these studies have not considered pneumatically actuated applications with membranes and skeletons. Pneumatic actuation using membranes and skeletons allows to control the transformation of linkage pneumatically. In this research, we explored auxetic structures with thickness optimized for transformation by air deflation, based on an inverse design workflow using kirigami structures. Furthermore, we simplified the manufacturing process by devising a single material skeleton realized

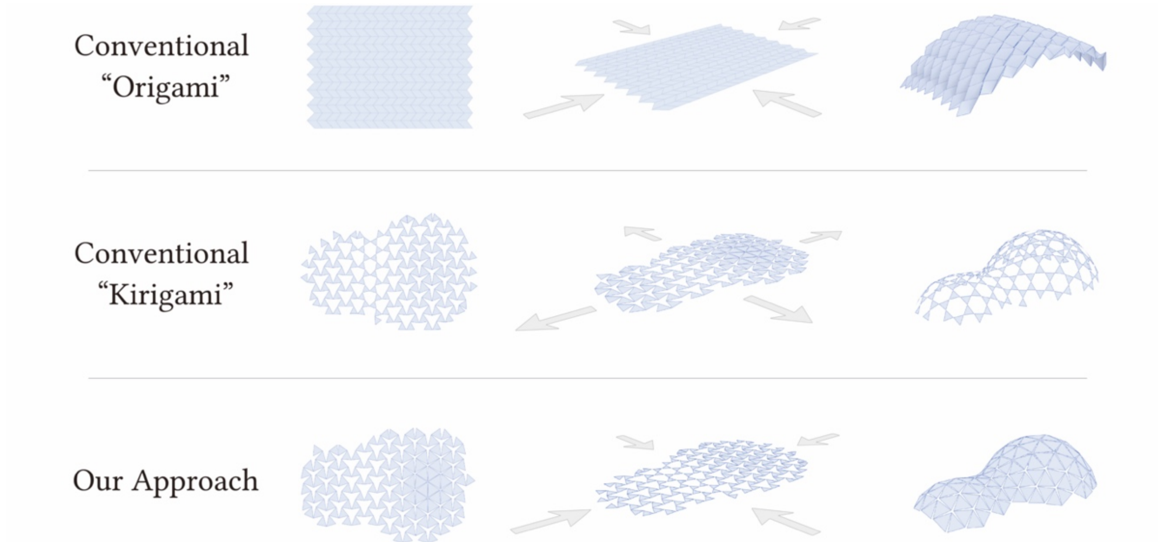

Figure 2: Three Different Approach of morphing

by a FGF (Fused Granular Fabrication) 3D printer. This allows us to fabricate interfaces that deform to produce hardness when the pattern is closed. It is also possible to fabricate interfaces that allow different amounts of light transmission by changing the size of the voids.

This research is positioned as an integration of pneumatic transformation (to create bi-stable morphing) and inverse design (to generate auxetic structures to transform into target shapes).

2 CONTRIBUTION

The main contributions of this work are as follows:

- Composite design method and original/kirigami simulator for pneumatical actuators: The inverse-designed sheet is 3D printed with a soft elastomeric material so that it produces a hinge and a rigid part at the same time. The single 3D printed structure transforms into the designed surface by sealing it in a membrane and removing air.
- Morphing Design of bi-stable shell structures: We present future applications and possibilities of bi-stable shell structures.

3 RELATED WORKS

3.1 Inverse design by Origami/Kirigami approach

These are some studies on structural optimization to inverse design the patterns from the target surface [4-11]. Programmable Auxetics [7, 8] is research on simulation tools for the auxetic pattern linkage that we chose as our base pattern. They introduce an algorithm for pattern mapping that optimizes for various surfaces. They also show the application that transforms the pattern by pneumatically inflating the membrane to unfold it. There are other research that includes inverse design algorithms using origami structures and other techniques [4-6], and a hybrid of kirigami and origami [11]. However, these simulators are design tools that do not consider thickness because they have been developed for thin paper folding as their background. For origami, there is a research field called rigid folding [12, 13], which shows design methods for fabricating structures with thick materials. Nevertheless, these methods cannot apply directly to pneumatic transformation with membrane. We present a method for generating an optimized model for pneumatic transformation.

3.2 Pneumatically Actuated Objects

In the field of soft actuator research, skeletal structures have been inserted into membranes to create morphing by removing air [14-18]. Origami-inspired artificial muscles [15] introduce lifting objects and moving joints like artificial muscles. Pneumatically actuated material [14] shows geometries that can be transformed into spherical shapes by tapering the skeletal structure. These studies create simple movements and transformations by combining simple geometries. We aim to generate complex geometries in order to produce the desired morphing.

There have been several studies on pneumatic actuators using inverse design algorithms [19-22]. These studies allow the transformation into a variety of surfaces, and it can change its shape depending on air pressure. All these methods actuate transformation by inflating with air. However, we propose the morphing by deflating. We introduce the skeleton inverse design tool into pneumatic deflation to realize more complex morphing.

3.3 Self Actuating/Folding Shells

In the field of HCI, the research of morphing and deforming patterns by 4D printing or fabric tension [6, 23, 24] has the same design vision as ours in terms of proposing a shell structure that rises to the designed curved surface. CurveUps [23] is similar in design philosophy as a method of creating curved surfaces by adding thickness to the triangle pattern. However, there are some differences between

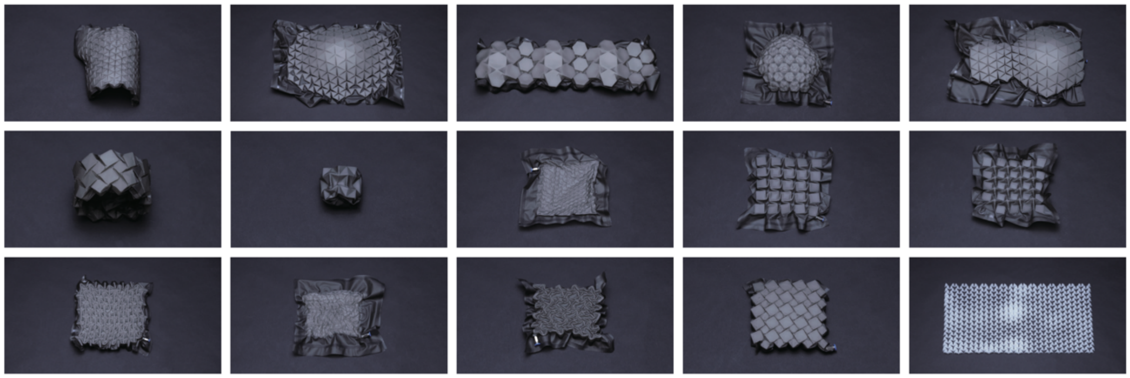

Figure 3: Samples of the very early skeleton variation

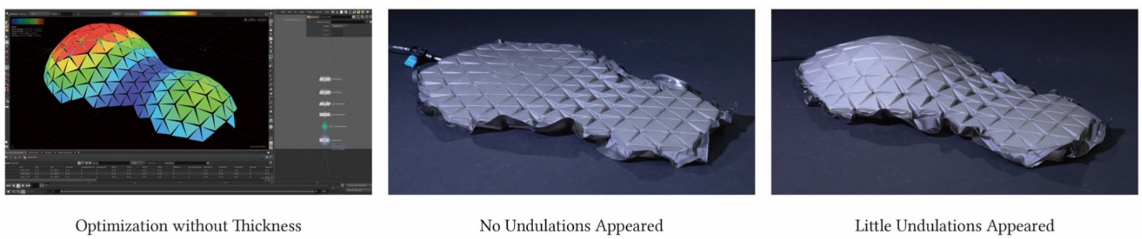

Figure 4: The extruded kirigami simulated model with no thickness does not deform as expected.

this project and our research. CurveUps cannot be transformed repeatedly because the pre-stretched cloth only provides force in the compression direction once. However, Pneumatic Auxetics can change states between flat and curved surfaces because we are transforming with air. In addition, the structure of CurveUps is made of independent pieces that are connected by fabric, which increases the amount of manufacturing processes. In contrast, our skeletons are manufactured directly by 3D printing a single geometry and packaging it in a membrane, which allows us to achieve results with a somewhat simpler process. CurveUps uses an inkjet 3D printer, whereas we use an FGF 3D printer that can be manufactured with soft elastomeric materials. CurveUps and we have fundamentally different base geometries and approaches to data optimization.

4 BASE SKELETAL STRUCTURE AND AUXETIC PATTERN

Figure 3 shows an initial design experiment to determine the skeleton on which to base the geometry. We 3D printed various structures with soft material and put them in the membranes and let them deflate to check their behavior. Some patterns deformed randomly, and some patterns deformed regularly. The softness of the 3D printed material not only characterize the flexibility of the structure in the non-actuated state, but also provides a smooth transition between different actuation states. The reference geometry, based on the Pneumatically Actuated Material [14], allowed deformation of the shell geometry. However, they have not done an infinite number of connections to that structure. In the reference paper, nine connected patterns are used as a single module, and the undulations are designed by combining them. We chose the pattern used in Programmable Auxetics [7] as a base geometry because it requires an infinite number of patterns to be connected and arranged without any inconsistency to enable the design of various undulations. Figure 4 shows a simple extrusion of this simulated pattern, but it is not deformed or only slightly deformed. Therefore, we found it necessary to design an algorithm that considers the thickness and would also allow us to control the angle of bending.

5 MORPHING DESIGN

In this section, we describe the workflow for designing the morphing. The 3D printed skeleton made of thermoplastic elastomer (TPE) material is sealed with a 0.15mm thick thermoplastic polyurethane (TPU) membrane and actuated by air removal. It can be returned to a flat surface by releasing the air (Figure 5). Figure 6 shows our simulator tool built on Houdini.

5.1 Inverse Design

Given the input surface, our goal now is to find the 2D layout of the triangular linkage with thickness that, when folded, approximates the input surface as closely as possible. Figure 7 illustrates the main steps of our workflow. Patterns are mapped with reference to Programmable Auxetics [7] (1-3). The same process is applied to the inner offset surfaces (the number of auxetic patterns must be the same as the number of outer triangles). The finished inner and outer surfaces are shown in 4. From there, the data is unfolded into a flat plane, by gradually scale the size of the triangles to make them 3D printable so that the shape does not overwrap.

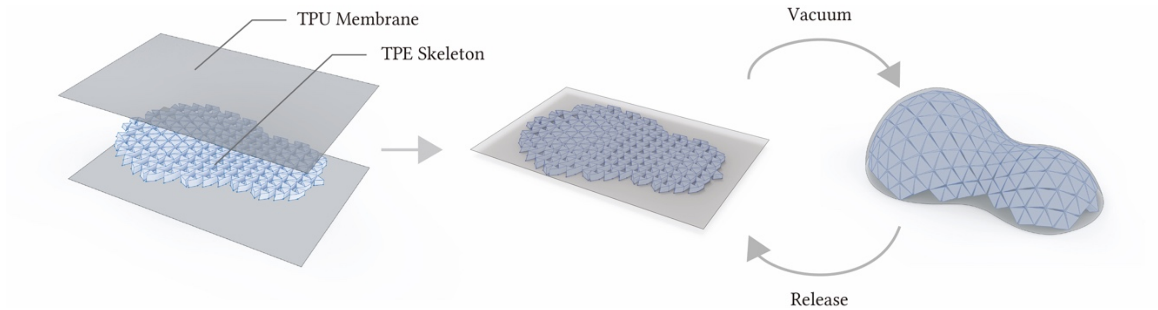

Figure 5: The 3D printed skeleton in TPE is sealed inside a TPU membrane (right). When the air is removed, it transforms into the target shape and when the air is released, it returns to a flat surface.

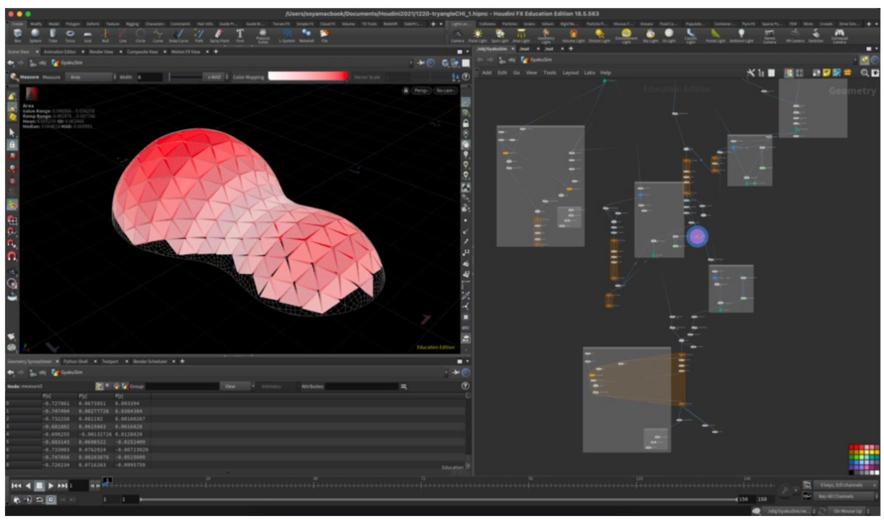

Figure 6: Screenshot of the simulator tool

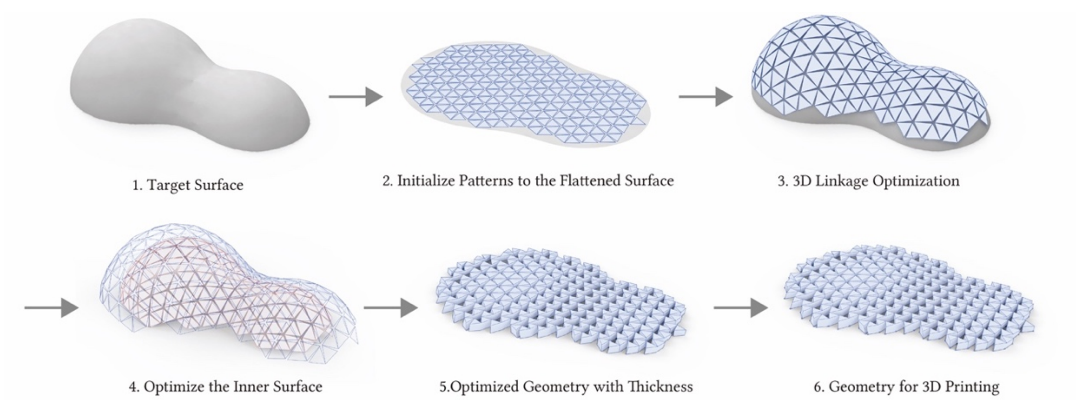

Figure 7: Sketch of the optimization procedure for computing the spatially graded auxetic linkage with thickness for a given target surface.

5.2 Fabrication

The FGF 3D printer with a 1 mm nozzle was used for 3D printing (Figure 8). We apply elastomer-based soft pellets and print skeletons. Figure 8 shows our achievements on printed flexible actuators. The use of flexible materials allows for both the movable parts of the hinge and the rigid pattern parts.

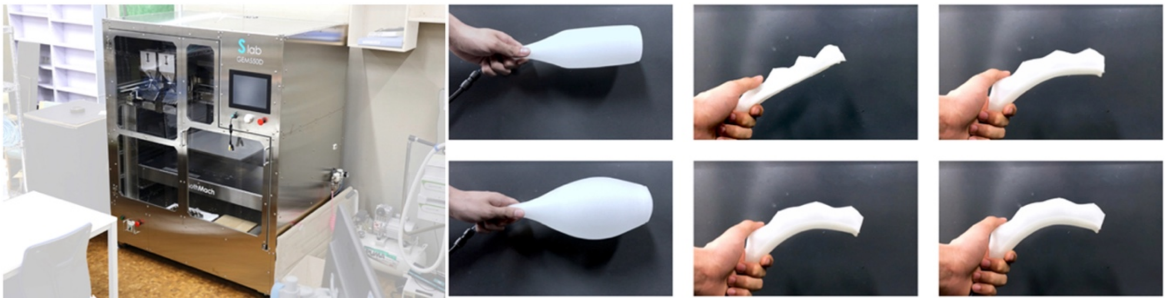

Figure 8: The FGF 3D printer called "ArchiFab irori" (left) and the sample 3D printed with TPE, being inflated (right).

Figure 9: Actuate process of Pneumatic Auxetics prototype

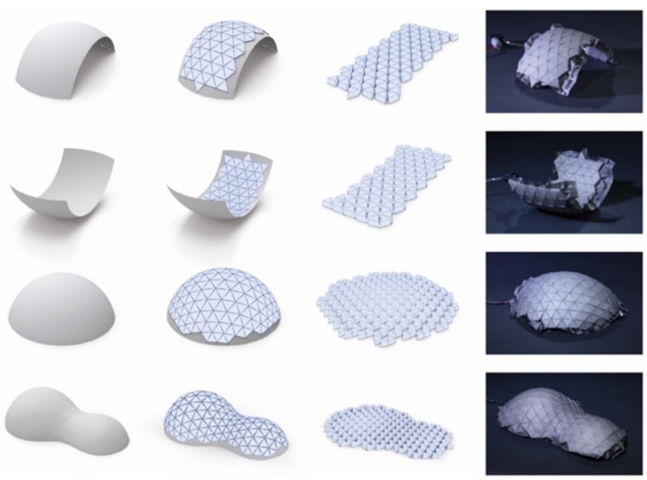

Figure 10: From left to right: input design surface, optimized linkage in folded state, data edited for 3D printing, actuated shell sample.

The 3D printed skeleton is enclosed in a TPU sheet. The TPU sheet is cut to fit the size of the skeleton and sealed by heat welding. Figure 9 shows an enclosed prototype of a 3D printed skeletal structure. In this 500mm size model, when we removed air from the sheet at a pressure of about -5kPa, membranes were gradually deformed into the stubby target shape. When we removed air from the sheet at a pressure of about -42kPa, it finally became a target three-dimensional shape. Figure 10 shows several examples of our deployable auxetic shells computed with the optimization algorithm.

6 APPLICATION

Figure 11 illustrates the potential of our method for medical applications. For this example, the patient's knee is 3D scanned and made into a supporter. When the air is removed, the supporter can support the knee as it morphs and stiffens by designing it to transform into the shape of the knee surface. In addition, the supporter can be softened by adjusting the pressure to remove the air. This function can be effectively used for rehabilitation.

Figure 12 illustrates the 1/5 scaled sunshade that adjusts the amount of sunlight. Pneumatic Auxetics has the feature of closing the pattern when the air is removed. This feature allows to control the amount of sunlight penetration. These membrane structures can also be inflated. Therefore, it provides transformation into three different states depending on the weather conditions.

7 CONCLUSIONS AND FUTURE WORKS

This research establishes a novel workflow for the fabrication and design of a pneumatically actuated shell, which can fold the patterns to create the target shape by adding the optimized thickness.

However, there are some limitations with Pneumatic Auxetics. One of them is the relationship between the skeleton and the membrane. While skeletons are deformed into a three-dimensional shape, membranes are still flat sheets. When the pattern deforms, the membranes wrinkle and some pattern may not deform properly. Specifically, the larger the gap between patterns are at the flat state, the easier it is for the front and back membranes to stick together. When both the back and front membranes stick together, the force applied for the deformation is obstructed. Therefore, it is necessary to pay attention to the thickness and gap of the shell. Currently, we are 3D printing and verifying the size of 400mm-600mm. Therefore, we do not know what kind of results we will get if we change the scale significantly. We are considering using a large 3D printer to

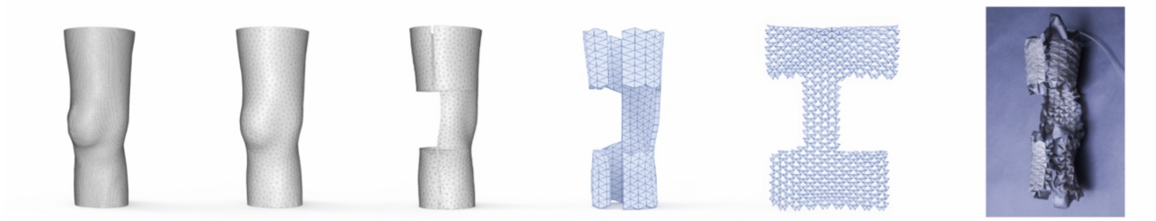

Figure 11: Pneumatic Auxetics provides support when deflated and can be adapted to the scanned surface of the patient's knee.

Figure 12: Pneumatic Auxetics provides a morphing sunshade. The amount of sunlight blockage is controlled by three different state changes: air released, inflated with air and deflated.

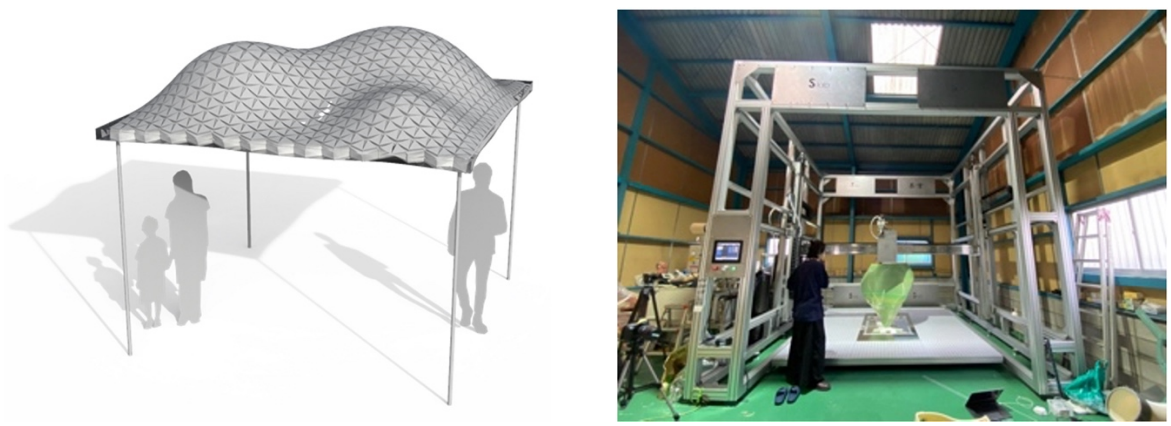

Figure 13: The 1/1 scale pneumatically actuated shell (left). Archi Fab "Chashitsu" is a large FGF 3D printer, with a build area covering 2.8m*2.8m*2.8m (right).

try to produce a 1/1 scale prototype shown in figure 13. These will allow us to study the behavioral changes when the scale changes and the loads are applied.

Furthermore, Pneumatic Auxetics has the potential to be further developed in combination with other technologies. For example, it would be possible to make a structure that interacts with the surrounding environment, by sensing the weather or temperature and automatically actuating structural morphing. It may also be possible to control movement as a colony by combining multiple independent shell structures. In addition, by 3D printing with shape memory polymers, it would be possible to actuate deformation in a 4D printing approach, which does not rely on any external stimuli.

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