Creating Auxetic Structures in Three-Dimensional Weaving

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Abstract

I use multi-layered three-dimensional loom weaving to create, explore, and learn about geometric auxetic structures for on-going work in art and design. In this paper, I will describe my initial experimentation and design method for translating and weaving one auxetic re-entrant honeycomb structure.

Introduction

Weavers often lean towards mathematical approaches to their craft, whether they are inspired by it or use it as part of their methodology. I use geometry as inspiration and a tool to explore three-dimensional woven surfaces that can be used for practical applications, including artistic expression. Conceptually, my artistic work involves simulating natural microscopic structures and systems in handwoven cloth, adding life-like movement via embedded technology. In recent years, the weaving industry has been investing research into auxetic woven microstructures, for use in biomedical, defence, and clothing fields [1]. After being introduced to the properties of auxetic structures and structural geometry [3], and fascinated by the shape activation opportunities, I explored how I could hand-weave them on a larger macro scale, using three-dimensional multi-layered techniques on a twenty-four shaft computer-aided loom. This paper aims to give insight into how I have achieved three-dimensional auxetic woven cloth, and consider further research directions.

Auxetic Structure

The geometry of auxetic structures has unusual, almost counter-intuitive properties when applied to a material. Regular materials expand in the direction we stretch them, and narrow in the middle perpendicular to the applied force direction, for example, stretching elastic. However, auxetic structures expand in both the pulled and the perpendicular directions. As a starting point in the weave design process, I chose one of the simpler auxetic structures, a re-entrant honeycomb cell [2] (Figures 1, 2), as the folds were similar to work I had previously woven, producing open hexagonal forms. Many auxetic structures depend on hinging at vertices activated by applying force or stretching the structure. The two-dimensional re-entrant honeycomb cell is a hexagon with two opposite corners folded inwards, and in this instance, I have included two lines that meet at these corners that would form part of the next cell. These lines are used to stretch the structure out, towards forming a convex hexagonal shape. By pulling these angles out, it causes the other lines coming out of the vertices to pivot, and in turn push the opposing vertices and lines, causing the shape to expand. It is important for the auxetic behaviour of the cloth that the shape is woven flat, as will be discussed further, with the four internal acute angles as close as possible to 0˚ and the two the obtuse angles as close as possible to 360˚. By using this form, I hoped to develop an understanding of the properties this two-dimensional shape would exhibit in three-dimensional woven cloth.

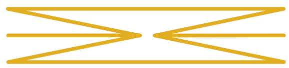

Figure 1: *Unit cell of the re-entrant honeycomb structure.*

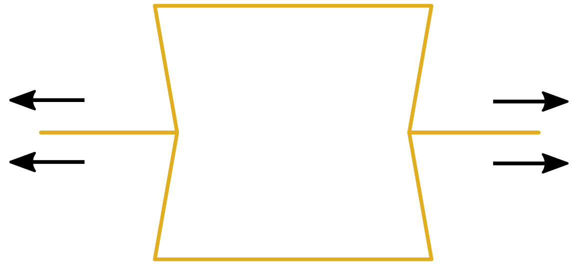

Figure 2: *Unit cell of the deformed honeycomb structure, when stretched.*

Expanding Multi-Layered Weaving for Auxetic Shapes

Loom-woven cloth always consists of a thread travelling over and under another group of perpendicular threads. The simplest structure is a plain weave, where a weft (horizontal or X-axis) thread travels over one warp thread (Y-axis) and under the next, alternating on the next weft row. Each warp thread is passed through a specified loom shaft, enabling the group lifting of particular threads. Two shafts are required to lift alternate threads for a plain weave, with adjacent warps alternately threaded through shaft one and shaft two. The weft passes between the raised and lowered threads. A standard traditional loom produces fabric on a single X, Y plane, creating pattern, texture and functionality on the largest surface area of the fabric.

The development of three-dimensional cloth has increased in the past fifty years [4]. Three-dimensional cloth such as interlocking and multi-layered fabrics are now used in industries from defence to aerospace due to weaving's flexibility, integrated strength. Artists and designers use multi-layered weaving to explore pattern design, layering metaphors, and for its sculptural qualities. Multi-layered fabrics, also referred to as 'hollow' or 'spacer' fabrics, are those where several two-dimensional surfaces are woven at the same time and usually interlock at specific points so the layers are connected as part of the whole cloth. For example, tubes and pleats are easily achieved by weaving two layers on a four shaft loom.

Multi-shaft looms offer opportunities to weave multiple layers simultaneously, one top of the other. Two shafts can produce one layer of cloth; four shafts can produce two layers of cloth and so on. Weft threads do not always need to travel the entire width of the cloth and can create folds when turned to connect to other layers. By manipulating these layers, the weaver can start to design within the depth or Z plane. As my artwork research focuses on creating with the X, Z plane of the woven cloth, my approach was to describe the lines of the two-dimensional re-entrant honeycomb cell on this plane using five layers.

Translating the cell into multi-layered cloth provided some challenges. To enable expansion when pulled, the structure is woven in its 'closed', flat folded formation (Figures 3, 4). Each straight line of the diagram represents one layer and requires separate control on the loom using two shafts each to produce a plain weave. Figure 3 shows the shaft allocation for the structure. Figure 4 shows the number and direction of the ten weft passages needed to produce one entire revolution of weft thread. The structure consists of two mirrored sections of five layers of fabric. To enable flexibility for experimentation, the five layers in on both sections needed to be controlled by separate shaft systems, hence weft passage three and eight requiring two separate shafts for each side. The central 'activation tab' lines of the diagram require four shafts (creating one layer of plain cloth with twice the density of warp and weft threads) for strength.

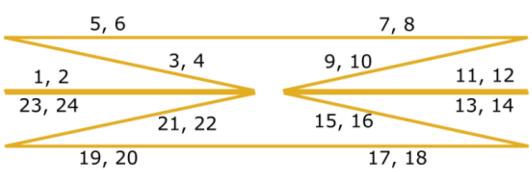

Figure 3: *Shaft allocation for the different layers to be woven*

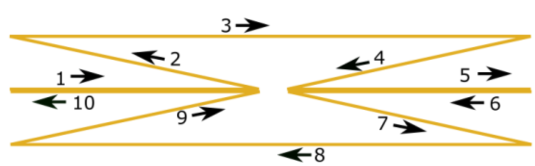

Figure 4: *Weft order and direction of a single weft passage*

Weaving is a progressive building of weft threads forming a cloth. In order for the auxetic behaviour to operate, the first and last wefts of the cell must be woven in plain weave through all layers. Layers must be arranged folded in the re-entrant, flat state. The auxetic expansion occurs in the mid-point along the length, between the ends, where the multiple layers have the most opportunity to expand. If the fabric was woven in the fully stretched position, needing only two layers, then the auxetic behaviour could not occur. When woven this way, topologically, the fully contained cell is equivalent to a sphere. The maximum expansion of the auxetic behaviour depends on the distance between these fully compressed ends. Experiments demonstrated that the longer the cell, the less contraction in the length. This also demonstrates that the structure is not auxetic in all three dimensions, only in the X, Z directions. I am continuing experiments with the terminus, exploring form and symmetric translation of the re-entrant honeycomb structure, with an aim to create a stable yet fully active fabric.

Deforming of the Three-Dimensional Structure after Weaving

The progress of hand-weaving this structure is slow, with ten separate weft insertions, as shown in Figure 4, when a regular fabric could have just one. This slowness brings with it the anticipation and satisfaction of waiting to see if an experiment has been successful (Figures 5, 6). Once removed from the loom, I explored the geometric changes emerging from the fabric structure. I pulled the tabs, and the top and bottom surfaces immediately expanded, significantly increasing the internal volume of the centre of the fabric, just as anticipated by the deformed honeycomb diagram (Figure 3). In the three-dimensional fabric, the deformed shape describes a quadrilateral at the mid-point, then tapers back into the resting shape at the beginning and end of the woven cell (Figures 7, 8, 9).

For this experiment, I used fine hand-dyed nylon monofilament, a similar thickness to a human hair. This thread was chosen for its ability to hold its form, and its translucency, enabling the viewer to see through the multiple layers of fabric. The weaving was 75mm wide (X-axis), 125mm long (Y-axis) and had a depth (Z-axis) of approximately 3mm. A gentle 35mm pull on both sides of the tabs produced a 57mm (1,900%) expansion in the fabric's depth (Z axis). Conversely, there was a slight decrease in the length (Y-axis) of 20mm (16%).

Table 1: *Changes in the fabric dimensions comparing resting and deformed*

	Width: Weft direction (X-axis)	Length: Warp direction (Y-axis)	Depth (Z-axis)
Resting	75mm	125mm	~3mm
Deformed	150mm	105mm	~60mm

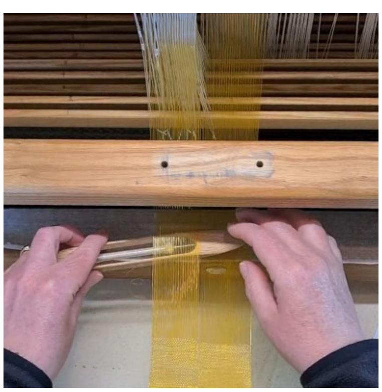

Figure 5: *Weaving in progress.*

Figure 6: *Testing the structure on the loom.*

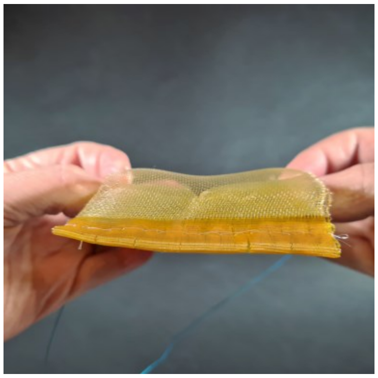

Figure 7: *View of the fabric, relaxed, from the X, Z plane.*

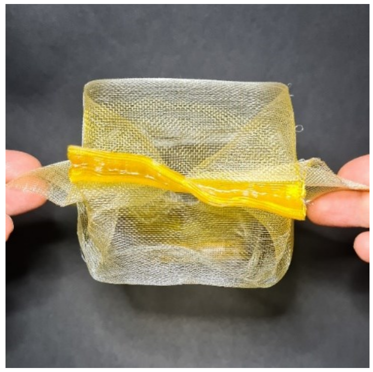

Figure 8: *View of the fabric, stretched, from the X, Z plane, showing the expansion.*

Figure 9: *View of the fabric, stretched, looking at the X, Y plane, showing the stretched direction.*

Conclusion

My experiments using a two-dimensional auxetic structure to produce a three-dimensional fabric have provided a positive proof-of-concept for future investigations and artwork. Since this experiment, I have activated the cell using shape memory alloy, creating woven artwork with the appearance of a 'breathing' entity. These conceptual artworks mimic a mesmerising sleeping creature taking a breath on activation and slowly releasing air as the structure relaxes back into the deflated state. The cellular geometry of auxetic shapes has led to my investigation of integrated movements within woven cloth, with future developments including audience-influenced algorithmic 'artificial life' concepts. In addition to the movement effects, and due to the diaphanous layering created by the auxetic weaving method and specialised threads, the woven colours blend into abstract shapes which morph with activation and the viewer's perspective. For example, when observed from different angles, blue areas overlay yellow threads, creating shades of green forms; yellow layers pass over red, displaying fields of warm oranges. By learning about the geometry of auxetics through art and weaving, mathematics has inspired and informed my experiments and art practice into new dimensions. As a result, these fabric developments continue to expand.

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