Customized Knit Membrane Deployable Hyperboloid Tower

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Abstract. Deployable structures have become increasingly popular due to their ability to transform from a compact form into a larger structure. They are also typically lightweight, resulting in a lower carbon footprint than heavy permanent building methods. These structures are popular within the field of architecture, as well as in robotics, aerospace engineering, and other fields.

This paper explores the design and development of a deployable hyperboloid structure with a connected knitted membrane. The knitted material is specifically designed to stretch and fit the transforming geometry of the hyperboloid. This is achieved by manipulating the types of yarn used across the membrane, as well as the number of short rows in the knit material, to create a more specified material. The design for this material was developed using Rhino3d and Grasshopper. Throughout the design and fabrication process, there was a feedback loop between the digital design models and physical material test samples to ensure that the knit would fit the final hyperboloid structure. The result is a two-meter-tall structure when upright and a two-meter-diameter circle when collapsed, with a knit membrane that supports the structure and transforms seamlessly by stretching and shrinking to the different shapes of transformation.

Keywords: Deployable structures · Hyperboloid · Transformable structures · Knitting · Computational design

1 Introduction

This paper provides an exploration of the design and development process of a deployable hyperboloid structure connected to a specified knitted membrane. It references precedent examples of deployable and lightweight structures, as well as examples of structures that utilize knitted membranes.

Compared to woven materials, knitted membranes offer elastic properties that are advantageous in this type of transformable application. The design pattern for this specified knitted membrane is developed using Grasshopper and Rhino3D, with a back-and-forth process between testing materials and digital simulations. The resulting membrane is knitted manually on a domestic Brother knitting machine using two different yarn types. The outcome is a two-meter-tall structure when erect and a two-meter-diameter circle when collapsed, with a knit membrane that supports the structure and seamlessly transforms by stretching and shrinking to the different forms.

C. Yan et al. (Eds.): CDRF 2023, *Phygital Intelligence*, pp. 433–442, 2024.
https://doi.org/10.1007/978-981-99-8405-3_36

2 Deployable Structures

Deployable structures are structures that can easily be assembled and disassembled quickly, making them ideal for temporary or mobile applications. Dating back to nomadic cultures that used deployable and portable structures for shelter (Rivas-Adrover 2015).

Folded and jointed structures are often made of linear members and use a membrane or fabric to create an enclosure (Guest 1994). Deployable structures find use in a wide range of applications, such as military operations, disaster relief efforts, events and festivals, as well as space exploration (Rivas-Adrover 2015).

Deployable structures are also typically lightweight, utilizing textile membranes for enclosure, resulting in a lower carbon footprint than heavy permanent building methods.

2.1 Deployable Structures Examples

Some of the best examples of deployable structures come from Buckminster Fuller's designs for geodesic domes. These structures consist of interconnected triangles, which are repeatable and easy to assemble and disassemble (Buckminster Fuller 1982).

More recently, Chuck Hobermen has developed designs using scissor structures, which can expand and collapse needing no assembly on site. Most known for his Hoberman sphere, but he has developed many geometries including domes and arches (Kronenburg and Klassen 2006).

The advantages of expandable structures is that they require less assembly on site and can be assembled off site and collapsed down to a small form for transportation and brought to a site and expanded to their larger deployed form.

2.2 Hyperbolic Structures

A ruled hyperbolic lattice structure is mathematical construct in three-dimensional space that consist of straight lines intersecting each other (Beckh 2015). The Hyperbolic lattice geometry is created by dividing a bottom and top circle into equal parts, with the number of divisions determining the number of lines required to construct the hyperbolic form (Maden 2015). Moreover, there are a few parameters of note to design a deployable hyperbolic structure. First is the length of the lines. Second is the number of lines, which is determined by the divisions of the circle, and third is the rotation angle of the lines.

In the example shown here an 8-division circle creates an octahedral hyperbolic form. The lines shifted clockwise and counter-clockwise directions along the division nodes define the crossing lattice structure.

It is important to note that the shift angle effect the resulting shape of the hyperbolic structure. For instance, a 0° shift will produce vertical lines and a cylindrical form, while a 180° shift will not result in a hyperbolic shape, but in two cone shapes (Maden 2015). Therefore, depending on these parameters there are only a limited number of possible shifted angles to create a desired hyperbolic shape. See Fig. 1.

When using consistent line lengths, the size of the circle must change based on the number of shifts as well. See Fig. 2. This results in more crossing of the lines as well as a more apparent hyperbolic curvature in the shape.

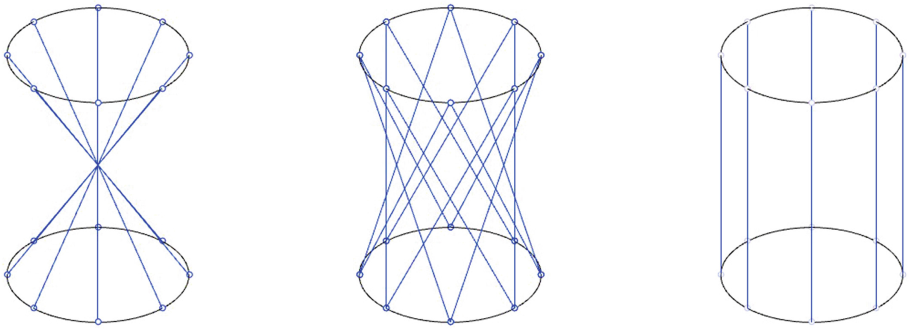

Fig. 1. Different hyperboloid designs based on different shift positions from 180° to 0°.

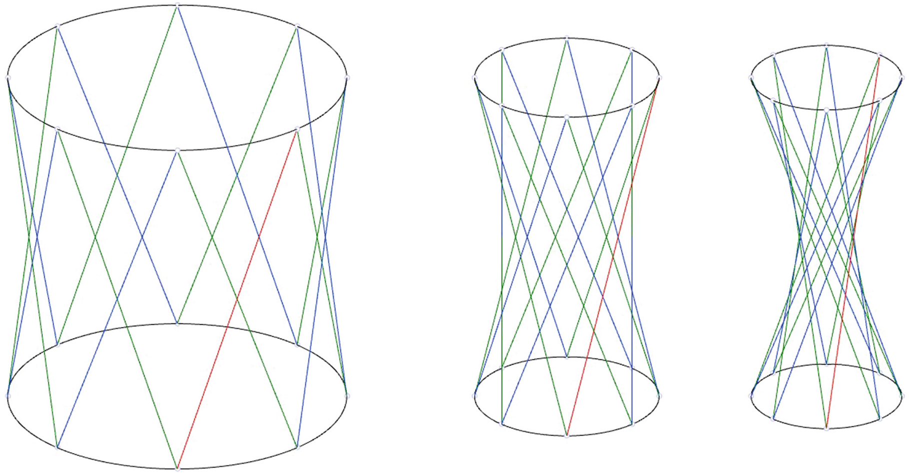

Fig. 2. Different hyperboloid designs based on different twist shifts between the bottom circles to the top with consistent line lengths.

Lastly when looking at deployable hyperbolic forms, the line length remains the same while the circle sizes expand and contract causing the structure to transform from an erect position to a collapsed circle position. See Fig. 3.

This collapsing form is advantageous for a deployable structure as there are two collapsed shapes where the form becomes flat and small for transportation. It can be collapsed fully in the erect position as a vertical set of lines or as flat circle. This can be advantageous for shipping and transporting in a flat form. While once at a desired location can be deployed into the more three dimensional positions.

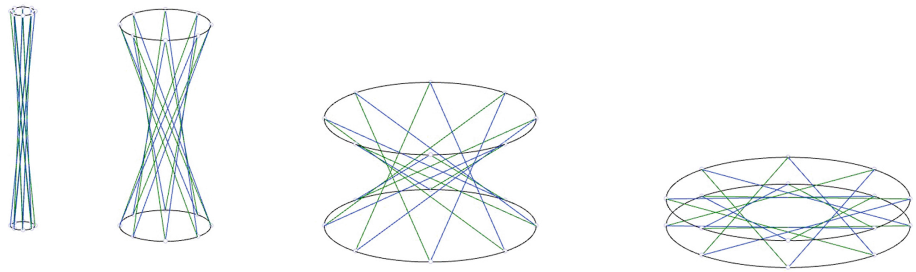

Fig. 3. Consistent line lengths and shifted angles resulting in a change in base circle size.

3 Knitted Membrane

To create enclosure on many folding and scissor structures membranes are used. Due to the transformative shape of the hyperbolic form, a membrane, which has some flexibility to stretch, was necessary. Knitted fabrics are formed by interlocking rows of yarn in loops. The interlocking rows of loops result in a flexible and stretchy material, unlike woven material, which are constructed of a warp and weft, made from separate yarns, and only elasticity is dependent on the material properties rather than the structure.

The stretch in knitted material is due to the structure of how the loops are interlocked. When a knitted material is stretched, the loops in the material are pulled and the yarn shifts and slips, causing the loops to elongate or shrink depending on the forces. Once the force is released, the loops shift back to their original relaxed state (Samuel Poincloux et al. 2018).

Like other elastic materials, knitted materials have a positive Poisson Ratio, meaning that when stretched in one direction they get thinner in the other. This property is very useful specifically when looking at the type of shape shifting that the hyperbolic form takes as it is collapsed from erect position to a collapsed position.

The elasticity of a knitted material can also be adjusted by changing the size and tension of the loops. For example, a material with larger and looser loops will be stretchier than a material with smaller and tighter loops.

Furthermore, different yarn types will inherently have their own elastic properties depending on the materials it is made of. For example yarns such as cotton have very little stretch while acrylic and wool have more amount of stretch. However, synthetic yarns using nylon and elastic materials can have a quite lot of stretch to over 4 times their resting length.

Also unlike woven materials, which use a warp and weft, knitted materials can also be shaped into different specific geometries by adjusting the number of stitches per row through narrowing or widening. As well as using a technique called short rows, which do not go all the way across the knit row to make different number of stiches on one side of the material compared to the other. See Fig. 4.

Overall, knitted material is a versatile and flexible material that can be customized to suit a wide range of applications. Its stretchiness and elasticity make it particularly useful for applications where flexibility and movement are important.

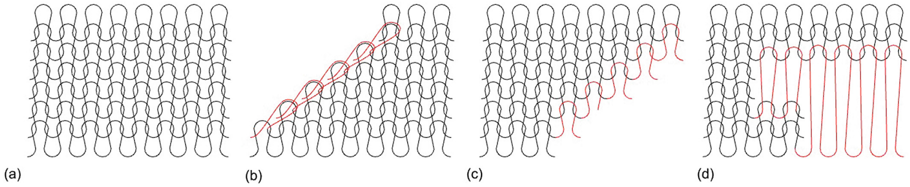

Fig. 4. **a** Normal Kitting **b** Narrowing, **c** Widening, **d** Short rows.

4 Design Process

The process for designing a prototype for the deployable ruled lattice hyperbolic tower used a process of computational design modeling to design and prepare a knitting pattern to be fabricated. When working with knit materials, the dimensions of a small swatch sample of that material are used as data and measurements to be input into the digital modeling to calculate the resulting number of stitches need for a full pattern of the final design to be fabricated.

4.1 Grasshopper to Model Hyperbolic Form

Based on the pervious mathematical understanding of hyperbolic geometries. The design and analysis of the desired hyperbolic form was done in a Grasshopper model which could be transformed using set of determined parameters was created. The desired model would have consistent line lengths and the circle diameter and height would change as the angle between the lines to be adjusted to create the deployment. See Fig. 5.

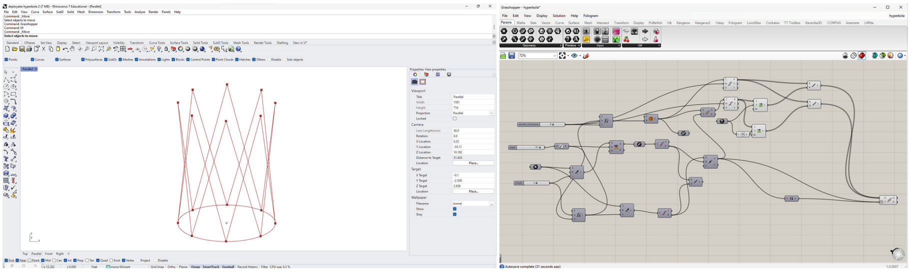

Fig. 5. Grasshopper model of a deployable ruled hyperbolic structure.

From this series of modeling a few decisions could be made on which design to build physically. First was determined which rod length to use. Based on the purchasing off the shelf rods. Standard rod dimensions were selected for the propsoal, which uses a rod length of two meters.

Secondly the number of rods to be used had to be determined. In the simulations it was shown that the more rods used the wider the resulting final diameter of the clollapsed circle would be. To keep this constraint somwhere in the middle range where the circle would not get too large compaired to its height. A decision was made to use 20 rods. This means each circle was divided into 10 divisions.

The final variable in the hyperbolic design was to select the number of rotations for the lines as difined the angle of rotation. Given a dechahedral hyperboloid, the possible shifted lenghts could be 36, 72, 108 or 144°. The decision was made to use a 108° shift so that the rods would cross 5 times and would create a curved hyperbolic shape as the form is collapsed. See Fig. 6. This would add a certain amount of deformation in the knit material to be developed.

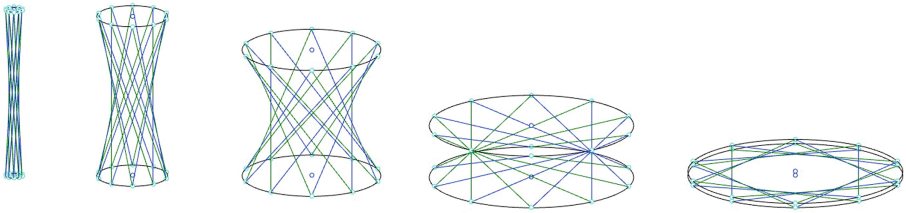

Fig. 6. Various positions of a deployment of the decahedral hyperboloid design with 10 divisions, 2 m lines, and a rotational shift of 108°.

4.2 Grasshopper to Model Membranes

The design for the knitted membrane surface was based from analysing the shift in size of the geometry from start position, as erect, to the end position, as completely flat. This was done by extracting the triangle meshes at the various stages in the design. When fully erect the size could reach almost zero so it was determined to use an almost erect state as the base, which would be more realistic given the material thickness of the rods.

Each face of the geometry could be broken down into isosceles triangles between the rods. In the erect state, these triangles would be very skinny where the height would be much more than the width of their base. Meanwhile in the flattened end position the triangles would be an obtuse isosceles triangle. The amount of deformation between these triangles was calculated to estimate the material transformation needed. See Fig. 7.

4.3 Knitting Design

To develop the actually dimensions of the knitted material to fit these the hyperboloid the size of the triangles were measured at the different states, and compared with sample knit materials. Different yarns were tested and stretched in each direction. These swatch samples used a base dimension of 60 stitches along 60 rows to get an estimate of a sample stitch size when stretched height wise and width wise.

Material swatches were made with different stitch lengths and different yarns. Each of the different material swatches were measured to see the amount of transformation, which occurred. The amount of deformation in the middle triangles of the geometry is much less that of the triangle at the top and bottom of the structure. This meant that there was a need for a larger deformation in that region of the membrane design.

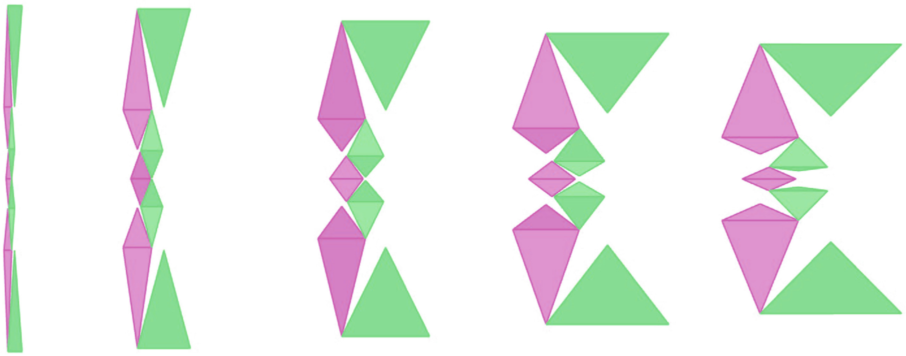

Fig. 7. Triangular panels at different stages of deformation from the proposed hyperbolic structure in Grasshopper.

The decision was then to use a 2/28NM acrylic yarn. 2 meaning 2 ply which is that 2 single yarns have been spun into 2 plies. Two-ply yarn is better than single ply because the ply twist offsets the torque inherent in a single yarn. 28NM meaning that 28 m of single ply yarn weighs 1 g. This is a common and readily available yarn. The color red was chosen to make it contrast the other yarn, which would be used. From the knitted swatch samples of this yarn a decision to use a mid-range stitch size of 5 was decided. This would allow for a decent amount of elastic properties in the knit. In the samples a tighter stitch length such as 1 did not allow for enough stretch. Meanwhile a stitch length of 10 would have resulted in too loose of a knit, given the yarn weight, causing lots of dropped stitches as well as too much porosity and transparency.

The shaping to create a circle from the knit design utilized short rows of nylon elastic yarn. The Nylon Elastic yarn used was LP-20C which is heavier weight and has a elastic core with nylon threads spun over it. In the swatch samples due to the yarns properties to stretch during knitting and shrink back to a relaxed state after, the swatches at small stitch lengths became very tight and did not stretch much. Although the thinness of the yarn a stitch length of 10 allowed it to still knit tightly and have quite a bit a stretch still available after knitted.

The amount of elastic material and pattern for this nylon material was calculated from the surface of the flattened geometry in grasshopper to determine how many extra rows were needed. This calculation created an irregular pattern which was then simplified in to a regular pattern, using Grasshopper, that would be more repetitive and easier to knit. Here by each line in the final pattern design is represented by a partial movement of the yarn carriage to the left and right. The blue lines represented the acrylic yarn and the pink lines the nylon. See Fig. 8.

5 Fabrication and Result

The final fabrication and construction of the two meter tall hyperbolic tower was divided into construction of the lattice structure made of 2 m by 8 mm thick Glass Fiber Rods (GFR) strut structure and by attaching the specifically designed knit membrane. In addition, using very few materials for the final structure the process of fabrication took a

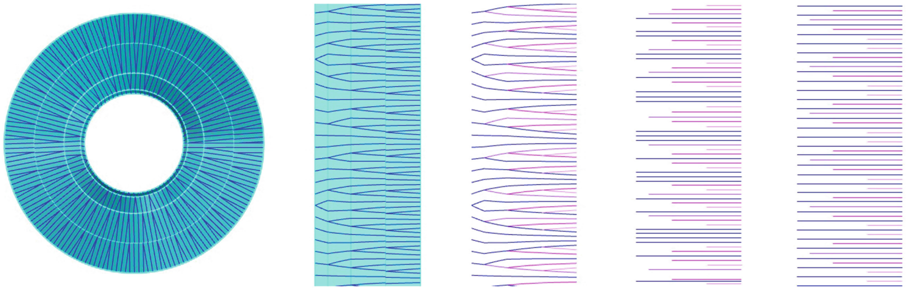

Fig. 8. Grasshopper development of short row and yarn patterns from the circular surface to knit short row design.

few days to fabricate the materials and attach it to the lattice structure. Once fabrication was complete, the deployment was a matter of pushing on the structure to transform its shape.

5.1 Knitting Fabrication

The knit material was constructed out of the simplified repeating pattern. The design for this pattern was printed on a piece of paper to help guide the knitter while making the design. Which needed little more information than how many short rows to make each length and when to switch materials.

Knitted on a Brother Ameno kh836-e domestic knitting machine, most of the design was to be manipulated by hand. The knit started with four rows of red acrylic yarn knitted with stitch size 5. To create the short rows several needles were moved to the hold position and the knitting carriage set to allow for partial knitting. The stitch length is then changed to 10 for when to knit the elastic yarn, and the yarn is knit for 4 rows at time across the partial needle bed.

The resulting fabrics was a total of 1560 rows in each panel. In addition, it took a total of 5 h to knit each panel. Because of the size of the knitting machine, it had to be knit in two panels, one for the top half and one for the bottom half. The two panels were then hand sewn together after being attached to the frame.

5.2 Result

The final structure was able to easily stand on its own in a balanced state both mostly erect position and once collapsed into a circle shape. The knit material was well calculated that when it is erect it is stretched height wise and has very little wrinkles and the elastic yarn is constricted into a small stripe which also causes a sort of pleating effect in the material. When the structure is pushed down the knit begins to stretch more width wise and the white elastic yarn begins to stretch more than the red acrylic yarn, exposing the pattern of the short row design to make the expanded circular shape.

This stretch in the yarn also creates more transparency as the holes from the loops open up and become wider allowing more light to be able to penetrate through. While when the knit is the more erect position, the holes are smaller and stretched vertical creating more enclosure and less light to penetrate.

Moreover, the tension in the yarn and the sticks provides the structure with balanced compression and tension and when the design is compressed to a certain height, it holds its shape at that height and position. Creating different stationary positions for the design rather than the expected possibility that the design would be more relaxed in one state. See Fig. 9.

Fig. 9. Completed tower design fabricated design at various different positions.

6 Conclusion

The final design proves the successful prototype of the ruled hyperbolic deployable structure. The advantage to which it is very light weight and can completely collapse into a flat circular form or a vertical linear form to be easily transported. The design is also lightweight and can deployed by a single person at this scale. The result was of a highly collaborative and iterative design process, which made use of advanced modeling techniques in Rhino3D and Grasshopper. Using material sampling to determine the different size and types of materials to be used. Furthermore, using that information to develop a pattern that could be knitted based on the defined needs for the specified material transformation. The materials design were specifically generated to achieve the desired shape and performance characteristics to transform from a small vertical form to a flat circular form. The hyperboloid lattice structure, which was connected to a knitted membrane, was designed to also be lightweight and have specific qualities of how the number of struts and crosses needed to provide support and form.

The resulting structure was two-meters tall when upright and 2-m round when collapsed, and the knit material was able to transform with this shape change by stretching and shrinking. The success of this prototype demonstrates the potential of advanced modeling techniques and materials to push the boundaries of what is possible in architectural design and construction.

With further research and development, such structures could have a wide range of applications, from temporary shelters to large-scale buildings that transform as well as possible infrastructure. Furthermore, the study into deployable structures with knitted membranes provide many opportunities to provided enclosure and to be transformable and stretch with the shape-change of the geometry while it is in different positions.

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