TOWARDS A TOOL KIT FOR MEMBRANE TENSEGRITY SHELLS

Exploring The Relationship Between Struts And Geometry

LANCE MARCO YU[1], YING YI TAN[2], SACHIN SEAN GUPTA[3], and KENNETH JOSEPH TRACY[4]
[1,2,3,4]*Singapore University of Technology and Design.*
[1]*lance_yu@mymail.sutd.edu.sg, 0000-0002-1043-4801*
[2]*yingyi_tan@sutd.edu.sg, 0000-0003-0545-7061*
[3]*sachin.sean.gupta@gmail.com, 0000-0003-4978-7740*
[4]*kenneth_tracy@sutd.edu.sg, 0000-0002-5143-6053*

Abstract. Our paper demonstrates a computational design workflow that creates and maps optimal 2D strut layouts based on input 3D shell geometries that function as membrane tensegrity shell (MTS) structures suitable for human occupancy. This workflow links conformal mapping, structural analysis, and optimisation algorithms to iterate through a series of strut layout parameters. From these layouts, we generate digital MTS models that, under structural loading, closely match their respective target models. We validate this workflow across five different geometries and this has produced low average local deviations that range between 47 to 65 mm, proving that our workflow is viable for non-standardised wide-spanning (8.0m) shell geometries with openings.

Keywords. Membrane Tensegrity, Conformal Mapping, Optimisation, Computational Design Workflow.

1. Introduction

Membrane tensegrity shells (MTS) belong to a novel structural typology which employs the principle of tensegrity to create self-supporting shell-like spatial enclosures. It uses a network of discontinuous linear members to tension a continuous membrane surface instead of individual cables that are typically used in tensegrity systems. These interconnected components can maintain a static equilibrium of tension and compression forces to create free-spanning curved spaces without needing intermediate columns. Moreover, in comparison to other existing membrane shelter systems like pole or frame tents, MTS enables the creation of doubly curved enclosures without relying on curved elements manufactured using stiffer materials. This broadens design freedom while easing manufacturing processes and costs in the making of non-standardised spaces.

In our team's research, we are currently exploring how MTS can be used as deployable shelters by designing a kit-of-parts that can be prefabricated and assembled quickly on-site. This has manifested in two built prototype pavilions of: (i) a Bamboo tensegrity shell of up to 5.0m span and 2.6m height using bamboo struts and knit stretch fabric (Tracy, et. al., 2019); (ii) a Knit tensegrity shell of up to 3.5m span and 3.0m height using carbon fiber tubes and a customised machine-knitted elastane with polyethylene pockets (Gupta, et al., 2020).

While these have proven to be successful demonstrators, these pavilions required months of extensive iterative prototyping before they could be realised on a larger scale. We believe that this prototyping process could have been reduced in duration by improving our computational design workflow to more accurately simulate the final form of the pavilions under real-life loading conditions. In particular, we hypothesize that by understanding the relationship between the arrangement of the struts and its resultant geometry, designers will be able create strut configurations that best suit a given input shell geometry. Thus, we ask the following research question, "How can we derive optimal strut layouts, leveraging on structural analysis, that are suitable for an input non-standardised curved shell geometry viable as a MTS structure fit for human occupancy?"

We tackle this question by systematically exploring the design space using conformal mapping, structural analysis and optimisation algorithms to produce strut layouts that create simulated resultant geometries that closely match the input models. This builds upon previous research by streamlining the computational processes to be able to quickly iterate strut arrangements to identify the optimal layout which, when pretensioning the membrane at specific locations and subjecting the structure to simulated loads, can maintain its geometry with minimal average local deviations from its target model. Our goal is to develop a computational design tool that can generate ideal strut configurations for large-scale MTS structures suitable for human occupancy. This takes into account requirements of spatial (i.e. headroom for openings, volumes for programmes), structural (i.e. gravitational and wind), fabrication and assembly (i.e. manageable sizes of struts, number of struts). From an architectural standpoint, this would also consider non-standardised geometries, which may be challenging for MTS structures since membrane tensegrity geometries are currently limited to repeated tessellated shapes (Gupta, et. al., 2020, Peña, et. al., 2011). Thus, this computational tool would present a first step in designing strut layouts for MTS geometries with arbitrary and freeform curvatures.

1.1. LITERATURE REVIEW

The resultant shape of a Membrane Tensegrity Shell is dependent on a complex interplay of forces between the network of compressive struts and continuous tensile members. However, understanding the structural behaviour of MTS is a non-trivial endavour as the continuous elastic membrane has inherent non-linear mechanical performance and the disconnected struts are suspended in 3D space by the membrane. While iterative prototyping has been the go-to convention to relate how strut placement determines geometry, designers and researchers have moved towards more computational-driven means to design MTS systems, namely: (i) Rationalisation of the geometric form into tessellable shapes and/or (ii) Computational form-finding and optimisation methods. The literature featured here focuses on enclosure-based MTS systems which either use strategy (i) or a combination of both strategies (i) and (ii).

MTS structures can be rationalised into a series of modular repeatable strut units that pretension the membrane surface into a 3D polygon. As demonstrated in earlier works by Shigematsu, et al., (2009) and Peña, et. al., (2011), these can be represented as interconnected building blocks that agglomerate to affect the overall geometry. One prominent example is the MOOM pavilion (C+A, 2011) where the designers referenced a 'water bomb' origami pattern and positioned the compressive aluminium struts at the alternating ridges of the pattern. Feng (2019) adopted this principle and developed several speculative computational design strategies such as: (a) populating interconnected tetrahedrons along a curve; (b) remeshing an input 3D freeform surface to map pyramids. Additionally, our previous publication catalogued the relation between strut types and output overall geometries (Tracy, et. al., 2019). This led to the selection of an overlapping reciprocal-like cross layout which biaxially tensions the fabric. The layout can be parametrically mapped onto input flat surfaces to alter the resultant MTS geometry.

On the other hand, computational methods aim to form-find the resultant geometry of the MTS under dead and live loads when a designated strut layout is used. This procedure can also be paired with optimisation algorithms to alter the geometric parameters to obtain a desired geometry. Thus, these methods provide a better understanding of which parameters of the struts and membrane have a more significant influence over the resultant geometry. This can be seen in the work of Ratschke, et. al. (2017) where they systematically adjusted several geometric parameters identified in the MOOM pavilion (e.g. strut length, overlap factor, spacing) to determine how much influence these parameters have over the load bearing performance and geometric form of the pavilion. Yang et. al., (2020) performed computational form-finding and structural analysis of their 'memboo' structure using the K2Engineering plug-in combined with the optimisation plug-in Octopus to adjust the depth and width of their geometry. This ensured that all their bamboo struts were in compression to avoid slippage from the membrane, maintaining a self-supported pavilion in static equilibrium.

1.2. COMPUTATIONAL WORKFLOW AND RESARCH OBJECTIVES

Our research improves upon our former workflow (Gupta, et. al., 2020) and adopts a combination of the two types of strategies. This paper expands on the computational aspect of the current workflow as shown in Figure 1.

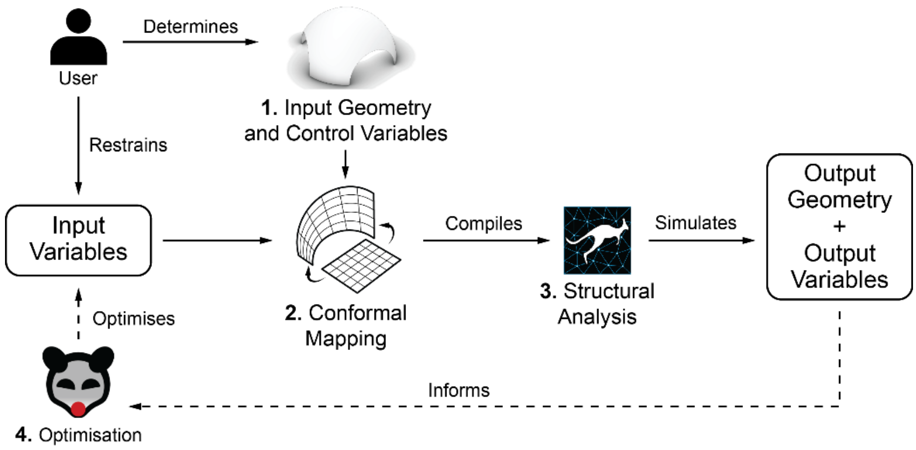

Figure 1. Overview of methodology.

Firstly, a user inputs a shell geometry and the script will employ a conformal mapping algorithm to map an initial layout of struts. Next, a Delaunay mesh will be generated from the struts' endpoints and this will be converted into a cable-net model for non-linear finite element analysis under gravitational and wind loads. Once analysed, the model will be compared to the original input geometry to identify regions of localised deviation. Lastly, the Radial Based Optimisation (RBOpt) algorithm will iteratively search the strut placement parameters (e.g. strut size, rotation angle, x/y positions) to reduce the average deviation. The result is an ideal strut layout with the least deviation from its target geometry.

Our research objectives can be summarised as: (1) to develop a computational design workflow to map, analyse and optimise strut layout configurations based on input non-standardised shell geometries with openings, and (2) To assess this workflow across three different typologies of shell geometries.

2. Methods

Our workflow can be categorised into four main steps, namely: (1) Geometry Generation; (2) Conformal Mapping; (3) Structural Analysis; and (4) Optimisation. This section will breakdown the different steps and how they contribute to the ideal strut layout.

2.1. GEOMETRY GENERATION

In this work, we decided on three dome-like geometric typologies. We chose these geometries due to their positive gaussian curvatures, making them more appropriate as self-supporting MTS structures. As our work investigates the application of MTS as large wide-spanning (~8.0m) structures which are suitable for human occupancy, we listed the following constraints for the base forms of each typology: (a) Domes must have a minimum of 4.0m radius; (b) Openings must have a minimum of 2.0m height.

2.2. CONFORMAL MAPPING

In this work, the strut layout starts as a 2D grid of crosses formed by two discrete struts placed perpendicular on top of one another. This arrangement allows each strut-cross pair to support compressive forces in their respective local X and Y planes. When considering the strategy to map the struts to the input 3D surface, we chose the conformal mapping method to preserve the angles between the crosses which ensures the efficient distribution of compressive forces throughout the membrane surface. This references the algorithm and workflow adopted by Song, et. al. (2013) in mapping reciprocal frames to freeform shell geometries. Another consideration is to create strut patterns with manageable components. We impose a constraint on the lengths and quantity of struts that the script can explore to produce components of manageable dimensions and amount when fabricated and installed in real life. Our script parametrises the starting position and arrangement of struts, namely the length of the struts, the struts' rotational axis, and the position of axes (Fig. 2). These will serve as input parameters for the optimisation algorithm in step 3.

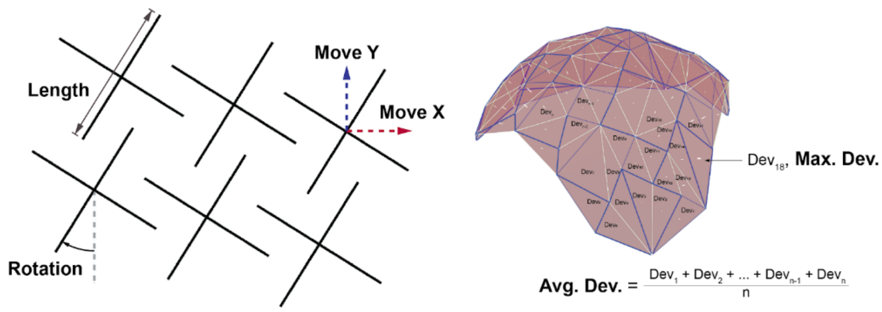

Figure 2. Input and output variables.

2.3. STRUCTURAL ANALYSIS

Once the algorithm generates the optimal strut positions based on the input variables, we analysed the model using K2 Engineering (2021) - a structural engineering plugin by Cecilie Brandt that specialises in form-active structures and can simulate non-linear behaviour with large deformations together with Kangaroo. Our script simplifies the membrane tensegrity shell into a cable-net system based on the endpoints of the mapped struts. It then assigns material properties to the membrane surface and the struts. We assume the membrane as a network of rectangular cross-sections, as seam locations, assigned to each mesh edge of the cable-net to represent the membrane surface. This membrane interacts with the struts which are assigned as aluminum hollow tubes. These material property attributions are seen in Table 1.

Type	Material	Cross-Section	Density	Young's Modulus	Pretension
Struts	Aluminium	Hollow tube (59.7 mm2)	2720 kg/m3	68.9 GPa	N/A
Membrane	Laminated Polyester	Rectangular (39.4 mm2)	1.75 kg/m3	3.5 GPa	1000 N

Table 1. Material properties of struts and membrane.

Our script applies loads to the model, namely gravity under self-weight and a simplified wind load (20m/s in the global x- and y-directions). We then connected K2 Engineering to the Zombie Solver from Kangaroo with a high maximum iterations of 50,000, tolerance of 0.01 and threshold of 1.0 e-10. The Zombie solver reduces computational time and resources when paired with the optimiser in the next step while the high iteration count ensures that the simulated model would converge at the change of any input parameter. The key output from this analysis was the local average and maximum deviations between the simulated model and the input mesh. We derived these values by projecting lines from the centroids of the mesh faces of the simulated model, based on the normal vector, to intersect with the input mesh. Our script then extracts the distance of this projected line as the deviation and calculates the average and identifies the maximum deviation across all the different models.

2.4. OPTIMISATION

The optimisation step uses OPtimisatiOn Solver with SUrrogate Models (OPOSSUM), a black box optimiser based on the radial based optimisation algorithm (Wortmann, 2017). This iterates the given input parameters of the strut layout to find the lowest average deviation from the input mesh geometry. We set OPOSSUM to run through a maximum of 2000 iterations for each input geometry with a limit of 1500 iterations without improvement. We performed this step for three separate runs to check that the parameters do not converge within local minima and that the optimiser identifies the most ideal set of parameters.

3. Results and Discussion

We tested the workflow against 3 types of curved shell geometries:

1. Dome with 2 openings
    a. Wide front leg
    b. Narrow front leg
2. Dome with 3 openings and equally sized legs
3. Lofted domes with 2 openings
    a. Opening in front and back
    b. Opening in front and side

These different geometry typologies can be seen in Figure 3.

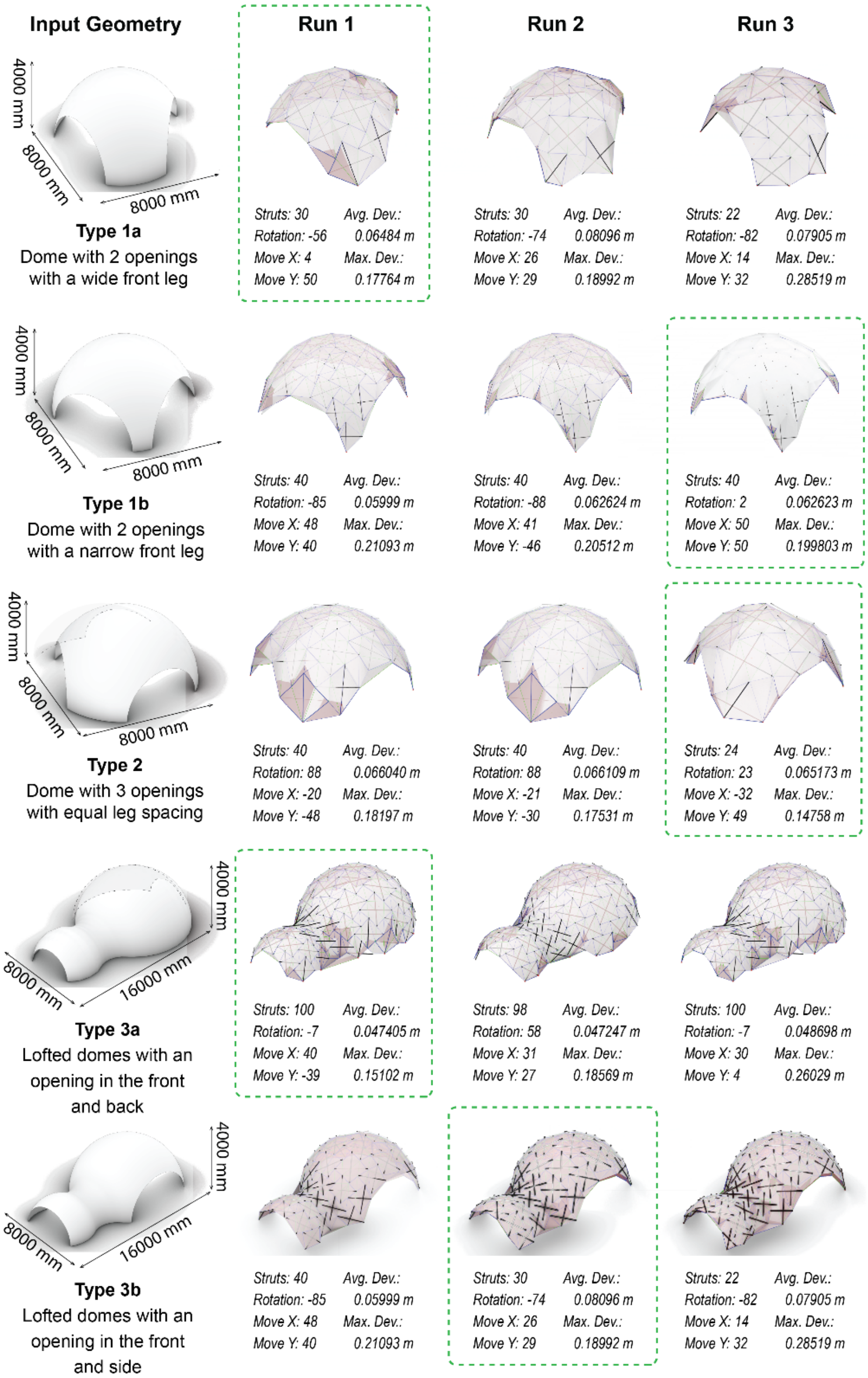

Figure 3. Optimised iterations for each geometry

The average deviation from the input meshes across the five different geometries ranges between 47mm (geometry 3a) to 65mm (geometry 2). The maximum deviations range from 148mm (geometry 2) to 234mm (geometry 3b). This demonstrates a good match between the simulated geometries produced by the optimised strut configurations in comparison with the intended input geometry. Thus, it proves that our computational design workflow can successfully identify the optimal set of strut parameters to minimise local deviations. Moreover, the average deviation values are consistent across the three runs per set which indicates that the optimisation step can identify the ideal set of strut parameters for non-standardised geometries. Each run took 45 minutes on average with an average of 1700 iterations to achieve these results.

Comparing the input strut parameters to output deviation values shows that the lengths of the struts, or total number of struts, do not affect the average and maximum deviations. This is evident in geometries 2 and 3b which have a lower number of struts than the others in their group, yet they produce resultant geometries with the lowest average and maximum deviations across the three runs. Additionally, while having a higher number of shorter struts could provide a more accurate mapping onto the 3D curved surface, it could also increase the overall self-weight of the system and would cause the MTS to deform more under gravity and increase overall deviations. Conversely, there are no discernible correlations between the other strut positioning parameters, such as rotation, move x and move y. This may be due to the parameters being dependent on one another in minimising the overall deviations of the resultant simulated model.

Analysing the output values across the three base geometries, we observe that the complexity or asymmetry of the input geometry does not influence the average deviation but more so its maximum deviation. An example is geometry type 3, which has a comparatively complex form of two merged domes with positive and negative curvatures. In this type, geometries 3a and 3b generally have lower average deviations than the other geometry types, but 3b has the highest maximum deviation possibly due to the asymmetry of its openings' positions.

4. Conclusion

Understanding how the strut parameters influence the membrane tensegrity geometry is a non-trivial process due to a multitude of input parameters needed to be considered in the search for an ideal strut layout of a given non-standardised geometry. Our paper simplifies this search by developing a computational design workflow and assessing it across 3 different shell geometry typologies. This computational design workflow links conformal mapping, structural analysis and optimisation to generate ideal strut layouts based on an input geometry. After undergoing structural analysis, we show that it is possible to obtain an average local deviation that ranges between 47 to 65 mm across these different tested geometries within relatively short optimisation runs. Thus, the consistency of these results across the multiple geometry types validates that our workflow can produce strut layouts from non-standardised wide-spanning shell geometries with openings.

However, there is still room to improve the mapping and analysis aspect of this workflow by matching its real-life scenario. The fundamental disparity between the digital model and reality is that the struts are initially mapped as lines without material thickness. This would be problematic when considering that the aluminum pipes, for larger assemblies, would have fairly thick cross sections and we would need to consider whether the pipes are welded in-plane to form a single cross or stacked as separate disconnected struts. Thus, we would need to consider the fabrication procedure of these strut crosses in order to create and simulate a digital model that more closely simulates reality. Furthermore, we used a simplified wind loading condition for the analysis which does not consider more complex phenomena like uplift. Thus, a more realistic wind simulation would need to be considered in the future structural analysis step.

In addition to this, we plan to advance this research through several directions: (i) Developing this script to generate fabrication instructions by extracting the dimensions of struts and membrane cutting pattern automatically after the strut layout is confirmed; (ii) Large scale prototyping of a human-scale MTS pavilion based on the ideal strut layout; (iii) Translating the computational tool to be more user-friendly and ready for use within an online platform.

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