PNEULASTICS, pneumatically activated differentiated stretchable membranes

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PNEULASTICS, pneumatically activated differentiated stretchable membranes

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Abstract

The object of this research is the design of *pneulastics*, initially flat, pneumatically activated stretchable membranes with areas of differentiated thickness- and therefore elasticity- that respond with a different expansion rate and create complex tension conditions on their surface when sealed and pneumatically inflated. Previous work [1],[2],[4] has already shown interest in the analysis and acquisition of control over the geometry of inflatable structures, by introducing tension conditions upon the uniform pressure stresses, by means of additional third members other than air and membrane that raise the complexity of the structure. Other precedents [3] manage to embody constraints in pneumatic activation, laying emphasis on the activation itself rather than the final shape. *Pneulastics* introduce the integration of active material strategies in order to encode the differentiated activation into one single skin. With a series of physical experimentations that confirm the initial hypothesis, that *pneulastics* can provide a wide range of doubly curved shapes, we empirically decipher and describe material behaviour into digital simulation. Starting with a target shape input, our design method translates curvature and topology into flat membrane configuration that may lead upon inflation to the best approximation of the initial shape.

Keywords: pneumatic activation, inflatable structures, elasticity, auxetic material, target shape approximation

1. Introduction

Pneulastics attempt to produce complex geometries of double curvatures, both convex and concave in one single skin, out of the pneumatic activation of initially flat elastic membranes. Based on the hypothesis that stretchable membranes of differentiated cross sections (and therefore elasticity rates) across their surface may distend to consequently differentiated extents when sealed and inflated, we try to extend the capacity in form-finding of inflatable structures that tend to adapt to spherical shapes due to the uniform stresses applied vertically on the surface of plain, non-expandable membranes.

A complex tension-compression system is developed between areas of the same surface that distend to non-linearly different extents due to the different modulus of elasticity and thickness when forced by the same differential of pressure. Thicker zones act as compression borders for their neighbouring thinner ones, and on that very condition form emerges.

The aim is the control over pneumatic activation so as to map elasticity and thickness onto flat uninflated elements, thus inverting the inflation process. This controlled deformation has to remain within the limits of tolerance of the membrane, in order to be reversible, avoid failure or plastic deformation and maintain the flat original configuration when air pressure is no longer provided.

The reinforced zones replace external tensor elements, seen often as cables, in large span pneumatic structures. Surface stresses are accumulated on the reinforced thicker zones, which by definition have higher tolerance to tension. This integrated, compact skin solution eliminates the need for developing complex tensor nodes. In natural systems, performance variation and multifunctionality are often achieved with one single material, where active properties are inherent, as opposed to manmade ones with their distinct parts and multiple materials.

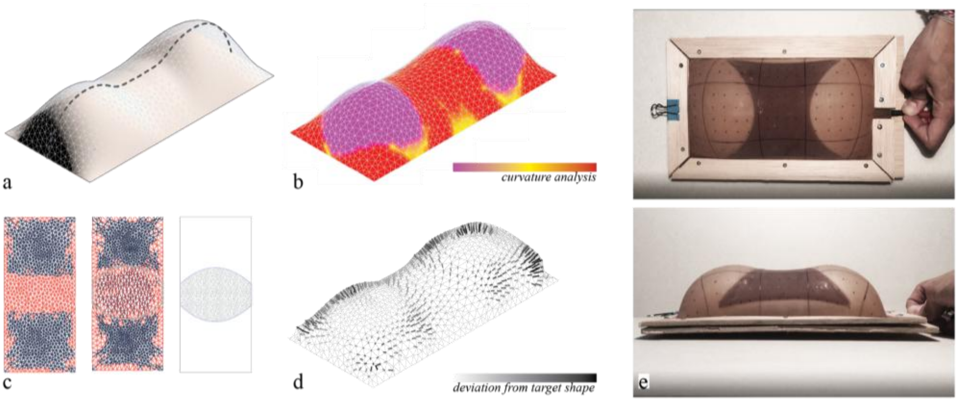

Figure 1: Pneulastics design routine: doubly curved shell as an input is discretized (a), and curvature analysis (b) isfollowed by a dynamic relaxation to a flat mesh (c), where the members of extreme negative curvature rates are marked as thick zones. Digital simulation and physical model (d & e) approximate the original form.

There is also an important simplification in the physical production of flat membranes, replacing cutting patterns of inelastic fabrics and cable-stiffening third members by a tool that translates topology into case specific local thickness of a flat membrane, that when inflated transforms into a tensile doubly curved surface. Elastic surface materials have the capacity to increase their surface up to several times their initial measure, when bi-directionally distended under tension forces. We could therefore provide a space-saving solution for the production of membranes of very large surfaces, that when fabricated only occupy a flat, relatively small and manageable footprint.

Finally, in terms of structural behaviour, given that they act as pre-stressed surfaces, pneulastic membranes demonstrate better performance against external loads, like wind, having developed very larger surface stresses that resist negative deformation due to compression stresses.

Even when pressure differential conditions constitute the interior of pneulastics inappropriate for inhabiting, their pneumatically derived form can be employed as formwork for shell structures. Comparing catenary to pneumatic forms, the catenary only ensures that the shell will endure compressive forces rather that tensile, formed by the self-weight of the cast material, supported at its ends, without accounting for bending and torsion moments.On the other hand, the pneumatic form, being the result of an outward pressure with vector forces that act upon the normal of the surface and change direction during inflation, achieves equilibrium combating wind forces.

When it comes to pneulastics as falsework, Quin and Gengnagel's ongoing research[7] with experimental measurements and FEM analysis both show that the method of pneumatically erecting a strained gridshell is feasible and more practical for simple shell shapes and curvatures, compared to the ‘lift up’ and ‘push up’ erection methods.

2. State of the art_ Current Related Work

Over the past years, there has been an increased interest in the analysis and acquisition of control over the geometry found by pneumatic activation in membrane structures. The challenge lies in defying the natural tendency of inflatables towards synclastic curvatures, as well as in the approximation of target geometries that are predetermined rather than form-found. Equally popular are the developments in the field of soft robotics, where the adjustment of pressure activates elastic elbows.

Typical methods used to achieve target geometries frequently include the use of third external elements as tensor constraints and modulations. These are met either as seams of a discretized cut pattern [1], secondary skins [2,4] or most commonly, external cables that restrain the growth of the membrane in specific “low” points[3]. In the case of elastic skins, additive manufacturing has been employed as a stiffening means [5], having material itself become the rigid condition on the zones dictated by the toolpath. However, most of these efforts focus on closed shapes with initial “resting”configurations that come from a complex mold and resemble the target[6], rather than start as planar shapes that would prove ergonomical in large architectural applications.

Our role in this evolutive thought is to integrate active material strategies and digital fabrication methods in order to embody this differentiated activation into one single multi-capable skin that initially lies flat, maintain the forementioned advantages of elastic inflatable structures in lightness, transportability, load bearing capacities and economic value, and also shorten the fabrication and assembly procedures.

3. Research Hypothesis

3.1. Bottom-up

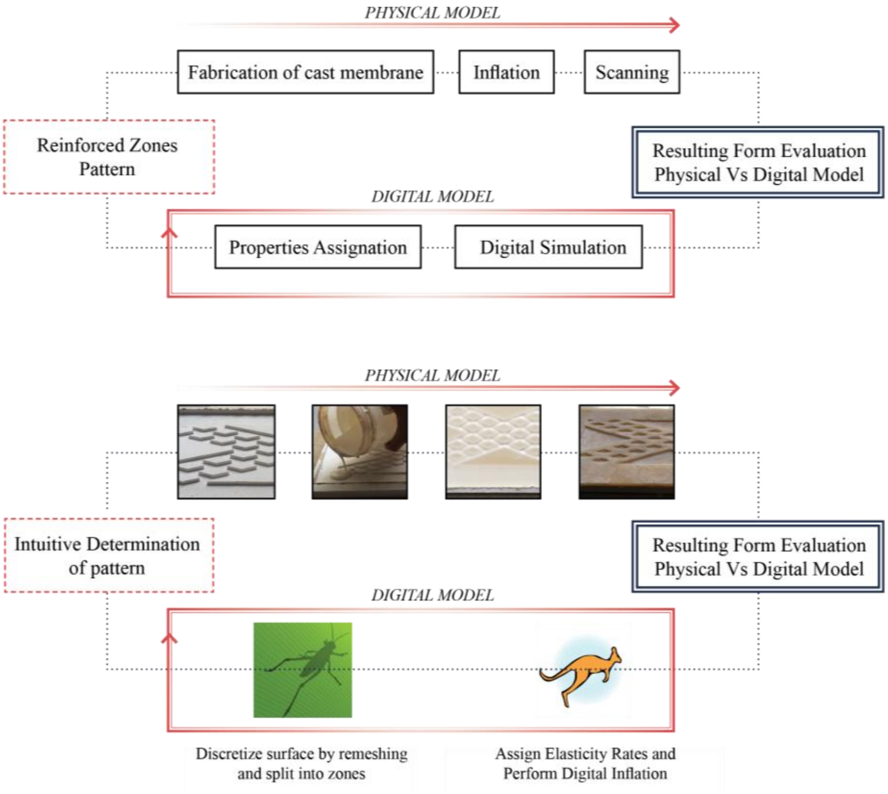

Figure 2: Intuitive bottom-up workflow and loop.

This approach includes the comparison of physical with their corresponding digital models of membranes with differentiated elasticity rates on their surface, under pneumatic activation. A first series of experiments was led by pure curiosity and the very initial binary hypothesis that on the border of the transition between two thicknesses, form and therefore negative curvature would emerge.

Material investigations and parallel digital simulations, proved the potential of reproducing the behavior of inflated cast latex membranes. With the help of Grasshopper plugin and Kangaroo by Daniel Piker, we have assigned differentiated stiffening conditions to the members of our interest. For this purpose, we have employed a plain discretized mesh with each of its elements having an assigned elasticity rate (which is translated into a freedom to deform) related to its local stiffening conditions.

Rubberlike materials have non-monotonic pressure-radius characteristic, and do not deform according to Hooke's law. However, the combination of different elasticity rates on one single surface subjected to inflation constitutes a very complex tension-compression model, which we did not hope to mathematically describe in this research.

3.1.1. Qualitative

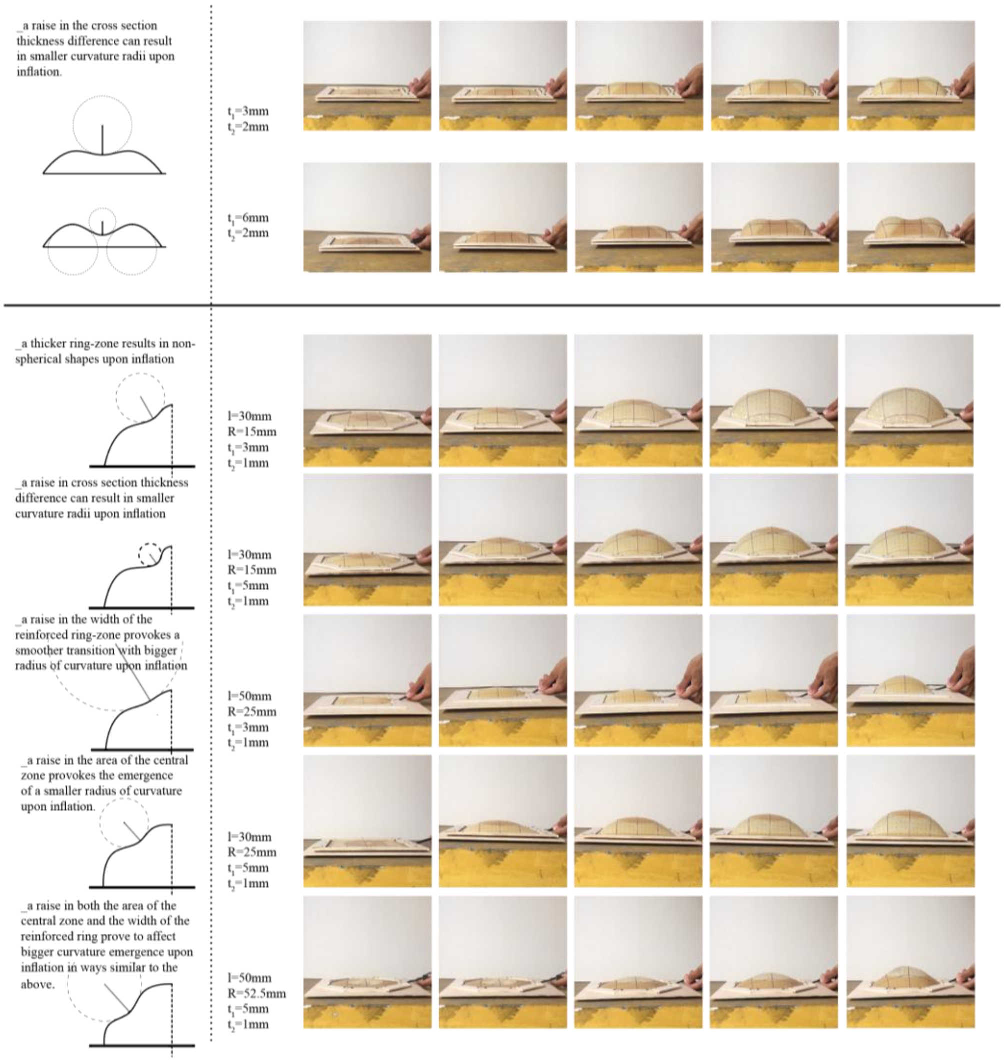

Figure 3: Quantitative hypothesis stated and checked upon with physical models of variable properties.

After getting familiar with the general principles of pneulastics'function, we asked ourselves a series of qualitative questions, to be answered by a series of material experiments:
How can a difference in thickness of the same shape perform?
How can a difference in the width of a zone affect curvature rates?

Comparing this property variation in two different configurations [Figure 3], we came to the following conclusions:

A. A transversal thickened zone can act as a tensor upon inflation, converting surface to linear stresses and transfering them to the perimetrical anchoring.
B. A thickened zone/patch may disrupt constant spherical curvature.Headings for third-level subsections, if needed, are 11pt italic [Style: Heading 3] and are numbered as shown in this example. Please do not use any further levels of subsections.

3.1.2. Quantitative

In order to describe more convincingly the pneumatic activation of pneulastics, we proceeded to a series of digital models for calibration and comparison to photogrammetric measurements of a physical inflated model. The aim of this step is to aproximate the elastic deformation seen in the latex membrane, fine-tune the representation of the differentiated inflation digitally and set a more accurate rule for our simulations.

Observing that a binary definition of stiffness (elastic-non elastic) is not realistic, we proceed to consider a functionally *graded object* depending on the distance of the boundary condition between two thicknesses. [Figure 4]

A comparative study of the results, compared to annotated points on the physical surface and their digital correspondants helped us evaluate the best simulation of the pneumatic deformation.

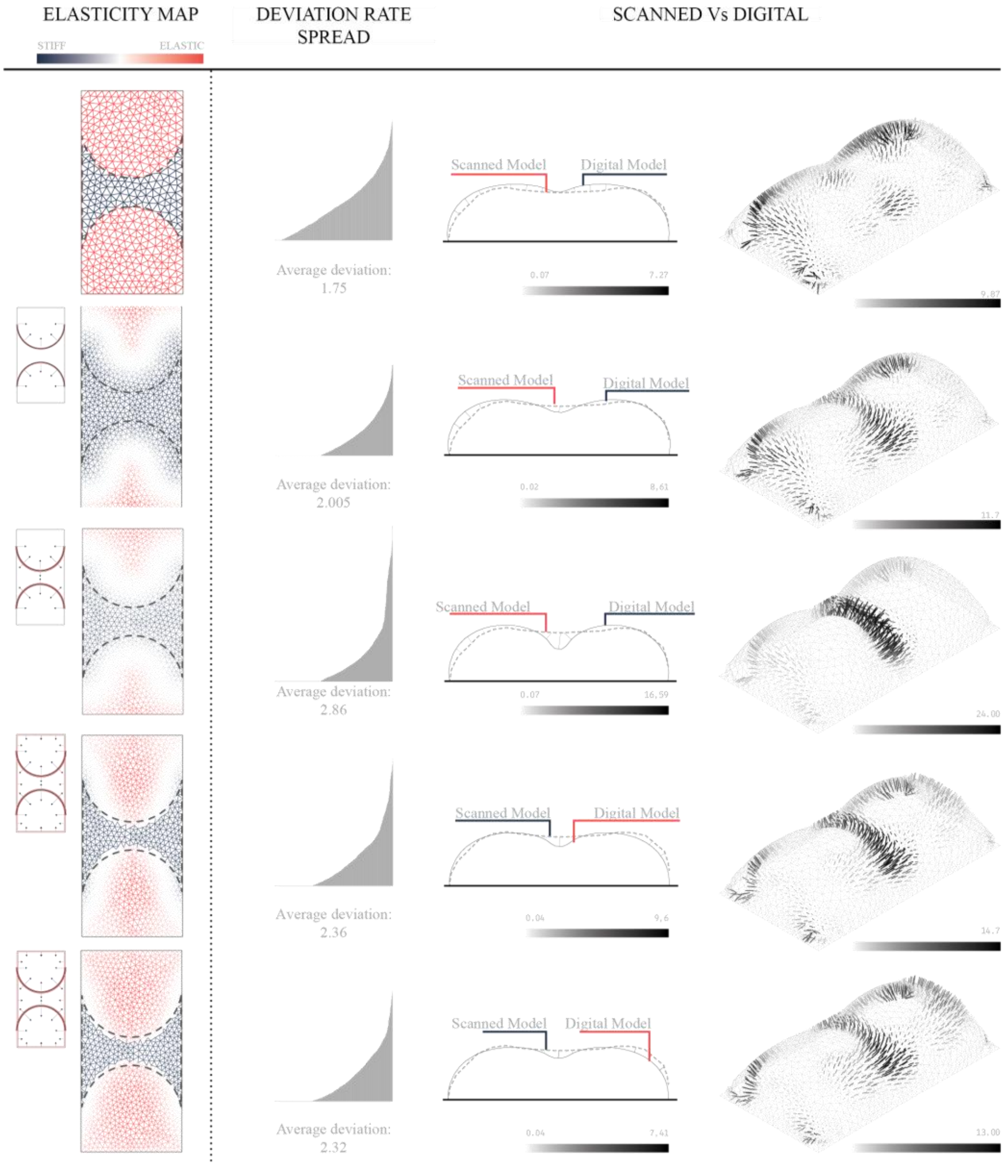

Figure 4: Gradient maps of elasticity and corresponding digital model compared to the scanned physical model.

3.2. Top Down

This approach aims to algorithmically automate the translation of an inflated geometry into a pattern for the fabrication of a differentiated cross-section, expandable membrane. It is a final step in the trajectory of our investigation that fully depends on the experimental findings that were presented.

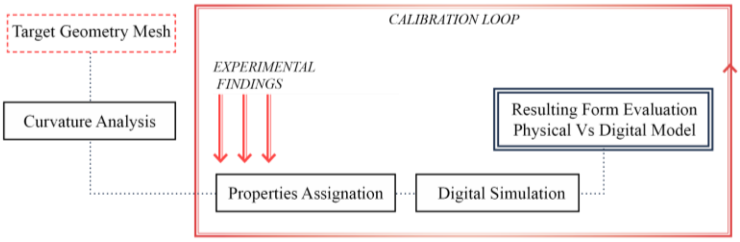

Figure 5: Systematic top down inversion of inflation process and loop.

3.2.1. Curvature-based Relaxation

A first approach starts with the mapping of the target shape on a flat configuration. A curvature analysis combined with the experimental quantitative findings of previous steps helped us redistribute the zones of elasticity on the plane.

The method begins with a curvature analysis of the mesh that is taken as an input, followed by a mapping of the distended form to a flat configuration, according to an inverted expansion mockup, that takes into account the differentiated properties of the zones marked by curvature. Here we can reverse the quantitative relations we found on the previous step.

The loop is closed with the evaluation of the digital simulation results, that may either be approximating satisfactorily the given target geometry, or not, in which case we shall return to the mapping phase and manipulate according to the error we detected the properties thickness and width of reinforced zone [Figure 6].

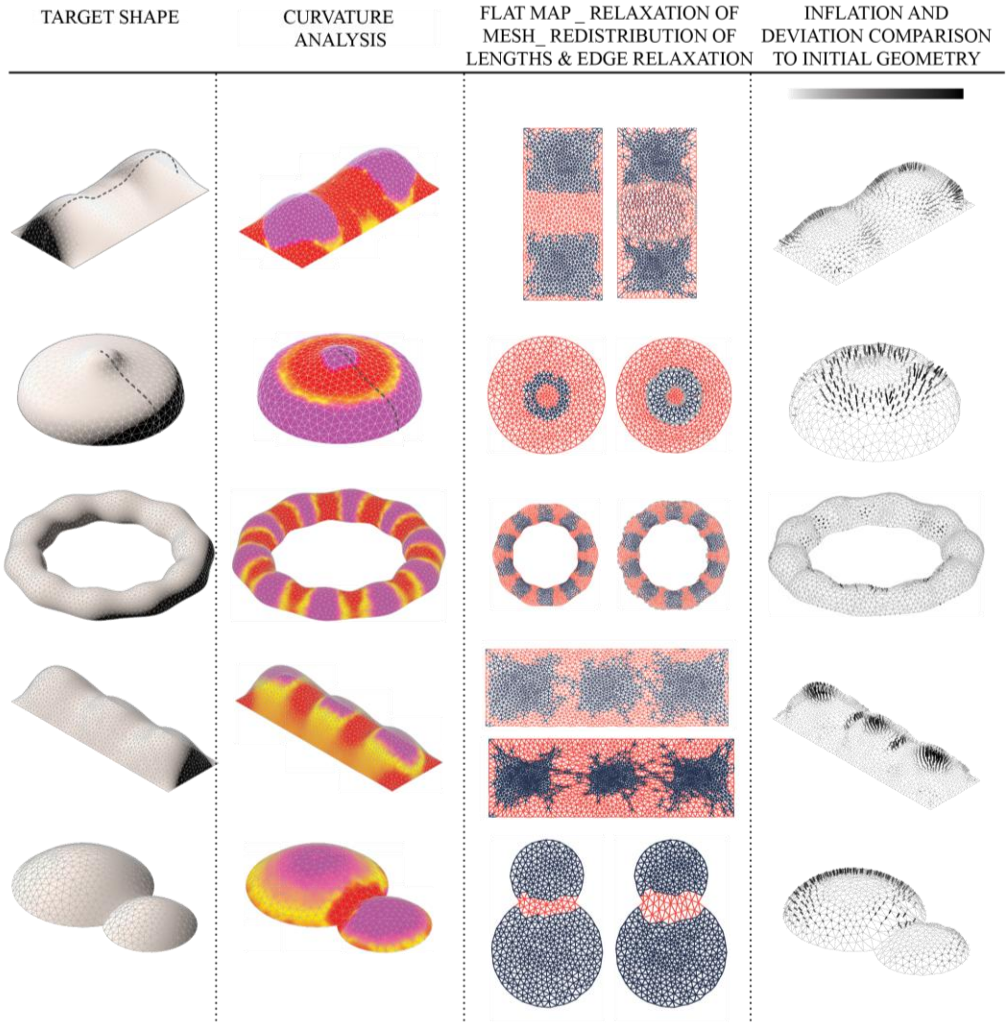

Figure 6: Method 1 applied to a series of shell shapes. These are analysed by curvature, then relaxed into a flat map, with their discrete members separated in patches. A second relaxation redistributes lengths of elastic and stiff zones, and a digital inflation will prove whether the estimation has been accurate.

3.2.2. Curvature-adaptive Remeshing

On a second hypothesis, we proceed to a curvature-adaptive remeshing of the target geometry, so that the zones of bigger stiffness are more densely populated, and therefore, when the flat mesh is relaxed, the thicker areas occupy a larger percentage of the membrane area.

Even though we find a lot of potential in this option, the current tool provided by Daniel Piker's Kangaroo cannot embody on no account the complexity of the gradient of growth that we have been trying to describe. The remeshing process includes all areas of tighter curvature, including the positive ones, and is therefore not satisfying the goals we pursue [Figure 7].

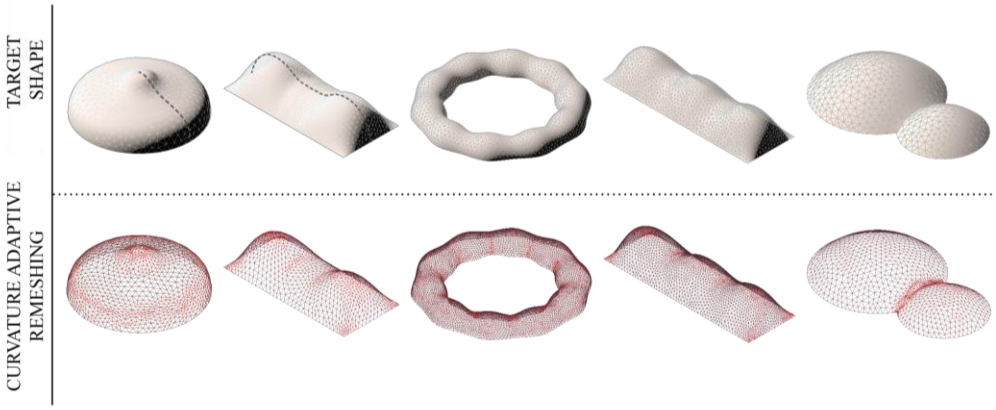

Figure 7: Curvature-adaptive remeshing raises mesh density in both positive and negative extreme rates of curvature, and therefore does not help in defining thick zone discrete members.

4. Conclusion _Results & Further Research

Our initial hypothesis was confirmed and the capacity of elastic membranes of differentiated thickness in adapting to complex geometries upon inflation was demonstrated. We have observed and quantified behaviours, until reaching a certain control over the differentiated inflation conditions and have inverted the inflation process in the format of an algorithm, in order to come up with the flat configuration of the un-distended surface that would lead to a given target shape approximation.

Transversal thickened zones act as tensors, transferring stress loads to the base, converting them from surface to linear and allowing for negative curvature capacity. Punctual zones allow for disruption and steering of the continuous spherical tendency.

This research has focused on the potential of combined elasticity/stiffness properties on a single expandable membrane, from an experimental design point of view, and has intentionally ignored the calculation of the non-linear growth of the membrane surface upon inflation, proceeding to a qualitative description of their behaviour.

We have proposed two methods for the inversion of the inflation, one of which has managed to provide us with satisfactory results-approximations of pneulastics' behaviour, while the other, based on curvature-adaptive remeshing, did not prove effective given the digital tools available at the moment. However, we consider it worth investigating and do not discard its further development.

Given the scope of architectural purposes, we have focused on shell structures and therefore open shapes. A more thorough exploration of the potential of pneulastics would require answers to the following questions: What is the design space for pneulastics? Which curvature rates can be encoded in thickness patterns? The range of feasibility for shapes that can be satisfactorily approximated by pneulastics would have to be defined.

When scaling up to architectural applications, big thickness ranges are not usual in membrane structures. We would therefore need consultation on material and fabrication alternatives that maintain the principle of embedding stiffness in one non-fragile single body, via density or other. We would also opt for a more efficient, digitally controlled and space-saving fabrication method, like an additive deposition of the elastic membrane material.

Even though the pressure differential levels required for the pneumatic activation of pneulastics are prohibitive for habitable spaces on earth conditions, the growing interest for space exploration and speculation on viability on other planets constitute pneulastics extremely relevant for pressurized spaces in conditions where external conditions of lower pressure and internal pressure don’t cancel each other.

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