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Plant-inspired Kinetic Systems for Architecture

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Abstract

This paper explores kinetic mechanisms which enable building systems with features belonging to the living systems, such as resilience and adaptivity. Adopting a bio-inspired approach, the research employs plants as biological models for the development of multi-performance kinetic structures. Nature-based kinetic principles are transferred at the micro, meso and macro scale, informing a compliant bilayer cellular membrane. Through the synthesis of environmental pressure and interior emergent requisites, an adaptable organic skin is here conceptualized to mediate environmental conditions such as energy flows and lighting in a dynamic way.

Keywords Bio-inspired Design; Computational Design; Kinetic System

INTRODUCTION

The provision of a dynamic relationship between user, building and environment has been a focal point of analysis and experimentation among architects and researchers in the last decades. Our surrounding environment, interior and exterior, is no longer considered as a stable and predictable system, but rather as one becoming increasingly dynamic, turbulent and constantly changing (Kretzer and Hovestadt 2014). Not only are architects expected to find solutions incorporating these dynamics within their designs by properly confronting the climate oscillations and the daily heat, lighting and humidity requirements, but are also encouraged to provide this through energy efficient results able to meet the growing sustainability demands. At the same time, the desire of the occupants to be directly involved in the definition of their surrounding space, implores for the creation of reconfigurable and flexible systems, granting freedom for modification. The consequent perception of the building as a mediator between external conditions and interior needs, an intermediate filter subdued to pressures and forces induced both by the surroundings and by the occupants themselves, has laid the basis for the emergent need of adaptive architectural solutions, able to incorporate a manifold of scenarios within a single multi-performative system.

Within this context the concept of kinetic system is a powerful tool for granting buildings the possibility to respond and adjust in relation to the changes around them (Schnädelbach, 2010). Aided by the development of technology, material science and computation within a convergent field, the quest for finding efficient principles for the engagement of kinetics in the architecture has motivated designers to look towards Nature as a source for dynamic solutions. The biological world has long ago developed mechanisms for its maintenance and survival within a context equally shared with the built environment. The key characteristic that enables biological organisms

to specifically react and adequately respond to stimuli, allowing them to adapt and evolve in relationship to their environment, is the ability to perform motion. This results in a versatile behaviour and functioning which sets up for multiple or even contradictory performances to exist within the same system (Schleicher 2016).

BIOMIMETIC APPROACH TOWARDS THE DEVELOPMENT OF COMPLIANT KINETIC SYSTEMS FOR ARCHITECTURE

The goal of the research, outlined in this paper, is exploring innovative kinetic mechanisms enabling buildings with features belonging to the living systems, like resilience and adaptivity. Adopting a biomimetic approach, the research employs plants as biological models for the development of multi-performative kinetic structures. Although seemingly tied into position and immobile, plants feature a rich palette of kinetic responses and ability to react to a wide variety of signals through conformational changes that require very low energy consumption (Dumais and Forterre 2012; Hensel et al. 2004). The focus here is on the compliance of the plants' kinetic mechanisms as a method for achieving strategic deformation. This property renders the motion dependent on the flexibility and elasticity of the structure, avoiding the necessity of rigid-body mechanics that can only introduce complexity and inhibit the efficiency of the kinetic system.

PLANT-INSPIRED ADAPTIVE CELLULAR MEMBRANE

The paper illustrates the computational and manufacturing processes involved in the development of a compliant bilayer cellular membrane - an actuation mechanism for shape-shifting interfaces. Through the analysis of plant movement mechanisms the aim is to transfer the sophisticated energy and material efficient motion formulas within an artificial kinetic system and provide a suggestive scenario for their application within an architectural context. For this purpose, the research

explores the micro-level cell arrangement, material organization and structural behavior of several plants serving as role models and employs Finite Element Analysis (FEA) to translate them within a double layered membrane with individually informed layer actuation. The system is based on cellular organization that allows for the individualized variation of the stiffness of each cell and thus the control of the overall curvature and topology of the membrane. A doubly layered structure permits the embedding of independent actuation within the same system, which induces variable pressures within the cells, changing the interaction between the layers and leading to differential geometry and complex movements.

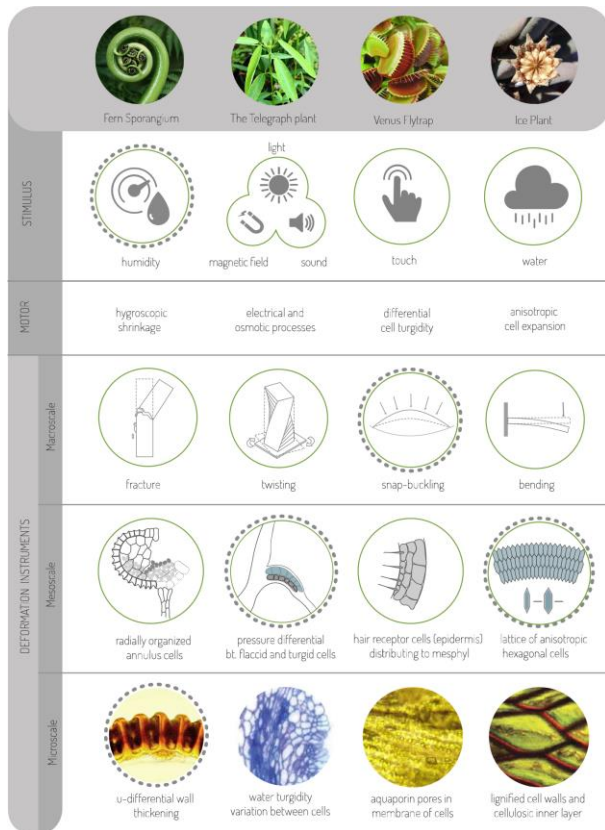


Figure 1: Schematic representation of the morphological and dynamic features of the role models. Source: authors.

METHODOLOGY

BIOLOGICAL ROLE MODELS

Five different plants are selected as role models and analyzed based on their inherent properties and distinctive kinetic mechanisms, informing the bilayer cellular membrane on three conditional organizational levels. The snap-buckling mechanism of the *Venus Flytrap* is applied as instrument for curvature direction change and typological transformation achieved on the macro-level. On a mesoscale pressure actuation mechanisms are inherited from the study of the *Telegraph plant*. The rigid-elastic material separation of the *Fern Sporangium* microscale configuration creates a U-differential shrinkage of the cells which results in bending, while the honeycomb cellular structure of the *Ice plant* is explored for allowing the membrane an anisotropic expansion in the pneumatically actuated layers (Fig. 1).

TRANSLATION OF KINETIC PRINCIPLES AND MULTI-LEVEL ORGANISATION

Each of the species features a distinct structural, morphological and material reconfiguration when undergoing motion, making the extraction of principles an essential analytical step for the achievement of the final solution. Here are defined the transfer of the stimulus and the actuation drivers, as well as the biologically inspired composition convergently uniting plant cell-organization, material logics and layer relationships (Fig. 2). The extracted mechanisms are linked in a coherent whole in order to generate the compliant system, informing it in each organizational scale:

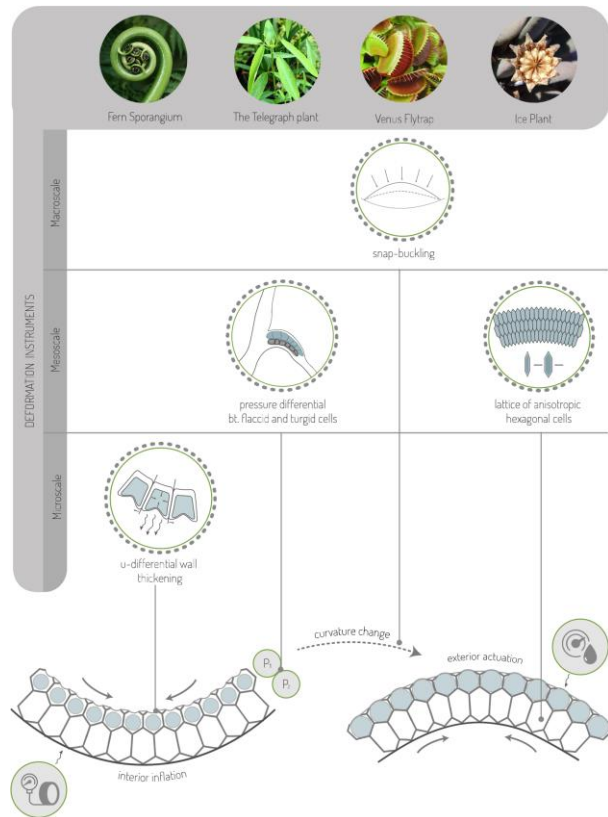


Figure 2: Schematic representation of the implemented kinetic principles and the multi-level organization of the membrane. Source: authors.

A. Macro-level - Topological studies for diverse morphological dynamics

On the macro-level are identified the morphological changes which establish the kinetics of the membrane and its dynamic behavior. In order to determine the zones of differential pressure and stiffness of the cells, a FEM analysis of the pneumatic actuation of the membrane is performed.

B. Meso-level - Pressure variation between the layers and geometrical layer coupling

The mechanism returning the structure in a horizontal position and further reversing its bending direction, based on the variation of pressure between layers, is tested in order to obtain critical stable and unstable conditions of the structure. Concurrently, the geometrical connection between the layers is examined as essential for

controlling their balancing and the curvature articulation using empirical examination and computational studies on the geometry. The balancing forces are analyzed together with the transformation of the system from concave to convex shape.

C. Micro-level - Geometrical and material organisation of the honeycomb cellular structure

Computational analysis and simulations are performed in Rhinoceros and Grasshopper to determine the optimal dimensions, aggregation strategy and connection between the honeycomb cells. The cells forming the two layers have diverse geometrical characteristics that address the different stimulus and accommodate the pressurizing pipes (Fig. 3). Passive and active material zones are assigned within each cell and, based on their relationship, is determined the degree of freedom of deformation and movement. The material differentiation is achieved through a combination of rigid and flexible segments within the same cell that allows differential expansion upon the pneumatic actuation.

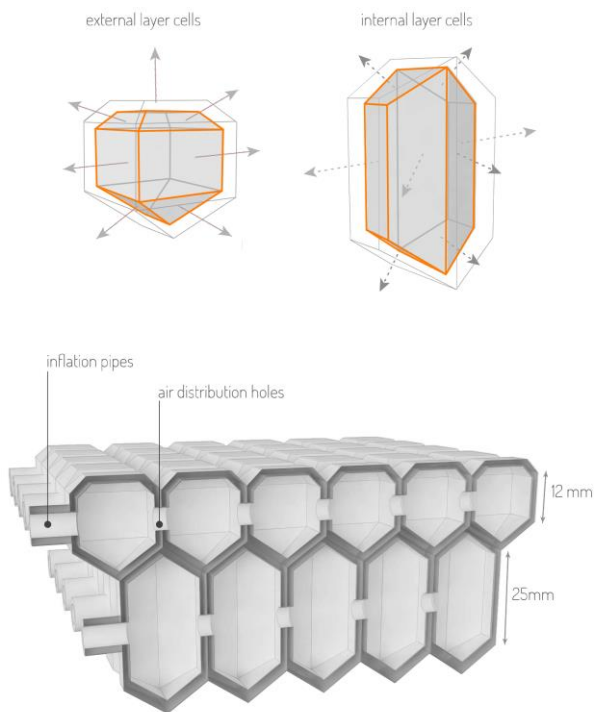


Figure 3: Geometry and cell organization of the bilayer membrane. Source: authors.

STRUCTURE

Taking into account the stimuli, the bilayer structure has been defined with a cellular composition, diverse on each side. The pulvinus of the Dancing plant shows that the entire bending of the leaflets is dependent on the differential turgor pressure of the upper and lower zone of cells (Volkov et al., 2012). In a similar way, two regions are defined, which pressure relationships are able to produce changes. The curvature shift required for the transition of the system from convex to concave shape is inspired by the structural failure of the Venus flytrap. Thus, the differential pressure in the two layers is able to reach a critical unstable intermediate position and

produce a snap-buckling, reversing the direction of bending (Li and Wang, 2016).

The geometry of the cells on both sides of the membrane have their origins in simple equilateral hexagons, considered as an ideal shape for efficient packing, which are further articulated in order to optimize their behavior and actuation with a smaller amount of energy. The external layer of the membrane is inspired by the U-differential thickening of the annulus cells of the Fern sporangium, featuring thin lateral cap allowing interaction with the environment (Noblin et al., 2012). The cell has been tailored in a similar way in order to aid the final curvature upon stimulus due to the walls' stiffness variation. The external layer, on the other side, has elongated honeycomb cell geometry inspired by the Ice plant seed capsule which is able to generate predominant expansions, due to its anisotropic behavior (Harrington et al., 2011). However, different from the plant tissue where the cells are tubular and entirely packed, here they are multifaceted, sharing their entire wall only with the sides of the neighboring cells. The multifaceted geometry of the cells, both on the interior and the exterior layer, provokes multidirectional expansion upon inflation, which can result in double curvature and permits interesting deformations of the structure.

SIMULATION AND ANALYSIS

The simulation experiments allowed for understanding the behavior of the geometry and characteristics of the membrane and the assessment of its variation possibilities. An evaluation is made of the preconceived shapes, material distribution and cellular organization which are further modified and optimized for the achievement of a more efficient inflatable structure. This analysis is conducted not considering a precise mass, forces or pressure values, but rather focuses on the "geometry of motion" in order to demonstrate the dependence of the system on the variation of certain parameters. Therefore a kinematic rather than a kinetic approach is adopted revealing the deformation potentials of the system.

TESTING OF CELL GEOMETRY

An assumption was made that even after articulating a regular hexagon and abstaining from a tubular organization the characteristics adapted from the plant material and morphological assets are going to be maintained. For the purpose, a comparison was made between a multi-faceted cell featuring equilateral hexagon in section and the two cells preconceived for the two layers (Fig. 4). The first one was trimmed in the upper part in order to accommodate a cap which would play the role of the lateral thin walls of the Fern. As observed in the resulting simulation this modification allows not only for a high percentage of inflation, but also produces a curvature even in a single layer. This implies the high efficiency potential of the geometry and also its large deformation even with the same pressure when combined with another layer.

The geometry modification for the internal side of the membrane takes advantage of the honeycomb principle of anisotropic expansion after elongation in one direction of the cell.

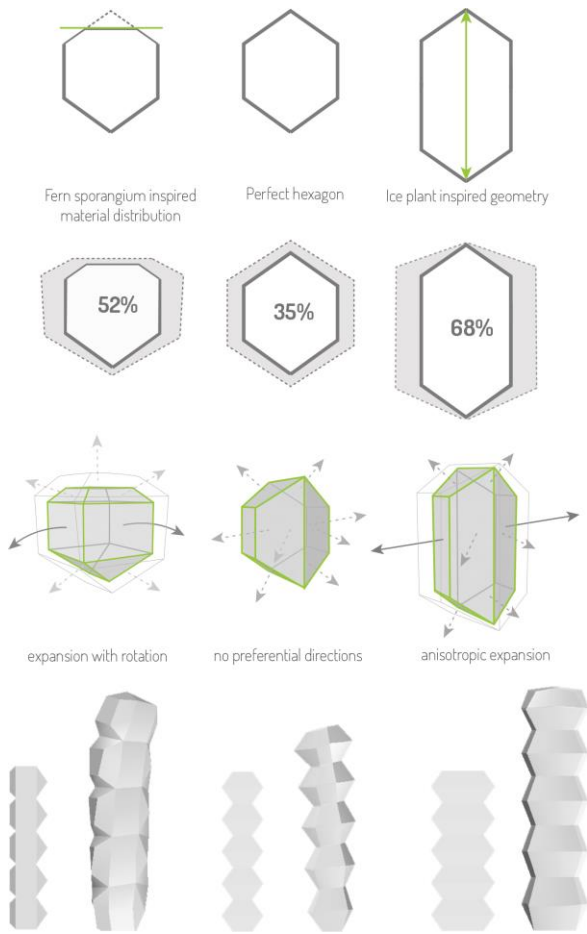


Figure 4: Cell geometry analysis. Source: authors.

As observed from the results this principle is perfectly retained in a non-tubular shape making an increase of the cell length in the X direction with 68%, almost twice more than the number obtained with the regular geometry. This suggests that a layer following this form can provide significant curvatures when attached to the other one without the need of material differentiation.

LAYER COMBINATION

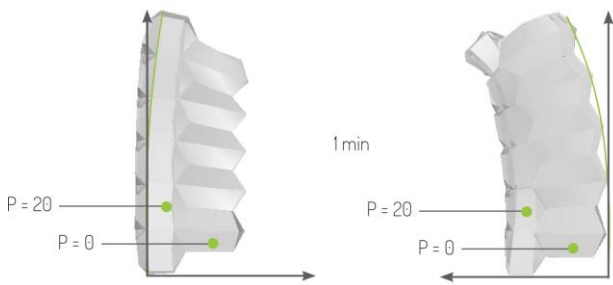


Figure 5: Layer combination and pressure variations. Source: authors.

Based upon the previous simulations and aiming to understand which of the two cell typologies is more efficient, a simulation was made inflating the small cells with pressure with a magnitude of 20, while no pressure was exerted on the other cells. Then the inverse procedure was conducted, with equal pressure inside the layer with elongated cells. The results show that the hexagonal shape supports the final curvature of the

structure better and produces a clear deformation, predicted earlier for the functioning of the membrane (Fig. 5). On the other hand seeing that the exterior layer did not produce a satisfactory result, a modification and exploration of various parameters was required explained in the following steps.

OPTIMIZATION OF EXTERIOR LAYER

Several parameters were varied regarding material distribution, stiffness, and cell geometry, which allowed for significant transformation to occur just with slight modifications. One of the most significant results is detected when comparing the curvatures after changing the extent of the u-differential thickening which translates the structure from straight to deformed. As a consequence, the material distribution becomes a critical parameter controlling the larger scale topological definition as it affects the behaviour of the cells. Furthermore, we have seen that the interior layer exhibited a better performance even if it lacked variations in material distribution, meaning that an anisotropic shape has a noticeable impact on the curvature. An elongation of the small cell walls was made which further increased the deformation (Fig. 6). These changes also led to a more regular curvature and demonstrated that it has an influence on the torsion, meaning that the shorter the cell, the bigger the twisting effect.

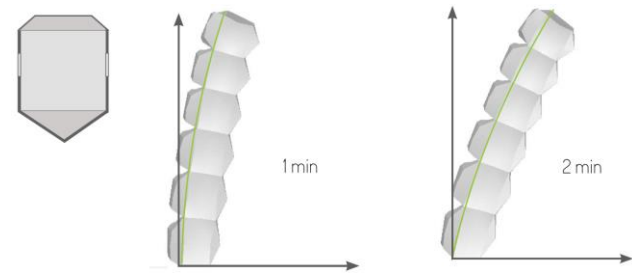


Figure 6: Cell elongation simulation. Source: authors.

After elongating the shape, a further modification was executed considering the bottom triangle walls and the angle at which they meet (Fig. 7). An assumption was made that, a smaller inclination would inhibit the deformation. Therefore a larger angle was pursued which demonstrated the expected enhancement of the bending.

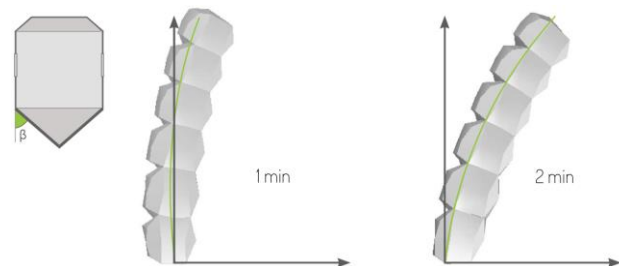


Figure 7: Bottom angle modification simulation. Source: authors.

SIMULATION OF THE OPTIMIZED STRUCTURE

The response upon inflation was significantly improved after the optimization steps. Applying little pressure in the bigger cells increased the curvature and made the shape more defined (Fig. 8). Consequent increment in the inflation force led to the conclusion that, until a certain

value, the higher the pressure of the interior layer (however always smaller than the exterior one), the smaller the curvature radius.

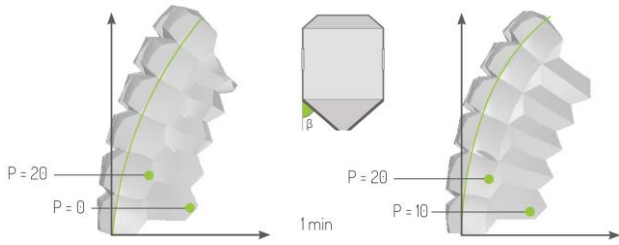


Figure 8: Simulation of pressure variation in the layers. Source: authors.

In the following step, differential pressures were provided in the two layers with a magnitude of 30 and 20 (Fig. 9). They were consequently reversed in order to understand in which of the situations we obtain a better deformation.

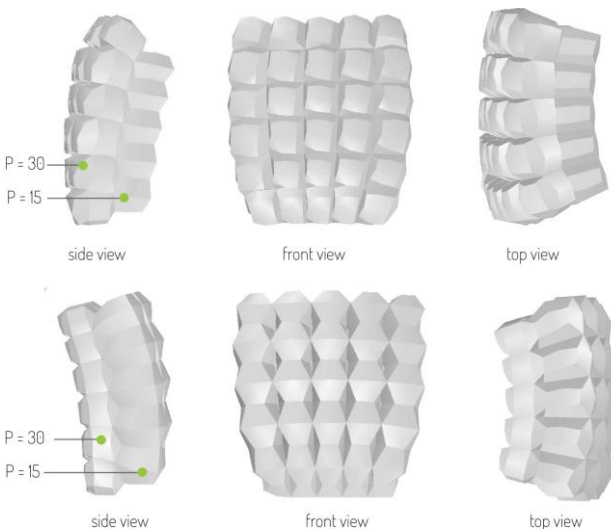


Figure 9: Simulation of pressure variation in the layers. Source: authors.

Moreover, in order to snap the structure in the opposite direction the user overriding of the interior layer should always surpass the supplied initial pressure. Thus the occupant intervention would involve only the supply of a minimum energy input, which endows the system with the pursued efficiency.

This has fundamental design implications giving multiple opportunities for the manipulation of the system. For example, the bilayer structure can be integrated in a multicomponent system in which each element has its unique geometrical and material characteristics, able to produce singular curvature. Therefore the same amount of pressure distributed to one side or another can generate a gradient of deformation or openings.

The opportunity for punctual intervention on specific points due to the non-tubular cellular organization allows for a variability of the parameters not simply from one panel to the other, but also within a single element. Therefore a multitude of curvature typologies can be achieved through tailoring specific regions of the structure differing the previously explored factors of cell elongation, wall stiffness, material distribution, and geometry.

Furthermore, even the size of the holes through which the air passes, can be varied in order to produce regions of higher inflation. Respectively, several factors can be combined for the generation of constrained zones, which are going to articulate the overall typology of the structure (Fig. 10).

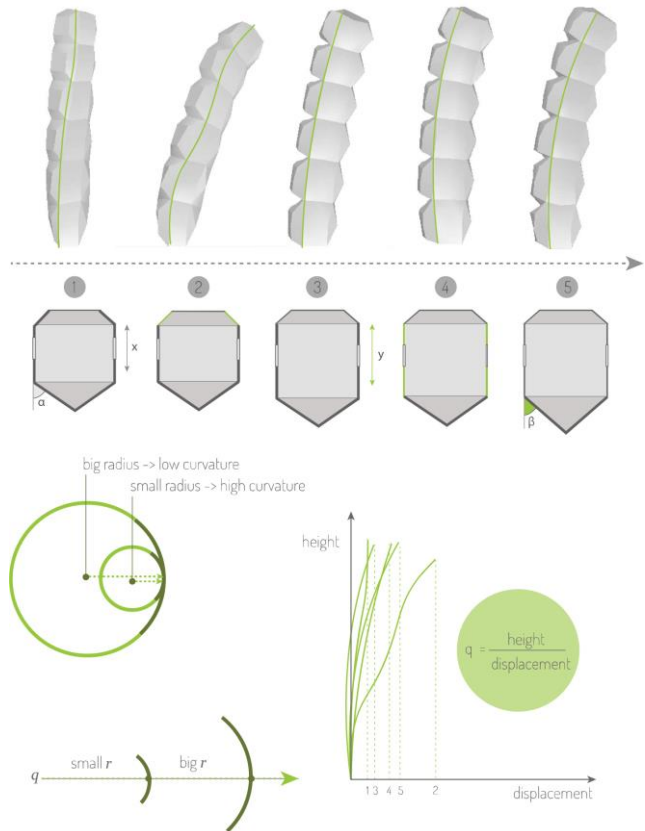


Figure 10: Curvature comparison. Source: authors.

PROTOTYPING

The fabrication of the compliant mechanism poses a number of challenges. The bilayer composition of the structure requires a connection between the two cellular sections and a void inflatable system. This in return inquires a multi-step production process. 3D printing and silicone casting have been selected as a technique for the production of prototypes to demonstrate the functionality of the membrane.

The generation of empty cellular structure requires the fabrication of its negative volume, together with the void parts around which silicone is poured (Fig. 11). To allow the effortless take-out of the voids, encapsulated in the bilayer membrane a melting substance - wax, was used. The casts for the wax voids were made out of silicone, which was poured in a 3D printed negative. A silicone of lower shore and high curing time was selected as a material for the positive part and further details were added in order to provide a proper fixing of the external and internal geometry.

CELL GEOMETRY

Both the shape of the interior (negatives) and exterior cells were varied through the empirical trials, aiming at the creation of an optimal morphology, according to the type and position of casting. For example, the wax pouring was

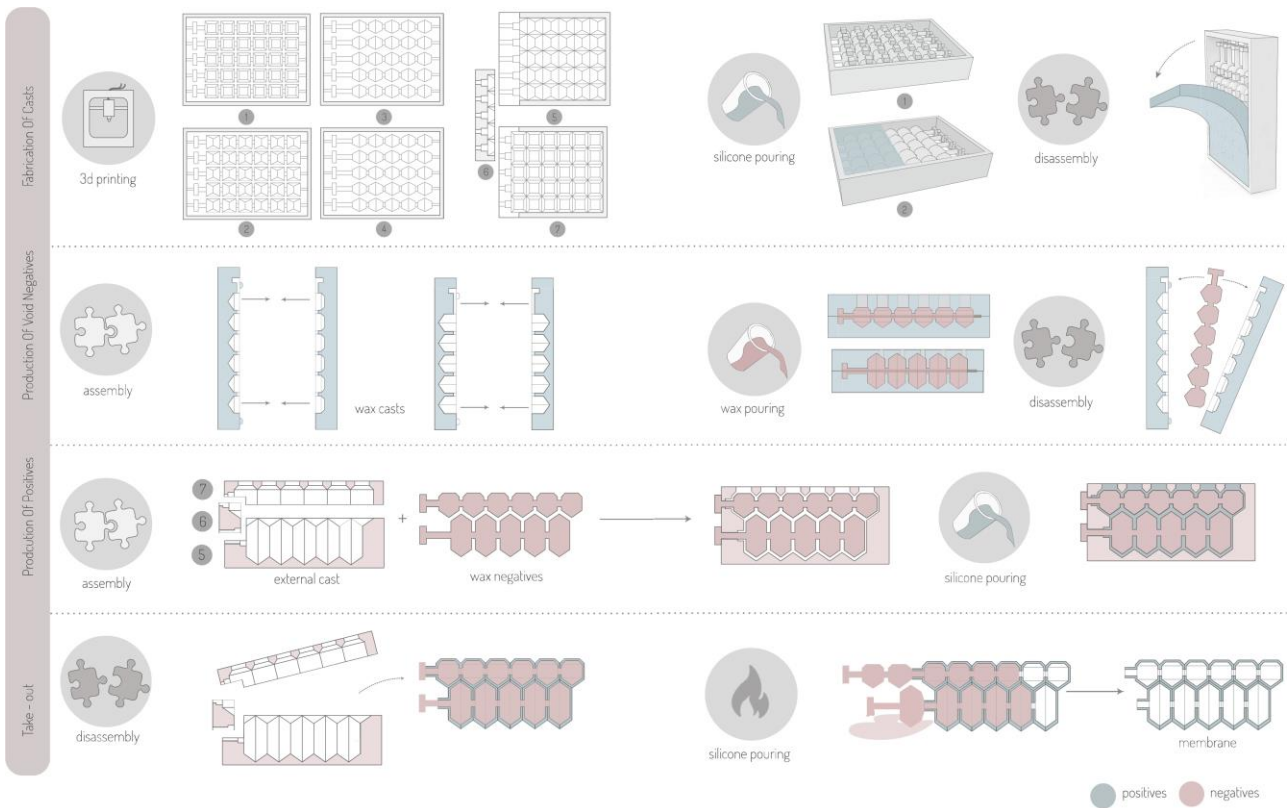


Figure 11: Prototype fabrication process. Source: authors..

initially executed in a vertical position which necessitated the creation of a more aerodynamic cell shape for the easier flow of the material. It was also observed that the relationship between cell shape and external cast geometry is of crucial importance for the effective removal of the final structure. The choice of a rounded cell form instead of a rigid one necessitated a careful manipulation of the external cast connection typology. The whole structure had to be extractable together with the wax.

MATERIAL CHARACTERISTICS

The balanced relationship between material resistance and elasticity was an important factor to be considered in the process. The silicone type used in the initial trial proved to create quite a rigid structure, obstructing the possibility of inflation. Therefore, silicone with lower shore (10) and a 24h curing time with a high resistance of 20 N/mm² was used which created a highly flexible membrane, simultaneously strong and easily inflatable. The alteration of material throughout the testing was combined with the cell thickness variation - from 3mm in the beginning and ultimately reaching 0.75 mm in the last trial.

CASTING SPECIFICS

The requirement of precision for generating a thin structure implored the very careful assembly and positioning of the wax negatives within the external cast (Fig. 12). For providing the exact distances, the positive parts were positioned horizontally in order to allow adding the cast components gradually, permitting the easy access of the material to all the empty spaces. Volumetric constraints limiting the movement of the rows were provided.

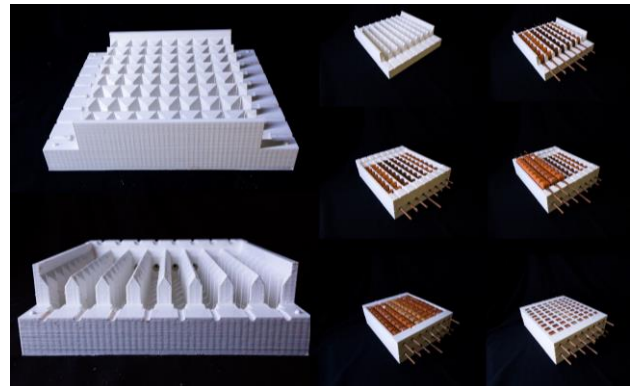


Figure 12: Casting process for the physical prototype. Source: authors.

RESULTS

As observed from the simulation analysis, the application of the adaptive compliant mechanism can be realized in multiple manners. The membrane can be installed as a part of multicomponent system, as an individual module existing on its own, or in a combination with another element. In the three cases the stimulus, the dimensions, and the material setup could vary, depending on the application purpose.

The possibility of creating a system of multiple elements gives opportunity for numerous configurations, derived from the variability of the curvatures of each module. Since the adaptive mechanism can be punctually modified in terms of material and geometry, this can create a rich palette of typologies and therefore a gradient of openings (Fig. 13). Such a setup could be an appropriate solution for an external shading device or as a regulator of air circulation depending on the stimulus chosen. In both

cases it represents an atmospheric and visual filter regulating light transmittance and porosity.

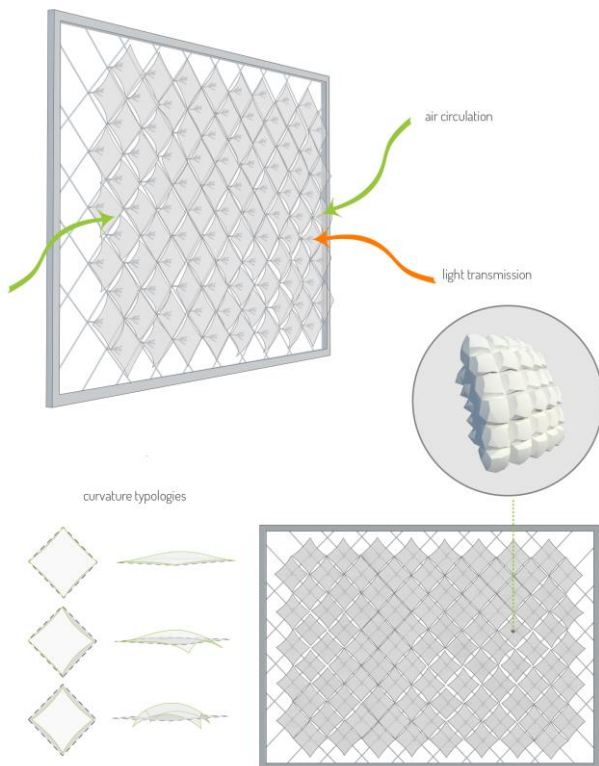


Figure 13: Possible application as an external shading device. Source: authors.

For example, adopting a hygroscopic substance in the external layer together with an appropriate material composition, can lead to swelling of the smaller cells upon higher humidity, resulting in deformation which allows for the passage of air. Current advancements in smart material technologies also allow for the incorporation of absorptive temperature-driven hydrogels which can render the membrane responsive to heat variations as well.

Finally, regardless of the exterior conditions the user is always capable of overriding the system in correspondence with the interior activities. Protection from environmental fluctuations can be addressed also with a singular compliant mechanism, whose dynamics are combined with another larger element.

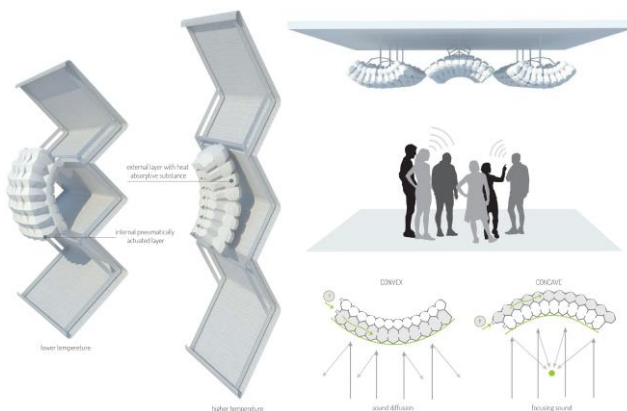


Figure 14: Other possible applications as an actuating mechanism for shading devices (left) and reflectors ensuring variable acoustic conditions (right). Source: authors.

For example, the membrane can be attached to a larger panel controlling its freedom of motion and thus regulating the access of light, heat or air. Potentially the system can remain entirely pneumatically driven and thus find place as interior element applied in the field of architectural acoustics (Fig. 14). The variation of pressure in the two layers can result in convex and concave geometry, modifying the reflection of sound.

DISCUSSION

The development of the research has brought about the applicational potentials of plants as biological models for kinetic structures. It attempts to demonstrate the advantage of their assimilation as movement mechanisms within an experimental adaptive development. This advancement pursues to propose a reconfigurable system with broad perspective of development, a kinetic skin that can be subjected to further articulations and expansion by following studies and experimentation.

Despite the simulations, empirical tests, and analysis, up to this phase the research has tackled only an initial stage of this concept. What has been accentuated is the study of the parameters which can regulate the deformation and the potential articulations. The system has undergone exploration in terms of its morphological performance and geometrical essentials. However, many aspects need to be further investigated and deepened so that a final design solution can be reached. Although the material organization has been studied as a crucial factor in the behaviour of the membrane, a specific material setup has not been settled. Silicone has been suggested and tested and in this case both layers remained pneumatically actuated, but the incorporation of an environmentally driven layer would presumably require the involvement of textiles and absorptive materials like hydrogels. In this case, the fabrication strategies can change and require the separate production of the two layers which should be consequently combined.

Another aspect which needs further research and testing is the actuation of the system. It has been hypothesized that the adoption of swellable substance inside the exterior layer would produce a pressure sufficient enough to yield satisfactory deformation. Nevertheless, since the work has not focused on the stimulus origin but rather on the force it is able to produce, the environmental input has remained as a future development step. Due to the kinematic approach of motion testing, the inflation dynamics and the optimization of the mechanism are also to be a subject of further exploration.

The following investigation and progress regarding the compliant mechanism would necessitate a multidisciplinary approach, implying the combined effort of material science, fabrication advancements, and adaptive design. The potential scalability and variation of the system give freedom for a number of configurations and applications which go beyond the ones addressed.

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