Using Tensegrity and Folding to Generate Soft Responsive Architectural Skins

Sherif Abdelmohsen[1], Passaint Massoud[2], Ahmed Elshafei[3]
[1]The American University in Cairo, Ain Shams University [2,3]The American University in Cairo
[1,2,3]{sherifmorad|drpassaint|a.elshafei}@aucegypt.edu

This paper describes the process of designing a prototype for a soft responsive system for a kinetic building facade. The prototype uses lightweight materials and mechanisms to generate a building facade skin that is both soft (less dependent on hard mechanical systems) and responsive (dynamically and simultaneously adapting to spatial and environmental conditions). By combining concepts stemming from both tensegrity structures and folding mechanisms, we develop a prototype that changes dynamically to produce varying facade patterns and perforations based on sensor-network data and feedback. We use radiation sensors and shape memory alloys to control the prototype mechanism and allow for the required parametric adaptation. Based on the data from the radiation sensors, the lengths of the shape memory alloys are altered using electric wires and are parametrically linked to the input data. The transformation in the resulting overall surface is directly linked to the desired levels of daylighting and solar exposure. We conclude with directions for future research, including full scale testing, advanced simulation, and multi-objective optimization.

Keywords: *Soft responsive systems, tensegrity, folding, kinetic facades*

INTRODUCTION

This paper explores the design of kinetic façade systems within the framework of soft architecture machines (Negroponte 1975), where advanced computing brings in possibilities for "living" in a "meaningful" and responsive man-made environment, thus allowing for a quality of architecture that incorporates different needs of building occupants altogether, including climatic comfort, spatial requirements and social interaction. Our main focus involves a "soft responsive system" (Khoo et al. 2011) that capitalizes on lightweight materials and tensegrity structures to develop low-cost and energy-saving kinetic building façade skins.

Early examples of responsive systems included systems that enabled responsiveness by means of a programmable façade such as the Aegis Hyposurface by dECOi (Goulthorpe et al. 2001), programmable audio-visual interior settings such as the Freshwater Pavilion by NOX (Lootsma and Spuybroek 1997), and responsive behavior through the changing form of a cloud such as the Blur project (Diller and Scofidio 2002). These "hard" mechanical approaches were challenging for adoption in large scale architectural skins and façade systems in terms of reliability, efficiency and durability. They also overlooked the functional component of responsive architecture, especially that which relates to environmental and structural integrity (Sterk 2003).

More recent work on responsive architecture capitalized on functional integrity, soft architectural components and material properties as opposed to highly mechanistic and complex components. Oosterhuis and Sterk adopt functional approaches to responsive architecture using actuated tensegrity structures and pneumatic muscles, where architectural skins respond to actual structural, climatic and spatial conditions (Oosterhuis 2003, Sterk 2005). Khan capitalizes on the unique material properties of elastomers to develop and construct responsive structures computationally (Khan 2009). Other approaches use digital and physical computation to develop elastic modular systems as a second skin to existing buildings (Khoo et al. 2011). This approach capitalizes on material behavior exploration to design morphing skins that respond to climatic conditions especially sunlight and provide aesthetically compelling shading devices and building envelopes.

Other advanced approaches to soft responsive systems implemented more sophisticated materials and mechanisms, such as the ShapeShift project (Kretzer 2011), which used electro-active polymers to develop kinetic and responsive membranes, and the Media-ICT building (Ruiz-Geli 2011), which responds to changing climatic conditions and moderates sunlight to the interior space using an ETFE kinetic façade system. While these projects offer many advantages for building skins and facades in terms of performance and aesthetics, they tend to overlook the full spectrum of necessary conditions and criteria. Sterk devises a hybridized model of control for responsive systems that extends to include: (1) "user input", including the possibility of manipulating building responses, (2) "building structure", which describes building responses to environmental conditions, and (3) "spatial responses", which involves the partitioning of internal space (Sterk 2005).

We explore the use of soft responsive systems within this holistic framework that extends beyond just performance and aesthetics to satisfy user needs "as a set of ever changing conditions" (Sterk 2005). We put forward that architectural space is changing from a static modular state into a fluid topological state that continually responds to human activity, social behavior and interaction, therefore addressing some of Negroponte's initial inquiries concerning human-environment relationship, user life style, and environmental control. In this context, we focus on designing building façade skins that are both soft and responsive. We implement this soft responsive approach in order to respond dynamically and simultaneously to multiple objectives such as maximizing daylight and minimizing solar radiation. We specifically use the principles of tensegrity and folding to generate a kinetic façade, where members in tension are triggered through the sensor-network mechanism to produce varying patterns and perforations in the resulting façade system.

We describe our approach below. We first experimented with tensegrity structures to build our mechanism logic. We then integrated a folding mechanism to generate a working prototype with different scenarios that respond to sensor-network data.

WHY TENSEGRITY LOGIC?

In line with the main scope of this paper, which involves exploring soft responsive systems, it was essential to study structures that serve the lightweight, efficient and dynamic nature of such systems. Tensegrity, as a structural principle and logic, was seen as potentially serving that purpose. Little literature exists that addresses architectural applications of tensegrity structures in building skins and facades, but rather it focuses on geometry, structural integrity and aesthetic appeal. Tensegrity structures, as described by the early pioneers Fuller and Snelson (Lalvani 1996), comprise struts or bars in compression, in a network of strings, cables or tendons in continuous tension. It is the properties of this integrated system that give it its unique behavior of lightness, foldability, deployability and strength. Another very important characteristic of tensegrity structures is the relatively flexible and easy shape control, where the basic shape of a tensegrity structure can be considerably altered and deformed with minimal change in the potential energy of the structure based on a given applied force.

Moreover, literature highlights a number of characteristics and benefits that are specific to tensegrity structures; namely natural inspiration, deployability, efficiency, stability, and control (Skelton et al. 2001). Tensegrity structures are mostly derived from natural and biological inspirations, where tensegrity behavior has been observed in cell biology. Transferable characteristics from nature can therefore possibly be seen in tensegrity structures at different scales, where smart structures could be developed to control energy flow and motion by means of a proper selection of geometry, parametric functions, and actuators.

Deployability is another direct benefit that can be easily achieved and is significant when attempting to design responsive systems. Typically, high strength materials would tend to exhibit little deployability or displacement capabilities. However, in the case of tensegrity structures, the ease of attachment and detachment of the compression struts and their connections renders the flexible and large displacement of tensegrity basic components and their compact assembly and storage a relatively light task with considerable savings. This characteristic is highly significant in complex buildings with sophisticated facade skins.

Another yet immediate benefit of tensegrity structures is the efficient distribution of its members and components through longitudinal members which are usually organized in a non-conventional and non-orthogonal manner to achieve maximum strength with minimal mass. As material is typically only needed in specific locations that address structural loading points, and not just arbitrary and unnecessary locations, this would result in an efficient three-dimensional configuration with high savings in terms of cost and resources. Simultaneously, the overall configuration is highly stabilized, where compression struts lose stiffness while tendons gain stiffness upon loading.

One of the features that we capitalize on as well in this paper is multi-functionality, where both compression struts and tendons can represent different and diverse elements simultaneously. For example, they can be load bearing members. They can also be thermal insulators or electrical conductors. They can yet represent a sensing elements, where they are able to measure length or tension, or actuating elements, such as nickel-titanium wire. This feature allows for a much larger role for the designed facade system, where it can possibly - using the appropriate selection of material or geometrical configuration - regulate thermal and electrical properties of the building envelope.

The aforementioned features allowed for an extensible set of properties, including (a) wholeness, where surfaces have the ability of responding as a whole rather than in parts, so local stresses are transmitted uniformly and are absorbed through the structure; (b) elasticity, where the overall structure could be deformed or displaced but retains its original shape when necessary; (c) expandability, where the structure is stable by itself, and so its sub-components could be joined together to create larger and more complex systems; (d) foldability, where surfaces could exhibit folding as a property, while requiring minimal energy in order to change to a new configuration, and (e) uniqueness, where the structure has no redundant parts, implying that all the sub-components of the structure are completely necessary for its overall stability.

PRELIMINARY TESTING WITH TENSEGRITY

In an attempt to reduce the highly mechanistic and complex nature of kinetic facade skins, we first developed preliminary testing with basic concepts of tensegrity. We used a 3-strut T-prism 30cm X 30cm X 50cm tensegrity module to generate a linear system surface and experiment with concepts of floating compression inside a net of continuous tension. After a brief physical testing and experimentation phase, we used Grasshopper and the Kangaroo plug-in to simulate the 3-strut T-prism behavior, where both the compressed struts and the prestressed tensioned members, or tendons, were represented (see Figure 1). In this simulation, we could alter the tension in each of the tendons to visualize the resulting behavior in different orientations. The color code in Figure 1 represents the tension values for each of the tendons. This allowed us to explore the scope of variation in configuration and transformation that could potentially take place within a building skin of depth 30cm.

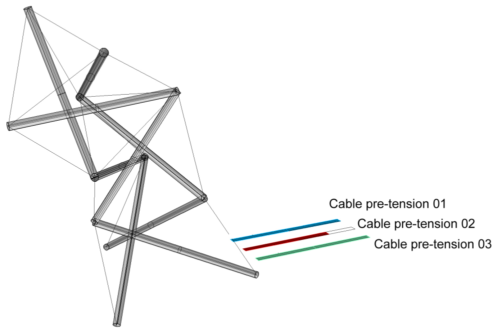


Figure 1
The 3-strut T-prism 30cm X 30cm X 50cm tensegrity module used for preliminary testing and generating a linear system surface.

In order to generate the required diversity of patterns for the ultimate purpose of responding to sensor-network data related to daylighting and solar radiation, we introduced parametric variations at three levels: (1) the modular level, (2) the one-dimensional network of interconnected struts, and (3) the two-dimensional network of interconnected struts. At the modular level, each 3-strut module can rotate and change its position and size, as shown in the previous figure. At the 1-D network level, manipulating each of the three tendons per strut induces transformation along the linear axis of connection (see Figure 2). At the 2-D network level, the manipulation of the tendons across the system surface results in a holistic transformation in aesthetic and shading patterns. This complex system of parametric variations results in a highly diverse range of possible configurations of the responsive skin, with only minimal alterations of input variables. This was seen initially to lead to a variety of daylighting levels and solar exposure inside the architectural space. As opposed to, for example, a group of hard mechanical piston movement to move or rotate merely one surface panel, a slight change in input tension values across tendons of the overall structure could achieve the same result more efficiently, with significant cost and time savings.

Figure 3 shows the Grasshopper definition that we used to define the transformation of the 3-strut module according to altering the values of its three tendons. We used the Kangaroo plug-in to identify the resulting geometrical configuration of the modules. Input parameters included the length of each of the compressed struts, in addition to the length of the tendons at rest and in tension. As the prototype was meant to stand vertically being a kinetic facade, it was important to take into consideration many factors. The plug-in allowed for accounting for many of these, including gravity, static and kinetic friction, stiffness, plasticity, and others. This contributed to an informed decision making process in the design of the prototype module, the dimensions of its panels, the location of its main anchor points, its weight, and consequently the type of lightweight material to be used in the construction of its final configuration.

In order to fully develop a framework for the geometry and control of a responsive facade prototype, the paper builds on two main systems as a departure point: tensegrity structures, and folding. It is important to distinguish here between pure tensegrity structures and geometrical configurations that share tensegrity logic and characteristics. We are more interested in tensegrity logic to generate the kinetic surface properties using linear tensegrity structures in a computational medium. It is not the aim of this paper to stay within "pure tensegrity" per se. Tensegrity structures are just considered as a basic departure point to develop new designs, as they comprise several interesting properties, especially when designing a responsive surface.

Figure 2
Scenarios of resulting configurations as a result of manipulating three tendons per strut, allowing for transformation along the linear axis of connection of struts.

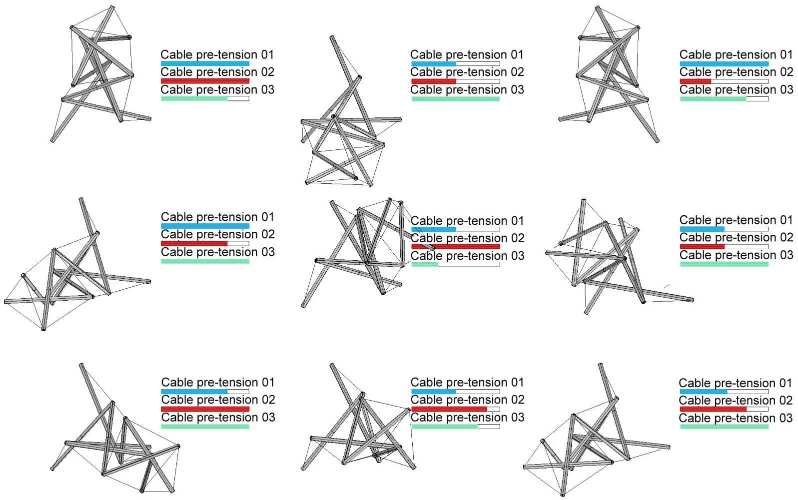
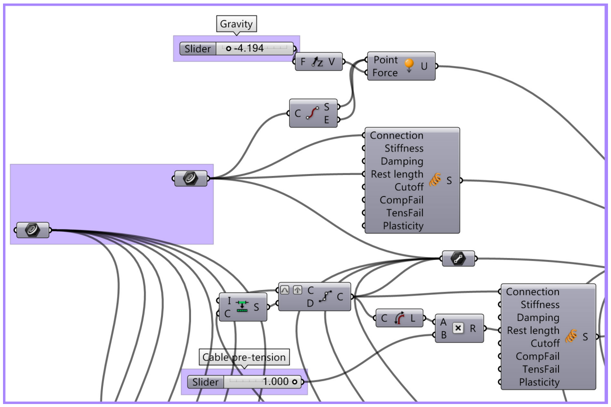


Figure 3
Extract from Grasshopper definition used to define the transformation of the 3-strut module based on manipulating its tendons (color coded).



FRAMEWORK FOR PROPOSED SOFT RESPONSIVE FACADE PROTOTYPE

After preliminary testing with tensegrity structures, we came to the following conclusions. Working with tensegrity allowed for producing a variety of curved surfaces. The generated surfaces were not only two-dimensional, but extended to three-dimensional surfaces. This was due to the fact that we used parametric variations at the modular level, and the one-dimensional as well as the two-dimensional networks of interconnected struts. Controlling these surfaces was allowed by manipulating the values for each of the tendons in all panels. The main problem however, which did not allow for full control of the panels, was that tensegrity behavior comprises both tension and compression, and therefore does not allow for control on each and every surface of a given panel. We thus incorporated folding as a mechanism for generating the prototype. We subdivided the given panel into a group of surfaces and applied the tensegrity logic together with a folding technique on its 30cm X 30cm panels. Folding, within tensegrity logic, allowed for a sequence of patterns across the overall structure, and a hierarchical setting where the overall panel was divided into a number of surfaces that transform in geometry, leading to a dynamic pattern that opens and closes, allowing for different solid-void ratio along its folds and side apertures.

We saw two components as key in controlling the tensegrity mechanism to allow for the required parametric adaptation: (1) radiation sensors, and (2) shape memory alloys. Based on sensor data from the radiation sensors, the lengths of the shape memory alloys connected along each of the 3-strut modules are altered using electric wires, and are parametrically linked to the input data. The transformation in the resulting overall surface is directly linked to the desired levels of daylighting and solar exposure, where the specific parameters pertaining to the percentage of perforations, orientations of tensegrity modules, and angles of solar exposure are fed in real time to the system to continually acquire the desired levels according to time of day and year. See Figure 4 for a generalized framework for generating soft responsive facade prototypes.

The framework builds on three main stages: (a) environmental analysis, (b) modeling and simulation of facade prototype infrastructure, and (c) physical testing and control. In the first stage, daylighting analysis using DIVA for Rhino, and solar radiation analysis using Ladybug plug-in for Grasshopper, are conducted in order to identify optimized values for percentages of perforations for the given facade screen. These values are given for both annual and daily data and are fed into the Arduino microcontroller to physically control the facade prototype.

In the second stage, the mesh infrastructure of the facade prototype is modeled using Grasshopper. Simulation is conducted using Kangaroo plug-in for the mesh and its folded mechanism , which is built based on tensegrity logic. Scenarios of configurations and folding behavior are explored within the computational medium, and then the model is physically constructed. Shape memory alloys are used as the prestressed tensioned members of the overall surface.

Upon applying electricity to the shape memory alloys, their lengths are transformed to respond to the environmental data coming from the sensor-network. The Arduino microcontroller regulates the general transformation logic of the folded mechanism based on the input data, resulting in a spectrum of configuration scenarios: (a) open mesh, (b) semi-closed mesh, and (c) closed mesh (see Figure 5).

The configuration possibilities for the prototype are constrained to the required panel depth in front of the building exterior wall, which was confined to 30 cm in this example. Changing the depth would typically increase the number of potential configurations and the nature of the resulting curved surfaces, and consequently the solid-void ratio and percentages of perforations for the overall prototype. A physically tested sample is illustrated in Figure 6. The physical prototype comprises a number of fixed points on each of the subdivided panels, in addition

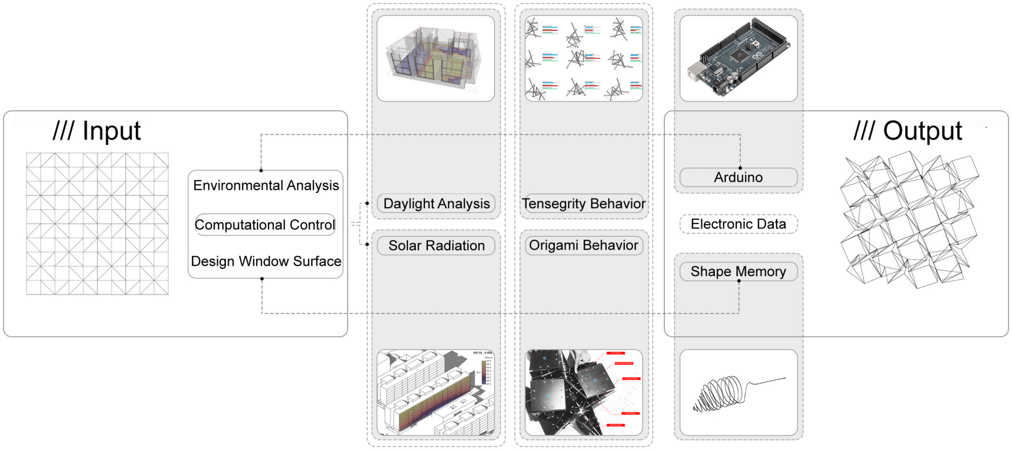


Figure 4
Basic workflow of the proposed responsive facade prototype.

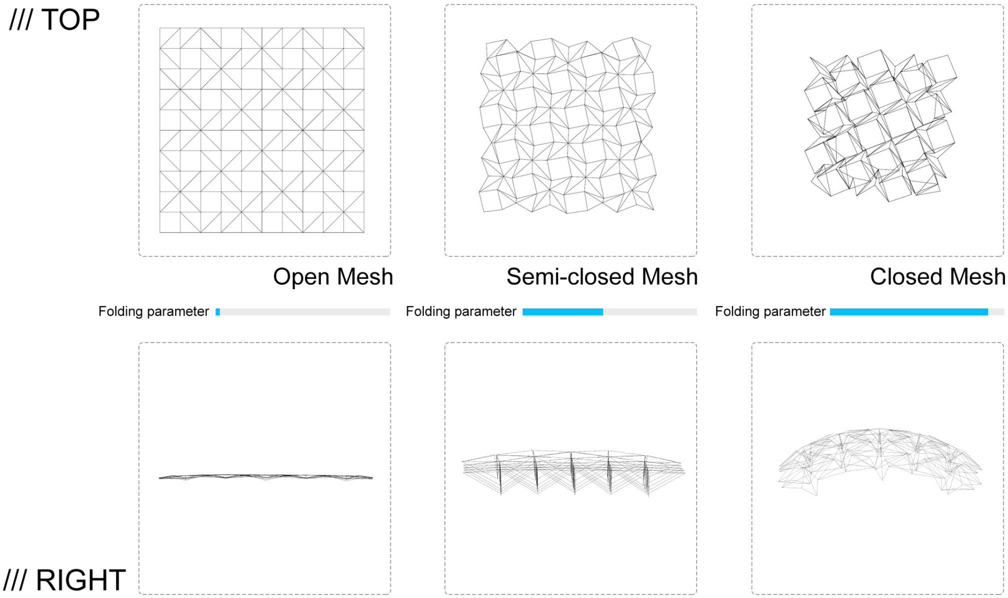


Figure 5
Possible transformations in the surface of the proposed responsive facade prototype. Left: Open mesh, Center: Semi-closed mesh, Right: Closed mesh.

to a folding mechanism and anchor points. The outer surface of the panel can be designed to host additional perforations for optimized daylighting considerations.

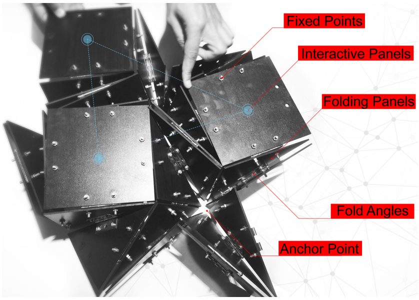


Figure 6
Physical prototype of the proposed responsive facade system.

CONCLUSIONS AND FUTURE WORK

This paper demonstrated the process of designing a prototype and developing a framework for a soft responsive system for a kinetic building facade. The prototype uses lightweight materials and mechanisms to generate a building facade skin that is soft, i.e. less dependent on hard and complex mechanical systems, and responsive, i.e. dynamically and simultaneously adapting to spatial and environmental conditions. We built on tensegrity logic, rather than a direct translation of pure tensegrity structures, and incorporated a folding mechanism to develop a lightweight prototype. We used radiation sensors with Arduino to respond to daylighting and solar radiation analysis in Rhino and Grasshopper simulations. We tested the prototype physically using shape memory alloys, where electricity is applied to transform the solid-void ratio of the panel surfaces based on the surrounding sensor-network data.

The scope of this paper is limited to digital simulation of folding and tensegrity using Grasshopper and Kangaroo plug-in and their behavior under the stimulus of preset values, along with some preliminary physical testing. This allowed for the generation of multiple iterations of façade patterns and testing the resulting patterns against the multiple objectives of radiation and daylighting. Further research aims at building a full scale prototype and conducting physical testing based on radiation sensors and local weather data.

ACKNOWLEDGMENTS

We would like to thank The American University in Cairo for sponsoring this research under faculty research support grant agreement SSE-CANG-SA-RSG-FY16-18.

REFERENCES

Diller, E and Scofidio, R 2002, *Blur: The Making of Nothing*, Harry N. Abrams, Inc., New York

Goulthorpe, M, Burry, M and Dunlop, G 2001 'Aegis Hyposurface: The bordering of university and practice', *Proceedings of ACADIA 2001*, pp. 334-349

Khan, O 2009 'Elasticity - the case for elastic materials for kinetic and responsive architecture', *Proceedings of the UbiComp '09*, Florida, USA

Khoo, CK, Salim, F and Burry, J 2011, 'Designing Architectural Morphing Skins with Elastic Modular Systems', *International Journal of Architectural Computing*, 9(4), pp. 397-419

Kretzer, M 2011 'Towards a new softness: The aesthetics of soft dielectric electroactive polymers and their application in an architectural context', *International Adaptive Architecture Conference*, London, UK

Lalvani, H 1996, 'Origins of Tensegrity: Views of Emmerich, Fuller and Snelson', *International Journal of Space Structures*, 11, pp. 27-55

Lootsma, B and Spuybroek, L 1997, 'Aquatic pavilion and interactive installation', *Domus: Architecture, design, art, communication*, 796, pp. 28-33

Negroponte, N 1975, *Soft Architecture Machine*, MIT Press, Cambridge

Oosterhuis, K 2003, *Hyper bodies - Towards an E-motive Architecture*, Birkhauser, Basel

Skelton, RE, Adhikari, R, Pinaud, J-P, Chan, W and Helton, JW 2001 'An Introduction to the Mechanics of Tensegrity Structures', *Proceedings of the 40th IEEE Conference on Decision and Control*, Orlando, FL, USA, pp. 4254 - 4259

Sterk, TDE 2003 'Using Actuated Tensegrity Structures to Produce a Responsive Architecture', *Proceedings of ACADIA 2003*, Indianapolis, USA, pp. 85-93

Sterk, TDE 2005, 'Building upon Negroponte: A Hybridized Model of Control Suitable for Responsive Architecture', *Automation in Construction*, 14(2), pp. 225-232