PHOTOTROPISM OF TENSILE FAÇADE SYSTEM THROUGH MATERIAL AGENCY

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Abstract. This paper researches material agencies, mechanical systems and façade designs that are able to respond to environmental changes through local interactions, inspired by biological systems. These are based on a model of distributed intelligence founded on plants and animal collectives, from which intelligent behavior emerges through simple local associations. Biological collective systems integrate material form and responsiveness and have the potential to inform new architectural and engineering strategies. The design approach of this research is based on a data-driven methodology spanning from design inception to simulation and physical modeling. Data-driven models, common in the fields of natural science, offer a method to generate and test a multiplicity of responsive solutions. The driving concepts are three types of evolutionary adaptation: flexibility, acclimation, and learning. The proposed façade system is a responsive textile shading structure which uses integrated actuators that moderate their local environments through simple interactions with their immediate neighbors. Computational techniques coupled to material logics create an integral design framework leading to heterogeneous environmental and structural conditions, producing local responses to environmental stimuli and ultimately effective performance of the whole system.

Keywords. Responsive facade; phototropism; material intelligence.

1. Introduction

Nature is a fundamental source of inspiration for the generation of responsive material systems, as all natural complex systems rely on interaction for their growth, development, and maintenance with a constant flow of energy, material, and information propagating between individual elements. From
cellular morphologies to swarm behavior at the level of ecosystems, interaction is the key aspect of arrangement and organization. Nature is a source of integrated design; there is no linear sequence of events that make up a tissue, organ, or an organism, but a constant feedback loop between form, performance, and materiality. Biological principles are able to inform a coherent architectural system triggered by the material’s own properties, leading to integral design solutions with eventually higher degree of responsiveness. (Figure1) “Integrating materiality, structure and performance into one system follows the biological model, one that finds a solution with the ability to do more with fewer resources i.e. a system that can anticipate different conditions and respond to them through dynamic adaptability”. (Doumpioti et al., 2010)

2. Material agency

2.1. MATERIAL COMPUTATION

The integration of computational systems into architecture allows for a new scale of material agencies which covers a wide range of complex setups from the morphogenetic generation to the morphodynamic alteration of form. “The greatest potential lies in computation’s power to provide a better understanding of material behavior and characteristics resulting to the organization of matter and form in design. Computation, in its basic meaning, refers to the processing of information. Material has the capacity to compute. In architecture, computation provides a powerful agency for both information and the design process through specific material behavior and characteristics, and in turn informing the organization of matter and material across multiple scales based on feedback with the environment. Material properties, characteristics and behavior can now be employed as active design generators, and the microscale of material make-up and the macroscale of material systems in architecture can now be understood as a continuum of reciprocal behavioral characteristics and performative capacities”. (Menges, 2012)
2.2. Material intelligence

Following the logic of integral design from biology, sensing and actuation functions can also be implemented into synthetic fiber composite material systems. Anisotropic and heterogeneous fiber composites offer the possibility for local variations in their material properties, creating specific desired structural effects. Embedded Shape Memory Alloys (SMAs) in the composite material could allow for integrated sensing and actuation.

The shape Memory Effect is the ability of a material to remember its initial shape above a certain characteristic temperature. This actuation is driven by the ability of SMAs to change their shape and take their initial manufactured form; they can be designed to have an actuation temperature of 35-40 degrees Celsius, a temperature easily achieved through direct solar contact. Shape Memory Alloys are a group of metallic materials that demonstrate the Shape Memory Effect. There has been considerable interest in recent years in developing shape memory alloy actuators because of their advantages in producing large plastic deformations, their force-to-weight ratio, one of the highest known, low driving voltages. This is of special interest to architectural applications focused on the implementation of material-embedded intelligence, as there is a need for both a sensing mechanism of the ‘smart’ composite with full integration of the system as a whole.

3. Responsive Solar Shading Façade | Goals and Methods:

The solar shading structure (Figure 2) was initially developed with a data-driven methodology to incorporate meaningful information as a transforma-
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tive device. The design is based on a responsive parametric model generated from contextual, phenomenological, and solar data. The textile structure was selected as the shading system mainly because of its flexibility. The test case utilizes this model to generate a system that provides better shading performance than generically generated shading configurations.

The focus of digital model is on creating effective day-long shading during high thermal gain seasons and planar with any façade surface. The data collected had to impact the parametric model with specificity, in order to define a number of design criteria as quantitative and geometric definitions. The shape of the component is determined by specific solar data for any given site, volumetric context, and climatologically conditions; the component size and accumulation pattern is determined by a number of phenomenological conditions. The combination led to a data-driven parametric model that was used to test a variety of configurations and simulate performance results. The parametric model also allows refining the articulation of shading strategy into a family of solutions that meet specific criteria (Figure 3). The site for generating and testing shading structure is a garage building located in Los Angeles, California.

3.1. DATA ANALYSIS

As a starting point to the design process, we required three sets of comparative analytical data regarding the environment, activation and adaptation of the system. For the environmental study, solar-norms were analyzed, solar norms are the three-dimensional sun path for our given test site, surface exposure relative to our test façade, a base reading of solar radiation, light levels from our site and orientation, and local obstruction and view corridors. The information collected from these variables, fall into two categories of data-geometric and numerical. Using Grassshopper + Rhinoceros and a small set of custom Python script, we were able to construct a parametric

![Image](Figure 3. Research methodology diagram)

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definition that produced calculations for areas of exposure with a specific set of output data. This information was utilized later to generate the three-dimensional shading structure. Activation of the shading system was through the amount of daylight required for the interior spaces. A regional parameter is controlling over the activation. Adaptation of the system is by giving individual users to adapt the system based on their own requirements which gives flexibility to system. (Figure 4)

4. Structure

A tensile structure consists of flexible, pre-stressed surface elements and flexible, pre-stressed, or stiff perimeter elements. (Figure 5) The three-dimensional arrangement of the perimeter elements in space and, possibly, further supporting elements in the surface creates a tensile form in double curvature. Such a tensile pre-stressed mechanically is stabilized by a state of equilibrium between the opposing sagging and hogging curvatures.
Tensile structures can carry external loads primarily by way of tension-compression stresses in the tangential direction (axial). One important factor for the loadbearing behavior of lightweight surface structures is the curvature of the surface which can be described by two different parameters: principal curvature and Gaussian curvature. The principal curvatures of a surface describe the magnitude and direction of the minimum and maximum curvatures at one point on a surface (Figure 7). These result from the intersection of planes with the curved surface. The intersecting planes are perpendicular to the tangential plane at the point considered and are arranged so that the lines of intersection exhibit minimum or maximum radii of curvature \( r_1, r_2 \). The principal curvatures \( K_1 \) and \( K_2 \) correspond to the inverse values of the radii of curvature is indicated by the +/- signs of the radii; positive curvature, curving towards the observer, is designated convex, negative curvature, curving away from the observer, is concave. Gaussian curvature \( K \) is a measure of the curvature of a surface; again, the +/- signs indicate the nature of the curvature, which is the product of the two principal curvature \( K_1 \) and \( K_2 \) (Knippers et al, 2011)
4.1. FORM FINDING PROCESS

“The term form-finding is often applied to such efforts in generating form through material organization under the influence of internal and external pressures”. (Ahlquist and Menges, 2012) Here both physical and digital processes have been utilized to have an iterative exploration of variable circumstances and also the simulation of a specific circumstance of elements and forces. Tensile structure has been utilized mainly due to its ‘dynamic’ character and ability to meet external changes. The characteristic feature of tensile structures is that they carry external loads by way of pure tension (cable, tensiles) without shear forces or bending moments. In order to achieve this, it is necessary match the geometry of the load bearing structure to the follow of forces. With varying external actions, the geometry must be able to change as well (i.e. deform). (Knippers et al, 2011)

4.2. DYNAMIC FEEDBACK

Focusing on the setup of a responsive system that relies on its internal feedback processes to trigger an innate material change in its architecture – in accordance with the climatic information received from the external environment – allows a more refined approach to the information transfer between a specific system and its influencing environment. Dynamic feedback is thereby employed as an effective method for researching adaptive behavior that, as a result, enables the system to dynamically adapt to different environmental conditions via internal feedback loops. This in turn, effecting
the resulting system behavior and expression, establishes a system that produces several different versions of the same startup configuration of a set of components; each version using a varied optimization policy in order to create the optimum state for the received information. Each generated constellation becomes the result of dynamic feedback that automatically determines the best formation policy, with each singular formation having a significant impact on the overall performance of the system as a responsive environment (Figure 9).

4.3. ACTIVATION

The material system developed for the façade for this research is a material composite, actuated by Shape Memory Alloys. Within the façade, these Shape Memory Alloys undergo phase transitions “as a result of molecular rearrangement taking place at critical points of intensity”. Changes in temperature and solar heat gain are the site-specific stimuli that trigger the reac-

Figure 9. Solar radiation analysis by Diva plugin for Rhino

Figure 10. Testing the physical model; activation of SMA by Arduino
tion and reorganization of the material system. These environmental changes directly actuate the Shape Memory Alloys embedded in the material system leading to local, regional, and global shape changes in the façade. This actuation is driven by the ability of SMAs to change their shape and take their initial manufactured form (Figure 10); they can be designed to have an actuation temperature of 35-40 degrees Celsius, a temperature easily achieved through direct solar contact with the façade. (Doumpioti et al, 2010)

4.4. ADAPTATION

Tensile structures are systems with complex structural behavior based on the morphology and connection logic. While conventional analog modeling and solving methods for analyzing and predicting the behavior of regular tensile structures is possible; for irregular structures, these methods prove highly complex, to understand, analyze and design. This research involves use of algorithmic approach for designing various configurations, simulation its behavior and its multiple stable states and digitally testing the structural performance under material constraints provides a more coherent process of design development for such complex systems (Figure 11). The main difficulty with tensile structures is that they only exist in specific, stable positions. Therefore, the control of an adaptive tensile structure must itself be adaptive. Adaptive control is a form of control that can modify its behavior in response to changes in the dynamics of the process and the character of the stimulus.

5. Conclusion

From experimenting with both processing algorithmic structures and material kinetic structures, it is evident that simple systems serve as more flexible, adaptable and robust organizations. A well-working performative processing system cannot perform without an equally agile and well-built material system. Focus to material systems supporting dynamic models, is thereby to be further explore in future works.
When applying multiple input information flows, funneled to responsive action via a complex adaptive algorithm to a series of actuators, a great versatility in response is constructed. However, simultaneously, is the danger of blurred performative processes that are equally-present. Processing systems with simple adaptive rules tend to perform rather advanced operational functions, which also allow easier understanding of the systems logic when implemented. The research thereby suggests simple organizations as open systems, to which differentiated expression and dynamic readings of the structure will be created from the changing climatic and occupancy patterns. The continuous research thus attempts to construct simpler, even more defined performative methods and prototypes whose objectives remain to explore material, structural, phenomenological, social and functional aspects. In doing so, future prototypes and models are developed within a described operational framework for response architectural typologies, with focus on two typologies; discrete-direct response and in-direct response. These approaches are all based upon separating the material system into a primary and a secondary system.

References