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Embedded Intelligence: Material Responsiveness in Façade Systems

abstract: This paper presents recent research for new 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 insect 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 proposed façade system uses integrated sensors and actuators that moderate their local environments through simple interactions with their immediate neighbors. Computational techniques coupled to manufacturing methods and 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.

1 Material Integration

Often in contemporary architecture there is little consideration for the potentiality of integrated material systems and their performance. The scope of a material is often limited to singular effects, such as permeability to light or its structural capacity. In this traditional thinking, the minor role of material solutions are only enhanced by the addition of a controlling system acting as a centralized "brain" and multiple external devices that act as signal transmitters to enable the system's actuation. These systems rely wholly on their mechanical properties, which allow certain devices to either rotate, open, or close according to a prescribed set of data of average climatic conditions. These mechanically-based systems take little consideration of material attributes, their thresholds, and their responsiveness, all of which could lead to more integrated design solutions and eventually, to dynamic architectural systems.

A shift from the centralized solution, with the inclusion of materiality as an integral factor of responsive kinetic systems, has the potential of empowering the mutual relationship between occupiers, spatial conditions, and the external environment. The intelligence of this system lies in the responsive interaction of smaller elements whose individual behaviors in response to different stimuli are propagated to their neighbors and in effect to the whole system. These local interactions between individuals can lead to dynamic emergent systems, whose behavior are unpredictable and have no direct centralized control *(De Wolf and Holvoet, 2004)*.

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, an organ, or an organism, but a constant feedback loop between form, performance, and materiality. Biological principles are able to inform a coherent architectural system, which rather than being based on external mechanical elements are triggered by the material's own properties, leading to integral design solutions with eventually higher degrees of responsiveness.

Integrating materiality 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.

2 Material-Embedded Intelligence

Following the logic of material integration 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.

Fiber composites offer incredible advantages for the design of a material system embedded with sensors and actuators. A specific type of bi-metal, known as Shape Memory Alloys, can provide both the sensing and actuation within a composite matrix. The Shape Memory Effect is the ability of a material to remember its initial shape above a certain characteristic temperature, after severe deformation at a lower 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, and 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.

In current centralized building systems, material, sensing, and actuation all take place separately and are only connected through indirect interaction with a central control mechanism. In the described material system, however, these three traditionally separate elements are synthesized into one system, working as a whole, and providing the structural capacity needed within the composite and the functionality of sensing and actuation with fiber composites and Shape Memory Alloys, respectively.

3 Design Problem

The following design addresses the necessity for a novel facade system for the Piraeus Tower, an 84-meter tall building with a fully-glazed facade in Athens, Greece. The building, abandoned for the past twenty years, has led to a debilitating interior setting due to its disregard for local environmental conditions. The proposed facade responds to interior and exterior site conditions, reacts to the problems discovered in the above case studies, and develops a new methodology for an adaptive building solution. The proposed façade is regulated through rule-based collective intelligence; principles stem from the material thresholds empowered by embedded sensors and actuators, as well as through the formal range that assemblies can obtain, restrained by preconceived geometrical patterns. Geometry and materiality are negotiated through a feedback loop, defining each other in order to find a solution capable of producing pluripotent results.

3.1 Embedded Computation and "Material Expressivity"

The logics of decentralized emergent systems are embedded within physical material systems' behavior and performance. The bottom-level interactive relationships among different variables that make up the proposed façade system become of major importance in its reaction to external pressures (i.e. environmental input), and thus yield preferred climatic and lighting conditions within the building. Matter expresses itself through intricate relationships defined by interconnectivity, geometry, and dynamic integration. This feedback between matter and energy is well established in the history of architecture and engineering, specifically in the field of structural performance, through the work of P.L. Nervi, A. Gaudi, F. Otto, and H. Isler. Form-finding was the main method established by those designers in order to arrive at structures developed through the self-organization of a material system with regard to load pressures. By taking this prolific research further, form-finding can anticipate more than only structural factors by encompassing environmental conditions as well.

The material system developed for the facade of the Piraeus Tower is a material composite, actuated by Shape Memory Alloys (see Section 2 above). Within the facade, these Shape Memory Alloys undergo phase transitions "as a result of molecular rearrangement taking place at critical points of intensity" *(de Landa 2006).* Changes in temperature and solar heat gain are the site-specific stimuli that trigger the reaction 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 change in the facade. 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 with the facade.

With the material logic defined, a digital form-finding process can be instrumentalized to achieve desired geometrical configurations for the deployment of an adaptive facade. The design framework employed is formulated within a computational environment that facilitates the design breeding of a variation of forms in association with material thresholds, resulting in desired performance. Digital form-finding can be utilized as a tool in the anticipation of material behavior as well as a decision-making tool, through which the overall design is constantly calibrated to better address and satisfy the design objectives. Moreover, this set-up allows for the establishment of a feedback loop between generation and analysis in search of coherent configurations within the range of versatile parameters of a rule-based system. The behavior of the resulting rule-based surface is ruled by specific parameters that define the sine-wave curvature through the ever-changing radii of the ellipsoids. The main variables of the parametric setup are the distribution and number of voids and the range of aperture of the elliptical geometry. These parameters are altered according to the results obtained from lighting and wind analyses and are thereafter applied to a physical prototype. It is a constant trial and error process, along which some patterns of behavior can be foreseen, thus driving the alterations by minimizing the number of testing attempts.

The formal expression of the overall facade system results from studies on continuous surfaces. By animating the surface through material-light interaction, different ambient conditions are achieved, varying from direct light penetration, to diffused lighting effects differentiated

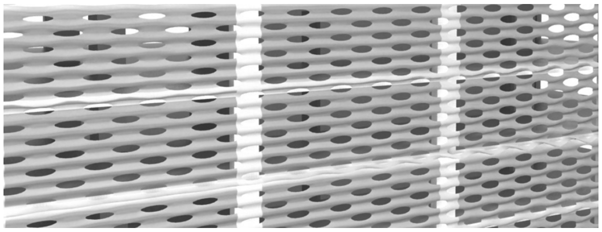

Figure 1. View of façade depicting variations in ellipsoid openings.

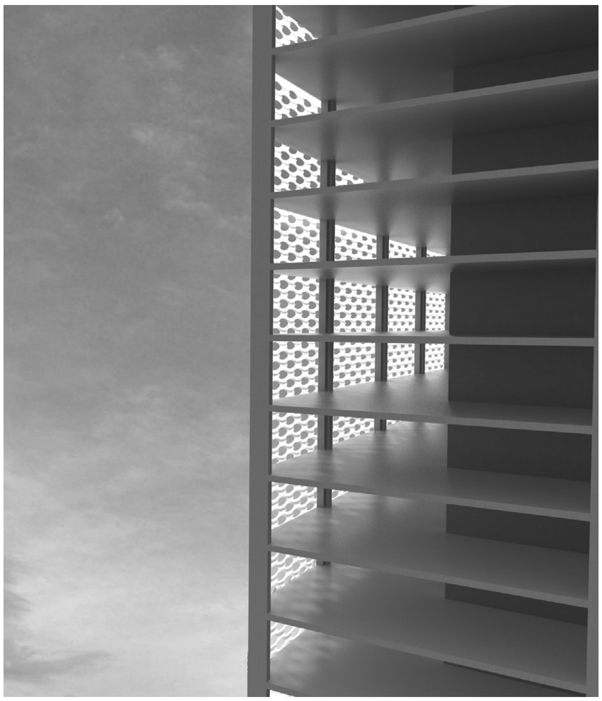

Figure 2. Interior view of façade.

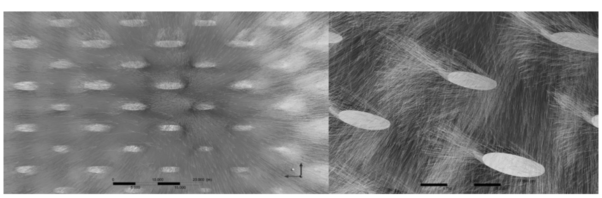

Figure 3. CFD Analysis of the proposed façade. Differential velocities are related to changes in opening sizes; the smaller the openings, the more accelerated the windflow.

according to the position along the facade in interaction with the sun's angle. Although the initial geometric input is given, the material's animated capacities work in tandem with the geometry, thus yielding different instances of porosity through their interrelation (Figure 1). The final outcome and the different geometrical instances emerge through the interrelation between matter, geometry, and performance evaluation.

The 'sine-wave' geometry is related not only to the material thresholds that allow for a certain degree of deformation, but most importantly to the desired internal conditions of differential light and heat intensities (Figure 2).

Shape Memory Alloys are embedded within the composite material vertically, spanning the edges of elliptical openings in the facade. As temperature on the facade rises and SMA's are activated, the sinusoidal geometry emerges. Each Shape Memory Alloy bends perpendicular to the building facade, creating greater diffusion of light to the adjacent interior spaces. At the same time, the contraction of Shape Memory Alloys creates smaller elliptical openings, increasing the velocity of oncoming wind, and thus enhancing natural ventilation of warmer areas inside the building (Figure 3).

The material system creates an interior environment of various gradients; where solar heat gain is high, the facade mitigates harsh sunlight while concurrently establishing comfortable ventilation conditions by increasing wind speed. Where sun exposure is minimal, the facade creates large openings that do not affect wind speed. While the facade is designed to provide comfortable interior conditions throughout the building, it is up to the user to initiate ventilation. Each user has the ability to open or close local vents, thus initiating ventilation and allowing control over individual comfort. Due to the continuous nature of composite materials and the ability to manufacture a component-based surface seamlessly, local changes in form directly affect their surrounding areas. As the facade begins to respond to environmental stimuli, other areas of the facade need not react in the same threshold, because neighboring areas provide enough shade from harsh sunlight for a particular space. In addition, there is a material threshold present throughout the continuity of the system; when one area is actuated, there is a gradient effect throughout the entire facade, causing all components to negotiate their level of responsiveness to the sun with their connectivity to adjacent activated

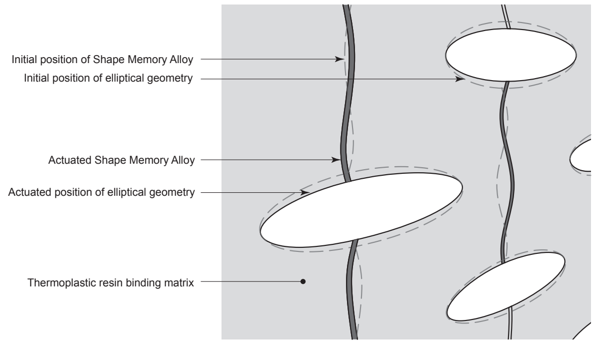

Figure 4. Diagram of elliptical openings: Each SMA lies between two elliptical openings in the facade; the facade operates within local thresholds governed by each SMA's proximity to its neighbovrs.

components. This collective intelligence embedded within the facade allows for minimal use of energy while still creating desirable environments.

4 Effective Performance Through Material Organization

The performance of the adaptive facade emerges from the complexity of a number of simple relationships. Material responds locally through the designed placement of Shape Memory Alloys in a thermoplastic resin matrix, reinforced by glass fiber strands. The response mechanism is a reaction to environmental stimuli: as the sun hits the facade of the Piraeus Tower, the Shape Memory Alloy strips change their form (Figure 4).

This creates local changes in geometry that in turn decrease the transparency of the facade while increasing the level of refracted light in the interior spaces of the building. While responding to solar conditions, this change in geometry caused by increased solar heat gain on the facade increases the size of the facades elliptical openings, thus increasing ventilation to the interior.

While these basic parameters govern the overall responsiveness of the facade, the connectivity of elements collectively create an effective global solution for environmental performance. Logics of collective intelligence can be found in natural systems, specifically in social insects such as bees and termites. Through careful calibration governed by different thresholds, simple organisms can collectively create efficient and effective environments, without any centralized brain controlling activity. Based on this model, the adaptive facade achieves effective results through minimal use of energy. While the sun follows its path in the southern sky, the southeast facade heats first. This environmental stimulus causes a geometry change where the sensors and actuators are first triggered; the self-shading caused in these areas immediately decrease the amount of shape-change in the components below. Shape-change only occurs thereafter in components where solar heat gain becomes large enough to cause a temperature change, and therefore geometry change in the facade. This neighborhood connectivity allows the facade to only change its form where necessary. By eliminating superfluous movement in the facade, interior conditions are only affected where necessary. This decreases any noise pollution or over-ventilation in interior spaces, ensuring comfortable climatic conditions. The flexibility, and ultimately, the effective performance of such a system is only possible through the precise integration of material and mechanism. Biology provides this inspiration; adaptability in nature is inherently built into the material makeup of an organism. Thus there is no separation between sensor, actuator, and the material matrix that binds it all together. This material integration regulated by interactions based on the principles of collective intelligence can create complex patterns effective for desired interior environmental and spatial conditions.

Patterns emerge through adaptation; this is in stark contrast to the mechanical paradigms in which pattern formation is preconceived and pre-anticipated, based on given time-based computer controlled data. The latter approach does not consider ever-changing environmental conditions or unanticipated behaviors of users. The performance of a system that relies on local interactions becomes synergistic in a way that encompasses more than one resource, eventually leading to emergent behavior within a system that is more than the sum of its parts.

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