SURFACE DYNAMICS

From Dynamic Surface to Agile Spaces

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Abstract. Behavior, adaptation and responsiveness are characteristics of live organisms; architecture on the other hand is structurally, materially and functionally constructed. With the shift from 'mechanical' towards 'organic' paradigm (Mae-Wan Ho, 1997) attitude towards architectural adaptation, behavior and performance is shifting as well. This change is altering a system of reference and conceptual basis for architecture by suggesting the integration of dynamics – dynamics that don't address kinetic movement only but include flows of energies, material and information. This paper presents an ongoing research into kinetic material system with the focus on non-mechanical actuation (shape memory alloy) and the structural and material behavior. It proposes an adaptive surface capable of altering its shape and forming small occupiable spaces that respond to external and internal influences and flows of information. The adaptive structure is developed as a physical and digital prototype. Its behavior is examined at a physical level and the findings are used to digitally simulate the behavior of the larger system. The design approach is driven by an interest in adaptive systems in nature and material variability (structural and functional) of naturally constructed materials. The broader goal of the research is to test the scale at which shape memory alloy can be employed as an actuator of dynamic architectural surfaces and to speculate on and explore the capacity of active and responsive systems to produce adaptable surfaces that can form occupiable spaces and with that, added functionalities in architectural and urban environments.

1. Introduction

Natural systems use adaptation to adjust to and to compensate for constantly changing environment that surrounds them. They also have unavoidably productive relationship with the environment by exchanging matter, energy and information. In biology, adaptation is a "mechanism" that insures the survival and reproduction of the species in their environment. The result of this process is a slow change of an organism over time (evolution). In his book *On Growth and Form*, D'Arcy Thomson (Thompson, 1992) explained the morphological transformation of the organism caused by its adaptation to the dynamic environment. This idea that form is not given or predetermined but is the result of the process has profoundly influenced the architectural discourse of the 20th century (and continues to do so). Many concepts and ideas have emerged that propose adaptation of spaces, structures or systems, including their configuration and behavior. Buckminster Fuller's work paved the way towards deeper understanding of the relationship between form and geometry. Frei Otto's work with form finding pointed out an inseparable relationship of form and material in nature. Several projects/ideas that developed in the late 1960s and early 1970s, such as Cedric Price's Fun Palace, Negroponte's Soft Architecture Machines, and Eastman's concept of "adaptive-conditional architecture", began to explore "intelligence" and programmability of architecture's processes and spaces in order to form a two way relationship between spaces and users and to accommodate environment, human use, or climate. Today, increasing complexity of the constructed environment is bringing adaptive capacity of buildings into focus. Latest advances in distributed computation, embedded computing, material innovation and digital architectural design are enabling development of integration strategies that facilitate further exploration of adaptive systems in buildings. An increasing number of projects are proposing buildings as productive participants within the larger ecology by emphasizing adaptability and responsiveness.

2. Precedents

2.1. MATERIAL VARIABILITY AND STRUCTURAL HIERARCHY

Adaptation and responsiveness of the constructed environment is not easily achieved. The challenge, in part, stems from the way we build and from the hierarchical nature of the design process. When we design a structure we choose among many load-bearing systems. After the design and analysis the system is realized by selecting materials (concrete, brick, timber, steel, etc.) with specific material properties. In nature this process is fully integrated and arises from diversity and variability of the material itself (Knippers, Speck, 2012). Naturally constructed material systems have a hierarchical structure on many levels that can bridge several orders of magnitude (Speck and Rowe 2006). Functional properties of materials can also vary and change from one structural hierarchical level to the next, producing variability that can adjust to and accommodate changes in the external and internal environment. The capacity to fulfill functional and structural requirements within the same material system makes natural construction extremely adaptable. In nature adaptation cannot be viewed separately from the "structural materiality" of the system; at the same time adaptability of the naturally constructed material system is deeply ingrained in the very "structure" of the matter from which it is made. Manmade material systems distinguish between functional and structural aspects of the material. They are constructed, assembled, and designed to respond to a specific design and performance criteria by separating functional and structural aspects of the system.

In the project presented here the point of departure for design of the material system was material variability and structural hierarchy of the naturally constructed materials. That was addressed on two levels. First, an attempt was made to distribute the structural hierarchy across several scales of the material system by using a gridshell lattice as a basic structure of the system. Second, the material variability was explored by adding shape memory alloy actuators to the structural lattice to blur the boundary between functional and structural roles within the system. Integrating shape memory alloy with the lattice enabled variation in the shape and behavior of the proposed structure, adding certain level of intelligence to the surface structure.

2.2. KINETICS AND SHAPE CHANGE

In his paper "Shape control in Responsive Architectural Structures" Tristan d'Estreee Sterk (2006a) stresses the importance as well as challenges of structural shape control. To design a system that can support responsive shape change, architectural structures demand re-evaluation. Sterk states that there are three essential characteristics of structural systems used in responsive building envelopes: 1) they must have controllable rigidity, 2) they must be lightweight, and 3) they must be capable of undergoing asymmetrical deformations. Together these three characteristics produce the most robust and flexible outcomes.

Jordi Truco and Sylvia Felipe (Hensel, Menges and Weinstock, 2010) employ such characteristics in their design of a gridshell. The project aims to advance the research on gridshells through the investigation of alternative form-finding and construction methods. The gridshell is designed as a uniform grid layout made from elastic members with the possibility to alter or adjust its form. What is particularly interesting about this design is that the local manipulation of members that define the grid "cell" geometry facilitates a global change of a gridshell form. The overall form of the gridshell can be repeatedly altered through local manipulation of its members, i.e. the distance between the members of the layered lattice. An internal force produced by the change in distance changes the overall form of the lattice. This aspect of the gridshell was instrumental in the development of the kinetic lattice system described in this paper.

2.3. ACTUATION AND ADAPTABILITY

In his book *An Evolutionary Architecture*, John Frazer (1995) suggests a new form of designed artifact, one that is interacting and evolving in harmony with natural forces, including those of society. To achieve that, architecture depends on information transfer. The relationship between information and physical response of an adaptive structure is supported by application of sensors and actuators as well as mechanisms that control and activate the intelligence of physical environment. Kas's Ostrehuis (2007) points out that a two way relationship between the user and the structure is extremely important to avoid the notion of simple interactiveness. The key to achieving this is to exchange information in both directions and engage not only the control and actuation of the motion of the physical structure but to also include human behavior input. Cohen de Lara and Hubers (2009) use game software to organize the dynamic relations between the input received by the sensors and the output from the behavior of the structure itself. With this dynamic feedback their interactive architecture project ("Muscle Body") becomes constantly aware of the movement of the occupant's body. At the same time the occupant perceives that the body movement is shaping the behavior of the space. When this is achieved, an adaptive structure/space could have a transformative effect on participants and on the environment itself. As John Frazer argues, architecture should be a "living, evolving thing". A truly responsive environment would enter into a "conversation" with its users and allow them to become participants. In other words, such an environment should not only sense and respond but also perceive and act (Fox and Kemp, 2009). Design of spaces that actively engage with their users goes beyond form and space delineation and requires design of complex behavioral and informational systems.

The project described here uses the shape memory alloy (SMA) as an actuator and experiments with integrating the SMA into a structural lattice of the surface and embedding it into a substrate material layer. Network of sensors is distributed throughout the surface. Sensors are grouped into several networks (internal surface control, external sensory input, and internal sensory input feedback) that exchange information, and control and activate the "intelligence" of the surface.

3. The Agile Spaces Project

The Agile Spaces project proposes an adaptable and responsive material system capable of sensing its environment and responding by changing its shape or revealing small occupiable spaces to a passersby. These adaptive spaces can provide shelter and can mediate the temperature environment, making public spaces in harsh, cold climates more vibrant. The "intelligence" of the surface's physical environment is capable of incorporating climate and human related conditions into its working. By sensing the environmental temperature the surface can mediate between the internal and external environments and provide localized heated regions. These regions can then act as attractors that draw people towards the surface. Also, the surface itself can sense the presence of people and can adjust its temperature as needed or it can move to reveal an occupiable sheltered space. The heat generation of the surface is closely related to its movement. When activated, shape memory alloy is generating heat. This heat is captured, stored and moved through the surface; it can "follow" movement and activity of people.

The backbone of this project is a kinetic material system actuated by shape memory alloy (SMA) springs. The material system is developed both as a physical and digital prototype. Its behavior is examined at a physical level and the findings are used to digitally simulate behavior of the larger system. The system utilizes a differential cell lattice structure and its structural behavior. It relies on elastic deformation of the constituent members, which allows the forces of bending to be distributed along a wider region of the surface. The system becomes kinetic when the SMA spring actuators are activated. Activation of the springs introduces tension into the lattice members which causes change in the geometry of the lattice cells. The result of this is bending of the wider region of the surface. Figure 1 shows the amplitude of bending and the cell deformation.

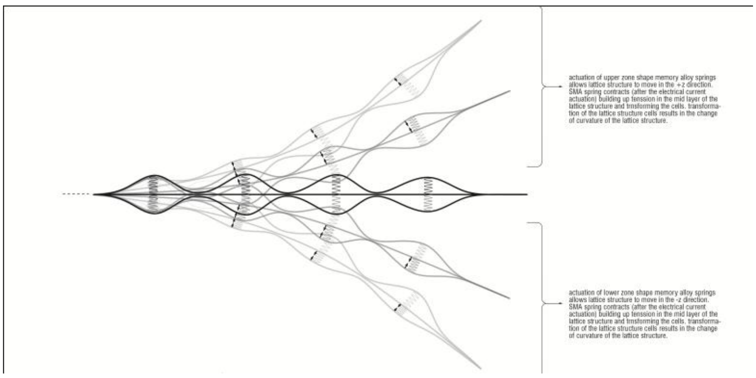

Figure 1. Amplitude of bending and cell deformation after SMA spring actuation.

Figure 2 shows a detail of the first physical prototype and movement of the activated lattice. The lattice can be actuated in the lower or upper zone. Depending on the zone of actuation the lattice deforms and moves upwards or downwards. The contraction of the SMA spring produces a tension in the middle layer of the lattice, which manifests through the deformation of the cell structure, bending an entire region of the lattice. Strategic placement of the actuators across the lattice produces accumulated bending effect and deforms the entire surface.

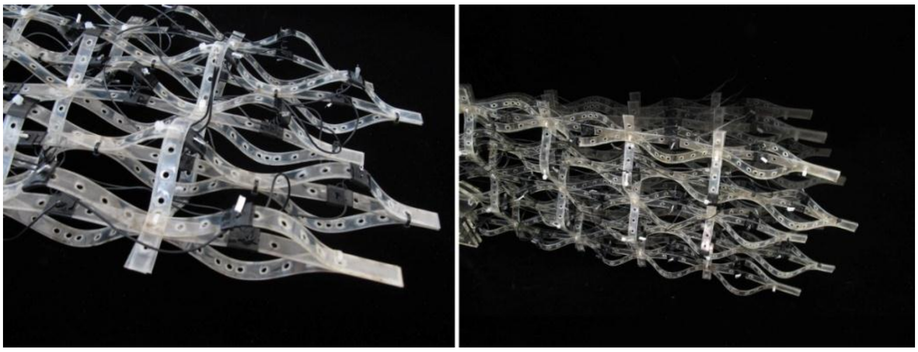

Figure 2. Lattice structure physical prototype.

Figure 3 shows the lattice assembly and the actuation logic that provides for bending in two directions. The lattice structure consists of lamellas of thermoplastic material (which were previously contoured) of high tensile strength and low stiffness. The material is oriented in a particular way to allow for bending and reversed elasticity.

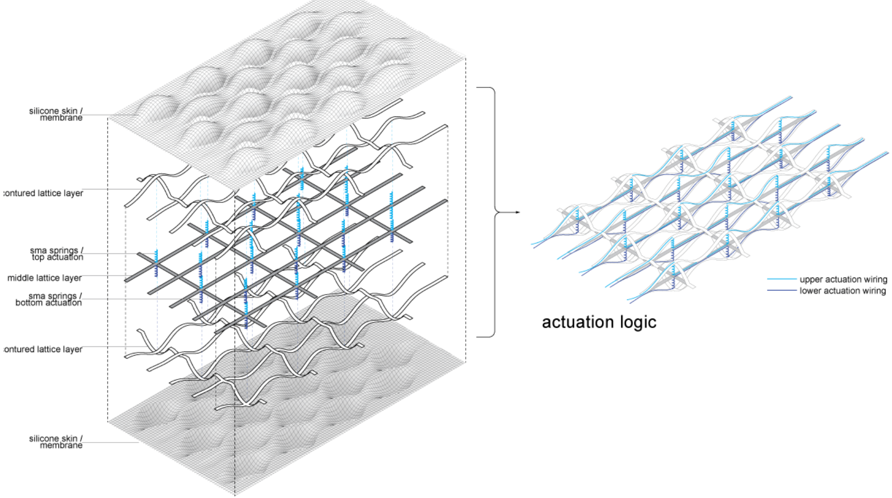

Figure 3. Lattice assembly and the actuation logic.

The second iteration of the project uses variation in the lattice cell size to change the amplitude of the deformation and produce differentiated movement. Components of variable size are joined into a lattice surface. This variable cell size produces variable thickness (cross-section) of the system's structure (Figure 4) and therefore, when activated, variable curvature of the lattice.

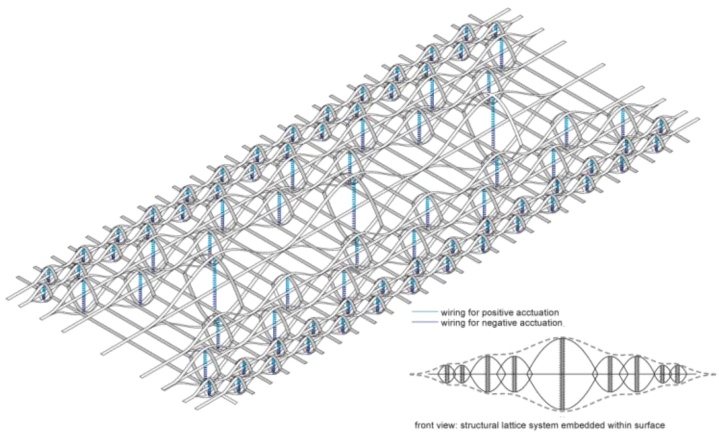

Figure 4. Differential cell size lattice assembly and the actuation logic.

The thicker regions have a larger deformation amplitude (Figure 5) and "structure" the space by forming the "pockets" that with adequate scale of the surface could be occupied when activated.

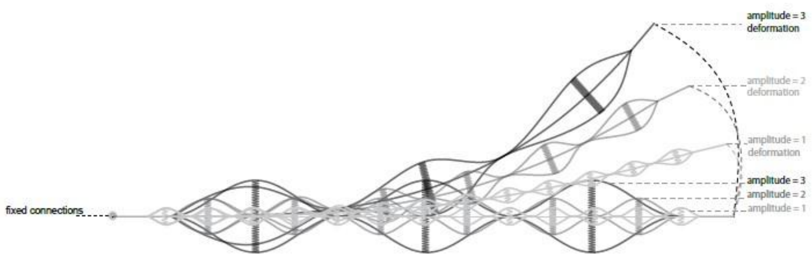

Figure 5. Differential cell size lattice and variable lattice curvature.

Sterk (2006a) writes about asymmetrical deformations of the surface and emphasizes two important reasons why asymmetrical deformation is needed: 1) to respond to sun or wind movement and take advantage of its shape to condition the internal spaces and 2) to cater to dynamic changes of load transmission through a structure. As shape control is closely related to structural rigidity, an asymmetrical shape control would enable the structure itself to respond to unpredictable loading conditions and by doing so improve the range of structural responses. Brian Culshaw (1996) suggests that the structure's ability to alter its stiffness rather than its strength is a key feature of any responsive structure. This is supported by the fact that a structure capable of dynamic response to its loads would require less weight, less material and most likely less complexity. Tensegrity structures are an example of such dynamic responsiveness. According to engineer Guy Nordenson, if a building was designed like a body, with a system of bones, muscles and tendons and an ability to change its posture, tighten its muscles, and brace itself against wind, its structural mass could be cut in half (Davidson, 1995). As Sterk states, “asymmetry enables loads to be transmitted along several dissimilar paths whereas symmetrical responses do not”. An asymmetrical shape control would enable the structure itself to respond to unpredictable loading conditions, and by doing so improve the range of structural responses.

The design of the proposed variable lattice structure took into consideration key features such as controllable rigidity, light weight and asymmetrical shape change. The movement of the proposed structure could be symmetrical and/or asymmetrical depending on the actuator activity. Figure 6 shows the second prototype of the differential cell size lattice in dormant and activated positions.

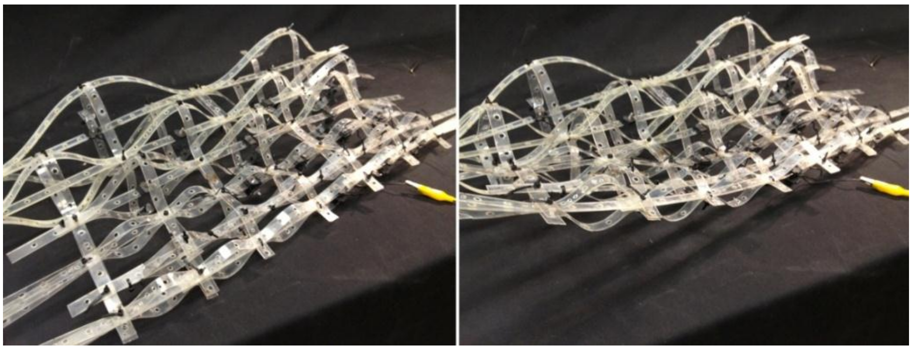

Figure 6. Dormant and activated differential cell size lattice.

In naturally constructed materials information travels through integrated material layers; functional needs inform material and structural distribution. This is facilitated by the lack of discrimination between material and structure as well as between structural and functional materials. Such logic of integration was key in the development of the physical prototypes of the lattice, in which the shape memory alloy is used to integrate the actuator and the building material of the surface into a single system that works in unison. The physical prototypes were used to understand and plot the movement of the structure. The collected information was then used to develop a digital model of the surface using Rhino modeling software and Grasshopper plug-in. Grasshopper script was then created to simulate the movement of the surface.

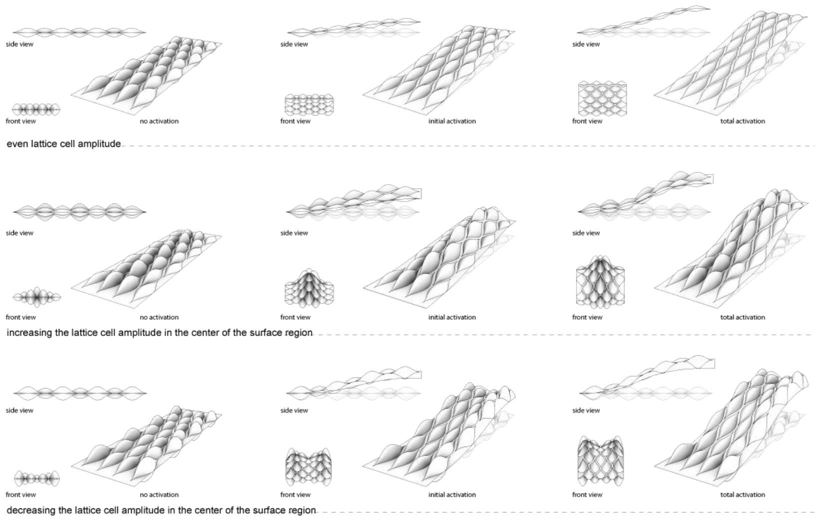

Figure 7. Choreographing the surface movement by changing the lattice cell size/amplitude.

Figure 7 shows a relationship between the lattice cell size and the movement amplitude. Regions or lines of lattice with a bigger cell size have a larger amplitude and therefore a larger deformation of the surface. Potentially, these deformations could be large enough to create spaces that can be occupied for various activities. The behavior of the larger lattice structure can be designed by strategically placing larger and smaller cells across the lattice which could be then actuated into 'ridges' and 'valleys' within the surface.

The surface is activated by registering personal mobile devices and duration of their presence in its proximity. When activated the structure gently moves up offering a shelter, privacy or passage. Figure 8 illustrates the possible scenarios of occupation.

Figure 8. Possible scenarios of occupation.

We are currently developing a network of sensors distributed throughout the surface. Sensors are grouped into several networks: internal surface control, external sensory input, and internal sensory input feedback. These networks exchange information, and control and activate the "intelligence" of the surface. The sensor input is collected and controlled through Arduino and Firefly plug-in for Grasshopper in Rhino. The behavior of the surface is programmed through the integration of the three networks. Internal surface control enables the surface to collect physical information from the environment (temperature around the surface), process this information and regulate the heating by activating motion within the surface. Movement of the surface produces and captures the heat generated by the SMA embedded in it. This movement is directly related to the physical inputs and outputs and does not involve any human behavior input. The movements initiated by the internal surface control are relatively uniform across the surface and don't produce significant deformation. External sensory input is generated by registering mobile devices. This input responds to the number and proximity of people; the surface responds to this input with more dramatic deformations, revealing and forming spaces. The user information feedback is correlated to the behavior of the system through an adaptation algorithm defined by the physical behavior of the kinetic system. This constantly changing information creates and recreates physical behavior of the structure, its form and its temperature to respond to the physical conditions of the environment.

4. Conclusion

One of the most interesting challenges of this project is to build an architectural assembly that integrates and fully utilizes the capacities and properties of smart materials. A key conclusion at the end of this phase of the project is that the functional qualities of smart materials and technologies that transfer energy and/or information would have to achieve a full overlap and integration with the structural functions of a material system necessary for architectural applications. That way the change of scale, currently one of the greatest challenges in the projects of this kind, could be more effectively addressed. Experimenting with a fuller integration of SMA was one of the aims of this project. This was addressed by changing the scale of the system and attempting to capitalize on discrete and local movements to produce a larger global effect on the surface. The focus on seamless material integration and capturing of emitted energy is related to a broader goal of having a more productive role of architectural interventions within larger ecologies. We are very interested in suspending a challenge of finding a non-permeable and clearly defined boundary between inside and outside in exchange for a surface that fosters constant flow of information, matter and energy.

As Sterk (2006b) suggests, employing feedback as a new way of form generation affords architects a way to conceptualize new kind of architecture that ties user needs and actions directly to architectural form. These agile spaces could be many things. They could change their functionality, perform several functions at the same time, change form and physical location, harvest and distribute energy.

Shifting situations and changing needs are evident not only in the dynamics of natural world but also in those of contemporary society. Adaptation as a transformation through time can address these indeterminate changes. To do so, however, this "constructed" adaptation should operate through responsive and flexible systems whose organization is based on resilience and feedback. Designing with responsiveness and flexibility as a basic principle could be, on one hand, an effective overall design strategy to integrate a project into the "life" of its larger ecology; on the other hand, such an approach could be employed in designing receptive and "intelligent" systems that can accommodate physical and material change and behavior and that can be integrated into non-adaptive models.

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