Using Actuated Tensegrity Structures to Produce a Responsive Architecture

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Abstract

The major theoretical roots of responsive architecture lie within the work of Nicholas Negroponte, and its most inspiring realization, to date, is found in the work of dECOi Architects. The work of NOX, and Diller & Scofidio provide two other built examples of responsive architectures. Each of these works is impressive within its own right. However, all of them have their shortcomings, suggesting that several possibilities for alternative visions still exist.

While Negroponte’s work identifies the characteristics of a responsive architecture, it does not propose a model that is suitable for implementation. On the other hand, the work of dECOi architects does not address the technical needs of a building envelope designed for real world conditions of weather and structural load. Diller & Scofidio’s work, also does not have a functional envelope, and NOX’s work lacks physical responsiveness, favoring a palate of virtual responses instead. This paper, after examining the four specific precedents of Negroponte, dECOi, Diller & Scofidio, and NOX, will examine how a fifth precedent—that of Buckminster Fuller’s model of tensegrity structures—may be applied. The paper will propose that by actuating a tensegrity structure a responsive architectural envelope that addresses real world weather and structural loading conditions becomes feasible.

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1 Introduction:

The common definition of responsive architecture, as described by many authors, is a class of architecture or building that demonstrates an ability to alter its form, to continually reflect the environmental conditions that surround it.

The term responsive architecture was given to us by Nicholas Negroponte, who first conceived of it during the late nineteen sixties when spatial design problems were being explored by applying cybernetics to architecture. Negroponte proposes that responsive architecture is the natural product of the integration of computing power into built spaces and structures, and that better performing, more rational buildings are the result (Negroponte 1975). Negroponte also extends this mixture to include the concepts of recognition, intention, contextual variation, and meaning into computing and its successful (ubiquitous) integration into architecture. This cross-fertilization of ideas lasted for about eight years. Several important theories resulted from these efforts, but today Nicholas Negroponte's contributions are the most obvious to architecture. His work moved the field of architecture in a technical, functional, and actuated direction. Since Negroponte's contribution, new works of responsive architecture have also emerged, but as aesthetic creations—rather than functional ones. The works of Diller & Scofidio (Blur), dECOi (Aegis Hypo-Surface), and NOX (the Freshwater Pavilion, NL); are all classifiable as types of responsive architecture (Diller & Scofidio 2002; Liu 2002; Lootsma and Spuybroek 1997). Each of these works monitors fluctuations with the environment and alters its form in response to these changes. The Blur project by Diller & Scofidio relies upon the responsive characteristics of a cloud to change its form while blowing in the wind. In the work of dECOi, responsiveness is enabled by a programmable façade, and finally in the work of NOX, a programmable audio–visual interior. All of these works depend upon the abilities of computers to continuously calculate and join programmable digital models to the real world and the events that shape it.

This paper proposes that from the general features of these works (their dependence upon computing, their connecting digital models of the world to the real world, and their desire to make continuously altering forms of architecture), two very simple categories of features are realizable. The categories of features are: 1) that responsive architectures must be able to cope with dynamic loading conditions that result from environmental changes; and 2) that the adjustments made in response to these changes must be controlled. To complement these categories a further category may arise if future responsive architectures are functional. This third category is, 3) that all responsive buildings must provide shelter from changing environmental conditions. By adopting the stance that responsive buildings provide a means of improving the functional abilities of architecture, this paper will focus upon those characteristics that arise from the first and third points. The paper will begin by describing four precedents, their features, and downfalls, then suggest how functional responsive architectures can be made by using actuated tensegrity structures.

2 Responsive Architecture's Built and Un-Built Precedents:

Understanding that responsive buildings belong to a type of architecture that is definable and that has three categories of features does not provide one with a sufficient understanding of the subject. Responses can be generated in many different ways and for different reasons, so it is advantageous to examine existing built and un-built precedents to gain an initial understanding about what variety of responses is possible—and the uses to which they have been put.

The precedents are few, and are deserving of a much deeper exploration than can be offered within this paper. Problems of performing research within this area should now be acknowledged. These are: 1) few precedents currently exist; 2) precedents that do exist are poorly documented; 3) precedents that do exist tend to focus upon aesthetic responses rather than functional responses; 4) until a built, functional responsive architecture exists, studies about efficiency, thermal performance, and social effects are impossible to perform with accuracy; 5) many of the reasons for producing a functional responsive architecture are hard to demonstrate without empirical data to back them up.

2.1 Diller & Scofidio's Blur:

The work of Diller & Scofidio, called Blur, was built by using a traditional (static) tensegrity structure to support an open deck. The structure, cloaked by a network of computer-controlled nozzles, was then shrouded by mist to produce a responsive building envelope that had the ability to change its shape whenever the wind blew. This technique allowed the size of the cloud, and therefore the size of the building envelope, to be directly related and responsive to the environmental conditions that surrounded the building. Only one changeable parameter controlled all of this—the density of the mist produced.

Sensors were placed to measure wind speed and the natural air humidity both within the building and along the shoreline in order to collect the environmental data used to control the rate of mist produced by the computer-controlled nozzles. A further level of control was then made possible by breaking the building down into several individually controllable zones that enabled portions of the building to be shrouded at different rates. The aim of controlling the building in this way was to produce enough mist to cover the entire structure while not allowing it to drift or stray too far from the building (Diller and Scofidio 2002).

While this work of architecture uses responsive technologies to control the size and shape of its envelope dynamically, the scope of control exerted over the building form is limited—although still sufficient to achieve a new design aesthetic. The architects of this building use the ability of a cloud to blow in the wind to evoke emotional responses from building users. They accept that a single parameter of control and the materials used do not produce a new type of architecture that is functional.

2.2 dECOi's Aegis Hypo-Surface:

By using very different techniques from those of Diller & Scofidio, the work of dECOi architects called "Aegis Hypo-Surface" was built upon a framework of pneumatic pistons, springs, and metal plates, all of which were used to deform a façade-like surface (Liu 2002). By reverse engineering the wall from sources of published information, a plausible picture of the inner working of the surface follows. Behind the façade's surface, many pneumatic pistons attach to metal plates that form the wall surface. Springs are then attached to both the pistons and the static structural frame, helping to control the location of each piston by providing it with a failsafe means of returning to a known starting point or resting state. By understanding the typical way pneumatic pistons are controlled, we can also understand how the wall is actuated by distributing air pressure between two different pneumatic chambers (within the body of a piston) in different combinations to allow the piston to extend, to contract, or alternatively jitter in a mode that enables it to extend and contract very rapidly. A computer was then programmed to fire each piston sequentially in order to produce a series of patterns that responded to environmental stimuli—sound being the particular stimuli used. A very traditional, static, frame supported all structural loads.

Like the Blur project, dECOi's work does not attempt to provide functional solutions for a new type of architecture. The strategies used to produce the wall do not resolve or identify how architectural facades or weather resistant responsive building envelopes are made. It also does not provide a connection between dynamic building skins and the structures that support them. Thus a responsive architecture that consists of a functional building envelope which shelters people from environmental loads by addressing the principles of cold bridging, rain screens, and the dynamic transferring of structural loads still needs to be resolved.

2.3 NOX's Freshwater Pavilion:

NOX's Freshwater pavilion in Holland provides another powerful example of what the future of responsive architecture may hold. The Freshwater Pavilion has a responsive interior that uses the advantages offered by virtual environments to produce programmable spaces.

It accomplishes this by connecting a virtual representation of the world to the physical world through a vast array of blob trackers and light sensors connected to three different "interactive" systems that operate together (Lootsma and Spuybroek 1997). These three actuating systems drive 1) projected animations, 2) a lighting system, or 3) an audio system. Each of these three systems is placed throughout the building to make a rich, multimedia environment. At close range, blob-tracking sensors monitor environmental changes such as the movement of bodies in space (blob tracking demands video sensors). In the distance, changes in light levels (sensed either by video sensors or photo-resistor technologies) further control how environmental responses occur. Lars Spuybroek writes, "Every group of sensors is connected to a projector that shows a 'standard' wire frame grid which translates every action of a visitor into real-time movements of (virtual) water. The light sensors are connected to the 'wave'. Every time one walks through a beam of infra-red light one sees a wave going through the projected wire frames . . . visitors can create any kind of interference of these waves" (Lootsma and Spuybroek 1997).

Although not yet of a physical form of responsive architecture this work does suggest the possibility of producing spaces that are completely responsive. Furthermore, the work suggests that by layering a digital world model onto the real world the depth and complexity of responses produced within a space can be very rich—a point echoed by traditional models of artificial intelligence. Incidentally, the computational model of this environment is based upon embedded computation. This model, with some 190 lights, driven by 190 different distributed microprocessors, differs significantly from dECOi's model that uses one computer to drive several hundred actuators.

2.4 Negroponte's Model:

For Negroponte responsive architecture is a function of intelligence (Negroponte 1975). He believes that the integration of artificial intelligence into architectural environments is critical to producing a responsive architecture that is capable of performing adequately (the recognition of just how much intelligence is required to identify the context of an event and the appropriateness of a response is important to Negroponte). He also believes that responsiveness in architecture will manifest itself in two different forms—as informational responses that are not physical—and as responses that are overt, physical actions (Negroponte 1975). Negroponte calls each of these two forms of responsiveness, reflexive action, and simulated action, both of which are functional.

Citing a hypothetical example of a reflexive architectural action, Negroponte quotes Avery Johnson's 1971 work called "The Three Little Pigs Revisited," and says "walls that move to the touch–relevant to the function of support or moving back in retreat–that change color and form: streamlining themselves to the wind or shrinking down when unoccupied, are all possible" (Negroponte 1975). Simulated actions, on the other hand, include a room that can emulate an environment to entertain users. Breaking these ideas down still further, Negroponte suggests that two different varieties of simulated or reflexive responses are possible and describes them as being either operational or informational (Negroponte 1975).

Operational responses include those that contribute to how a place functions (a robot that responds to clean a house is the particular example he gives). Informational responses are similar to operational responses but they specialize in the control and provision of information that is useful or desired by users within a space.

Summarizing all of these response types, Negroponte proceeds to describe the overall picture of a responsive architecture as being the production of a "dramatically different relationship between ourselves and our houses, one characterized by intimate interaction" (Negroponte 1975). He goes on to say that design processes within this type of architecture will change, one result of which may be the integration of design and building processes into a single, continually operational process. His work does not suggest how these architectures may actually be built—although he does favor the use of soft materials and structures (such as inflatable membranes) over hard materials and structures (no examples of hard materials are given) (Negroponte 1975).

3 Producing a Functional Responsive Architecture:

Against the criteria of function, the discussed precedents are not adequate. No built precedent provides for responsiveness in structure and shelter together. Negroponte's work, as an un-built precedent, does give us examples of what this architecture might look like and how it should function; however, it does not realize how it can be built. So, how can a functional responsive architecture be built? Are there any other precedents that can be used or modified to suit this cause?

The ideal version of a functional responsive architecture is one that can provide shelter against changing conditions, as well as calculate how these changes affect the type of shelter needed. It would also have the capability of calculating how dynamic and changing structural loads are distributed through the structure successfully. These loads come from two basic sources, those loads caused by the building's own responses (shifting walls, etc.), and those caused by external loads acting upon the structure such as wind, rain, or snow. To produce this type of architecture and ensure that it is functional, traditional principles of weather screening, cold bridging, and load transmission need to be observed.

The incorporation of these principles within a responsive architecture does provide a challenge for architects—many of whom turn to inflatable technologies or "soft" materials to solve perceived design problems. The following work results from the endeavors of this author to produce a responsive architecture from "harder" materials and structures. When modified, Buckminster Fuller's system of tensegrity provides one means of making a functional responsive architecture that meets the above criteria.

3.1 Using Tensegrity To Produce A Responsive Architectural Envelope:

In 1962, Fuller and Snelson patented Tensegrity (Oppenheim and Williams 1997). Tensegrity systems are those composed of two types of discrete members, tension members and compression members that form self-stressing structures. The type of tensegrity system proposed for use by this paper consists of a repeated module in which three compression members meet to form what can be simply described as a tripod whose legs are tethered by tension cables—as depicted in figure 1. Repeating this module in a regular pattern, results in the formation of two membranes that have variable and controllable rigidity—figure 2. In principle the act of controlling the rigidity of these two membranes results in the possibility of producing structures whose shapes can alter. Thus by actuating the structure, in the correct locations, a deformable, responsive, structure can be made.

Two important structural principles help us further understand this position; both are discussed in a book called *Smart Structures and Materials*, written by Brian Culshaw. Culshaw notes that restraints in load transmission must be met in all structures, whether or not they are responsive. Thus "the 75-kg weight lifter will make no progress on lifting his or her own weight unless the bench on which he or she stands is capable of surviving the 150-kg load regardless of how adaptive or intelligent the weight lifter may be" (Culshaw 1996). He also suggests that one of the key features to any responsive structure is its ability to alter its stiffness rather than strength. "In most cases the adjustable strength aspects of the structure will involve more material, more weight, and certainly more complexity than the more simple structure designed to operate under the full range of loading condition" (Culshaw 1996). His thesis turns to natural structures that employ variable stiffness to distribute loads dynamically through their bodies in order to overcome difficulties in load transmission.

3.2 The Location, Limits, and Role of Actuation:

Actuators are mechanical devices used to alter the state of a physical system or structure. Actuation refers to the application of a mechanical device to achieve a physical task. For this paper, actuation implies the use of mechanical devices to manipulate the rigidity of a structure.

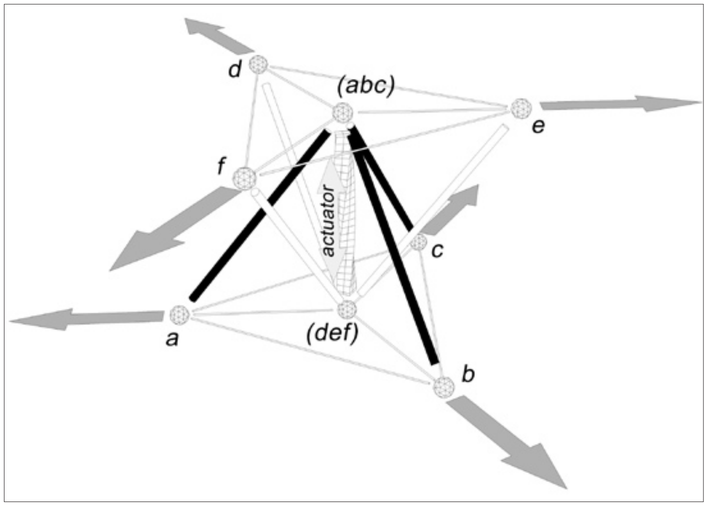

Figure 1. The simplest actuated unit of a tensegrity structure, made more rigid by pulling each apex towards its opposite, forcing each 'tripod' leg outward until the cables are tight.

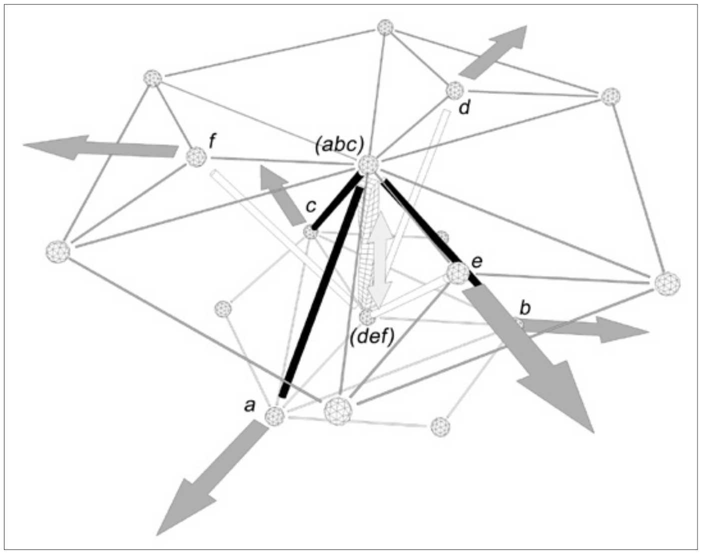

Figure 2. The simplest actuated unit of a tensegrity structure, but this time shown with a cable configuration that enables the unit to be multiplied out into a much larger structure.

Actuating a structure, however, is not enough to produce responsive architecture. Responsive architectures only come into being when actuators are coupled with other devices so that activities and changes within the real world can be interpreted, computed or processed, and then outputted back into the real world as an action or response. By tying these responses or actions to a structure and building envelope, responsive architecture becomes feasible.

The location or position of an actuator within a tensegrity structure is especially important and determined by two guiding principles, those being: 1) that cables can only be loaded in tension, and 2) that struts can only be loaded in compression. Culshaw's previous words dictate that actuation should also provide for the greatest amount of control over the structure's rigidity—this implies that the best location for actuation occurs at the apex of each structural unit, where the three compression members meet and where opposing structural apexes may be connected by an actuated component. Through the mechanical action of an actuator, force may be applied to each structural unit in combination, either pulling them towards each other to increase structural rigidity, or pushing them apart to decrease rigidity. Limits to the amount of applied force imposed by an actuator upon a structure are determined by examining the shape of a structure as well as the way in which a structure is required to operate (how much movement is desirable).

The manner in which a structure transfers its loads and the form (or shape) that a structure needs to adopt helps us know how much tension is required for the building to maintain or take a shape. With this in mind, the form of a tensegrity structure relates to both its physical design (the length of tension and compression members) as well as the ability for an actuator to apply forces to the structure and make it rigid. Accepting that the only readably changeable variable within a built structure is its rigidity further links building shape to actuated forces. Figure 3 describes this condition for the case of a parabolic vault like construction. In this particular example, the lower portion of the vault must remain rigid to maintain a vertical position, while the upper vault slackens to produce a curved surface. Removing tension from the lower region of the vault, by reducing forces applied by an actuator, allows deformation suggesting that the stiffness of this region may warrant a limit (to avoid possible structural collapse).

Actuators, when controlled by a computer, or several distributed computers, should be conceived of as programmable and thus as providing a means to connect computation to the physical control of a structure or building envelope. As a model, this opens the door to producing a responsive form of architecture that connects computation to a class of "harder" materials and structures that are capable of being responsive, and perhaps more suitable than structures made responsive through inflatable technologies. Responsive architecture demands that the role of actuation be linked to computation, no matter what its brand (be it analog computation or digital computation or a hybrid of both).

The methods I believe most suitable for establishing control and linking it to events within the real world will now be discussed in conjunction with issues of waterproofing, insulating, and future applications.

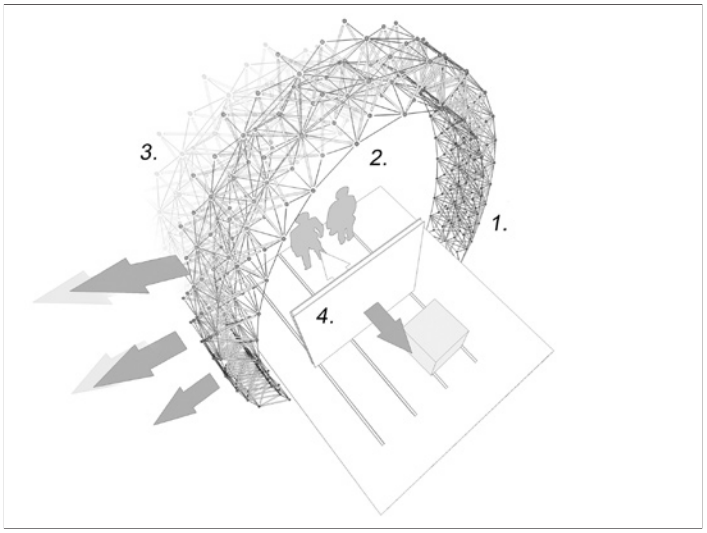

Figure 3. 1. lower structure must be more ridged to support loads without collapse. 2. upper structure can be less ridged. 3. by adjusting the tension and rigidity of the structure physical movements are enabled. 4. when coordinated with other responsive elements (ie. an internal partition) the functional abilities of buildings may be further extended.

3.3 Bringing It All Together:

To reiterate, all functional architectures must shelter people from environmental conditions as well as perform structurally. Responsive architectures must perform in a similar way if they aim to be functional.

The primary principle or method used to waterproof buildings today is the rain or weather screen. Rain screens work by separating building components that have different functions into two distinct layers of construction. One layer deals with insulating the building, and the other layer protects the building (and the insulating layer) from water. Each of these two layers is separated to allow for a natural airflow between the waterproof membrane and insulation. The function of this gap is: 1) to remove the chance of negative air pressures forming behind the waterproof membrane, thus stopping water from being sucked into the structure; and 2) to provide a draft that evaporates any moisture which collects upon the insulation, thus increasing its capacity to insulate. The layering required for producing a rain screen can easily be built into tensegrity structures because tensegrity structures also depend upon natural separations between three different functional layers—with two layers consisting of tension members between which a third layer of compression members is sandwiched. By cloaking one layer of tension members with a soft waterproof membrane, and the second layer of tension members with an insulating membrane it becomes possible to turn a tensegrity structure into a weather tight building envelope—Figure 4. By merging each discrete system, a responsive architecture that protects building users from environmental conditions becomes feasible.

To control the protective envelope a suitable strategy for integrating distributed computing into the structure becomes the next goal. After having previously identified the way in which the rigidity of a structural unit can be controlled, it is possible to realize that entire structures may be modularized and made controllable by distributed and embedded computing power. The simplest actuated control module thus consists of two opposing “tripods,” an actuator (that connects the structural units together), a processor, a sensor, and power source, which may or may not be modularized. The resulting active structural unit can then be designed to collect information from the real world (via its sensor), calculate and process the collected data, and then adjust the actuator to tighten or loosen the structure thus affecting the rigidity of an architectural envelope. Within this configuration, a structure that consists of many hundreds or thousands of actuators produces a very robust building envelope that moves in an emergent way.

The system may be constructed differently still to produce more useful behaviors. For example by pooling sensor data together from several regions of a structure (by connecting many actuators, processors, and sensors together), the scale of a response can be increased to enable larger (less localized) structural responses to occur. Larger scale responses add functionality to a responsive structure and enable it to cope with loads that are exerted over larger areas, such as earthquake or wind loads. Responses that are still more useful are generated by further modifying the system to allow for the inclusion of higher levels of processing (for example reasoning processes generated by Bayesian networks or other forms of artificial intelligence), to motivate actual building responses. The complexity of this topic is beyond detailed resolution within this paper—a recent paper by this author, dealing with issues in controlling responsive architecture is located within the proceedings of the eCAADe conference, Graz Austria, September 2003.

4 Future Applications In Architecture & Its Practice:

Actuated tensegrity structures may make a functional responsive architecture, but are visions for the practical use of this type of architecture foreseeable?

Theatres that dance with performers, houses that shrink to reduce their surface area and heated volume in the dead of winter or that cover themselves in the glare of a summer’s sun, and skyscrapers that alter their aerodynamic profile to reduce wind loads, provide three very different applications of this technology all of which are plausible and foreseeable. Further applications that deal with the networking of buildings to coordinate responses between many individual buildings and structures are also foreseeable. To envisage how a network of

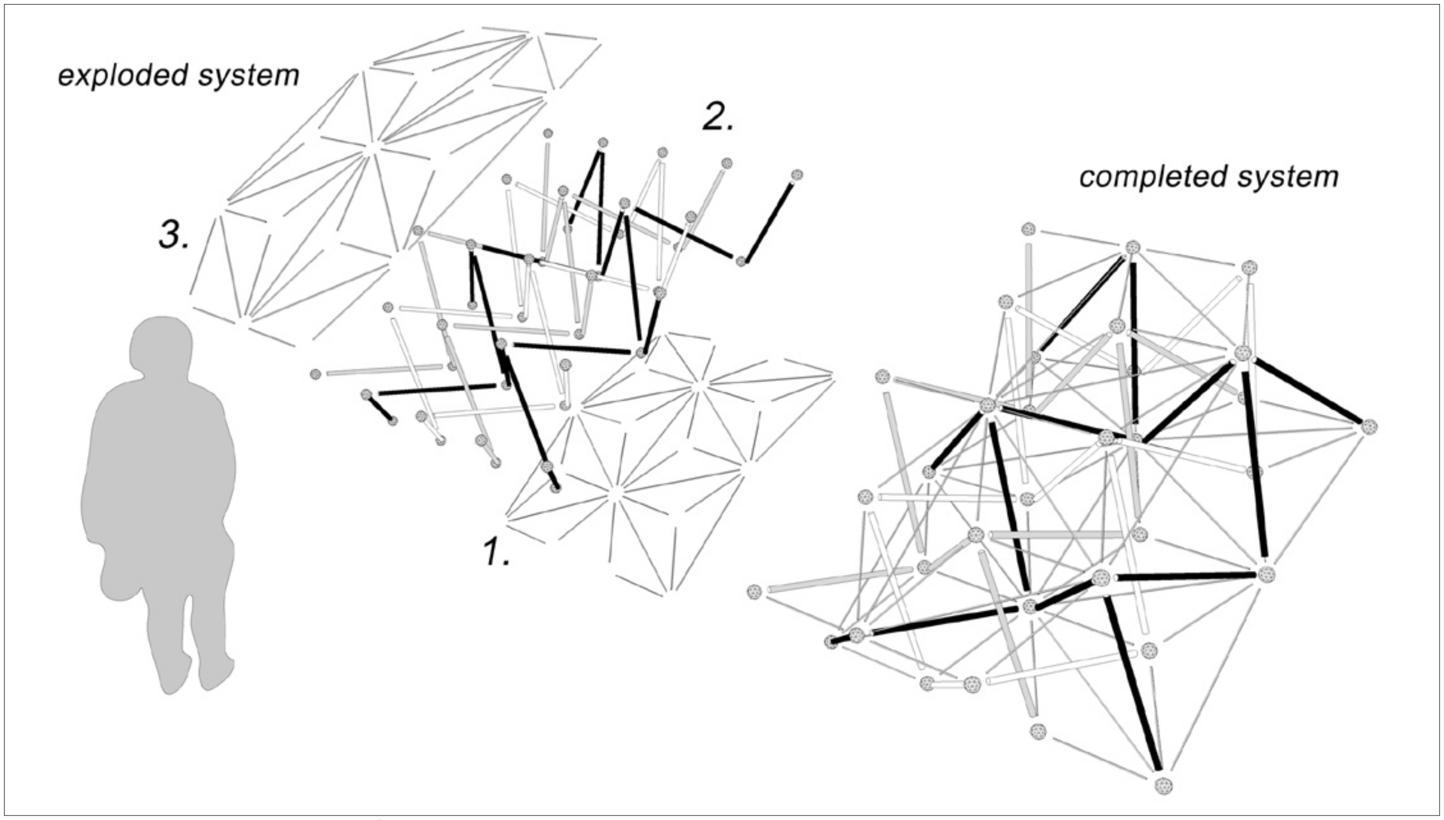

Figure 4. 1. the inner (lower) cable configuration is sheathed with an insulated membrane. 2. the compression members separate each membrane. 3. the outer (upper) cable configuration is sheathed with a waterproof membrane.

buildings can coordinate their actions to good effect, consider the following example. If a cluster of tall responsive buildings is exposed to wind, and one of those buildings changes its shape to reduce the wind load exerted upon itself, but in the process of doing so accidentally reflects wind onto a second structure, a situation may arise that harms the second building. The most elegant way of preventing this problem, or rapidly solving it when it arises, is to network buildings together so that the actions of one building and the consequences of that action (within a community) become associated, identified, and avoided (if the consequences are harmful). On the flipside of this same coin, it also becomes possible to envisage how the advantageous actions of a building can become more readily identifiable. For example, networks may allow a series of buildings to make unexpected discoveries when an action produced by one building enables other buildings to achieve a higher level of performance. Applications of this technology can occur within all types of building envelopes. They will occur whenever building envelopes need to demonstrate changes of function and use, or when responses help buildings become more sustainable. As a new type of architecture, it also offers the potential to challenge some of the conventional design methods and models used within architectural practice.

The aesthetic opportunities raised by a responsive building envelope make these technologies favorable for building types where the events that occur within a space should influence the shape of a building envelope. Familiar principles that generate this type of aesthetic come from some of the original arguments of modernism, as expressed by the notion of form following function, or the similar idea of having buildings reflect, and be the natural product of, truthful (or obvious) connections between the envelope of a space, its structure, and the events that fill it—all because responsive architectures have the ability to translate spatial activities into changing architectural form.

The sustainable opportunities of responsive building envelopes appear to be more promising still. The possibilities raised by an architecture that can respond to sunny, shady, hot, or cold conditions would suggest that responsive buildings possess the means to produce spaces that are informed by environmental conditions. As a by-product of this, it is entirely conceivable that actively changing spaces that monitor and adjust to suit surrounding environmental conditions will provide those who inhabit responsive buildings with new, active, relationships to the natural environment.

Other opportunities that responsive architectures raise are those that affect architectural practice. Responsive architectures, especially those based upon computational models that are heuristic, or artificially intelligent and self training, open architectural practice to the handing over of design activities to those who own or occupy space. Responsive architectures, are programmable by nature and as such offer any individual the chance to modify the way buildings behave. This change may result in an individual's ability to remove and replace the original architectural behavior of a design, with new, more appropriate, suitable, and useful building behaviors. One might conceive of this shift as being the "soft" equivalent of extending a house. However, as the earlier example of networking skyscrapers suggests, the ability to program a building to respond differently than intended may need to be limited. Reprogramming a skyscraper to purposefully deflect wind onto a neighbor might not be favorable—limits would have to apply.

Architectural practice is also likely to alter in a second, less anticipated way. It is very likely that the practice of architecture will change when the opportunity to access real world data collected by responsive buildings presents itself to the discipline. Architects who operate within this new environment, who have access to information about the performance of their buildings, would not just be bound to safeguard the privacy of a client but also use this data to improve future building designs.

5 Conclusion:

This paper outlines how actuating and applying rain screen principles to tensegrity structures produces a functional responsive architecture. It examines four precedents to understand the qualities of their manufacture, their functionality, and the intentions of their designers.

The ideas contained within this paper result from work carried out by the author to build a functional and responsive tensegrity structure (measuring 1.5 meters by 1 meter - flat), actuated by thermally sensitive memory metals. Each actuator is controlled through a mixture of distributed, embedded, digital, and analog circuitry.

I will soon be extending the work contained within this paper to produce a large-scale structure in the form of a parabolic vault (measuring 2.8 meters tall by 2 meters wide). The prototype will be built from aluminum, rubber, steel components, and controlled by a mixture of digital and analog technologies that are distributed through the structure. To further complement this work, a paper addressing control issues of responsive architectures has been written for the September 2003, eCAADe conference, in Graz Austria.

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