



ACADIA 2013 **ADAPTIVE ARCHITECTURE**

Waterloo / Buffalo / Nottingham

Proceedings of the 33rd Annual Conference
of the Association for Computer Aided Design in Architecture

Edited by Philip Beesley, Omar Khan, Michael Stacey



ALLOPLASTIC ARCHITECTURE: THE DESIGN OF AN INTERACTIVE TENSEGRITY STRUCTURE

Behnaz Farahi Bouzanjani,
Neil Leach, Alvin Huang
University of Southern California
School of Architecture
Michael Fox Cal Poly Pomona



1 Alloplastic Architecture: a performance artist dances with the structure that reacts to her presence

ABSTRACT

This paper attempts to document the crucial questions addressed and analyze the decisions made in the design of an interactive structure. One of the main contributions of this paper is to explore how a physical environment can change its shape to accommodate various spatial performances based on the movement of the user's body. The central focus is on the relationship between materials, form and interactive systems of control.

Alloplastic Architecture is a project involving an adaptive tensegrity structure that responds to human movement. The intention is to establish a scenario whereby a dancer can dance with the structure such that it reacts to her presence without any physical contact. Thus, three issues within the design process need to be addressed: what kind of structure might be most appropriate for form transformation (structure), how best to make it adaptive (adaptation) and how to control the movement of the structure (control). Lessons learnt from this project, in terms of its structural adaptability, language of soft form transformation and the technique of controlling the interaction will provide new possibilities for enriching human-environment interactions.

INTRODUCTION

How might we imagine a space that can build an understanding of its users through their bodily gestures, visual expressions and rituals of behavior, and respond accordingly? How might we envision a space whose interactivity is based not simply on pre-programmed operations, but on real-time feedback from its users? In other words, how might we envision a genuinely interactive space whose form and physical configuration can respond to and learn from its users? And how might such a space influence how we inhabit our environment, and change the way we live?

This paper analyzes an interactive installation project that addresses these questions. More precisely, the project looks at the interface between remote sensing and a responsive environment to explore the possibility of an interactive architecture that conditions and responds to the user's movements. The project does not seek to invent new technologies *per se*, but rather to use existing ones, show their possible application, and thereby understand new interaction scenarios and techniques that might inspire future research in this area. This paper remains grounded in "hard science" as opposed to science fiction.¹ So, as Michael Fox says, "the objective is to make convincing extrapolations based on where we stand today through inclusively appreciating and marshalling correctly the existing facts with respect to technological development" (Fox 2008:2).

In particular, the paper analyzes three critical issues within the project's design process:

1. What kind of structure might be most appropriate for form transformation (*structure*).
2. How best to make it adaptive (*adaptation*).
3. How to control the movement of the structure (*control*).

MOTIVATION

If architects designed a building like a body, it would have a system of bones and muscles and tendons and a brain that knows how to respond. If a building could change its posture, tighten its muscles and brace itself against the wind, its structural mass could literally be cut in half (Guy Nordenson 2005: 300).

For some time from cyberneticians such as Gordon Pask in 1960s to development on "intelligent environment" (IE) in 1990s until now, scholars have been discussing interactivity. "Responsive", "interactive", "transformable", "adapt-able" or "actively sustainable systems" are among the many terms that have been used by different scholars in this field. However, the first step to creating an interactive environment is to define parameters that contribute to the type of adaptation either through mechanical or biological approaches.

As Gary Brown notes, recent developments have indicated a shift in adaptation from a mechanical paradigm to a biological paradigm. "Organic theory emerges from nature, an environment that possesses evolutionary patterns that have a base code

where information is strategically interrelated to produce forms of growth and strategies of behavior, optimizing each particular pattern to the contextual situation" (Brown 2002:2).

To design a "biologically" adaptive system, observing how living creatures in nature adapt constantly to different external and internal stimuli can offer considerable inspiration, both in terms of their structural configuration and their process of adaptation. This considered, the issue is not simply how to create a system capable of changing but also how to research the quality of change and define the stimulus for adaptation.

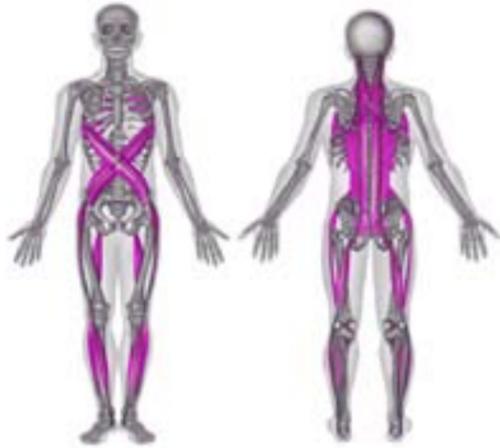
In "Alloplastic Architecture", the intention was to create spaces that could physically re-configure themselves based on user movements like any soft adaptive system in nature. As Sanford Kwinter observes, soft systems evolve by internal regulating mechanisms, yet are always in collaboration with forces and efforts arriving from an outside source (Kwinter 1993:218). Accordingly, this paper will focus on the installation's adaptive tensegrity structure that responds to human movement and the decision making process behind its design. The main intention behind the design of the installation was to address the potential of a reciprocal transformation between a user and an architectural element such that the architecture could adapt to the user, and the user adapt to the architecture. The impulse behind the project was a desire to engage with the psychological benefits of an environment that can respond to, and therefore empathize with, human emotions through its capacity to adapt physically to the user. As such, the environment can be seen to overcome conditions of shock or alienation by accommodating the user.

The name given to this particular installation is "Alloplastic Architecture." "Alloplastic" is a term taken from psychoanalysis. Used by Sigmund Freud, Sandor Ferenczi and others, the term refers to the individual influencing the environment and causing it to change. "Alloplastic" should therefore be contrasted with "autoplastic" whereby the individual must adapt to its environment. "Alloplasticity" may be construed as the more healthy condition in that "autoplasticity" is associated with neuroses. Within an architectural context, the term has been adopted by Mark Goulthorpe who identifies "alloplastic" with the possibility of a reciprocal transformation in which both subject and environment negotiate interactively (Figure 1).

STRUCTURE

We shall no longer be dealing purely with spatial qualities. The fluid capacities of interconnected and interacting material systems to move and to change, to correlate themselves to other external movements and changes, to embrace some bandwidth of the aleatory, and to undergo spontaneous transformation in time will be of increasing importance (Kwinter 1993:226).

What kind of structure might be most appropriate for form transformation?



sense, tensegrity structures can be “dynamic.” They have been inspiring for a number of researchers, including NASA’s Vytas Sunspirial who has been researching the possibility of a rover designed to explore the surface of the Moon and Mars based on an adaptive tensegrity structure. Adaptive tensegrity structures have many advantages, but can be highly complex to control. As Sunspirial puts it, the very properties that make tensegrity structures ideal for physical interaction with the environment (compliance, multi-path load distribution, non-linear dynamics, etc.) also present significant challenges to traditional control approaches. Indeed, an understanding of the behavior of dynamic tensegrity structures—both mathematically and computationally—is an important subject, which could be the topic of another paper in and of itself. The main difficulty is that tensegrity structures exist only in specific, stable tensegrity positions (Whittier 2002:14). In other words, the control of an adaptive tensegrity 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. As Chalam explains, adaptive controls have been successfully implemented in diverse practical problems since these techniques can cope with increasingly complex systems that require extreme changes in system parameters and input signals (Chalam 1987:1). Thus, adaptive control is a suitable method for the tensegrity structure as the geometry and properties of the structure can be altered from changing the string lengths (Tembak, Rashid and Handoko 2003:33).

But what is the relationship or similarity between the body and a tensegrity structure? Fuller described tensegrity as “islands of compression inside an ocean of tension” (Motro 2003: 2). But what does a tensegrity structure have to do with the human body? Researchers believe that many biological systems, especially the human body, have principles similar to tensegrity structures for they can be applied at every detectable scale in the body. All bones that constitute our skeleton are pulled up against the gravity force and stabilized in a vertical form by the pull of tensile members, not so dissimilar to the cables in Snelson’s tensegrity sculptures. D.E. Ingber states that, in the complex tensegrity structure inside every one of us, bones are the compression struts, and muscles, tendons and Ligaments are the tension-bearing members. At the other end of the scale, proteins and other key molecules in the body also stabilize themselves through the principles of tensegrity (Ingber 1998).

Bodies and tensegrity structures are similar not only in their components, but also in their force distribution. As Vytas Sunspirial posits, bones in the emerging bio-tensegrity model are still under compression, but they are not passing compressive loads to each other. Rather, it is the continuous tension network of fascia (muscles, ligaments and tendons) that is the primary load path for forces passing through the body³ (SunSpiral 2012) (Figure 2). Additionally, if the force in one of the tensioned members in a

tensegrity structure is changed, all cables share the force to find a new equilibrium. This is quite similar to force distribution in a human body (Figure 3). Sunspirial explains:

Instead of the common sense “bone-centric” model where force passes comprehensively from bone to bone, one should take a fascia-centric view that looks at the global fascia network (that is continuous chains of muscles and ligaments) as the primary load paths in the body⁴ (Sunspirial 2013).

As a result, we can argue that such dynamic tensegrity structures are suitable for interacting with a dynamic world and reconfiguring themselves through time.

ADAPTATION

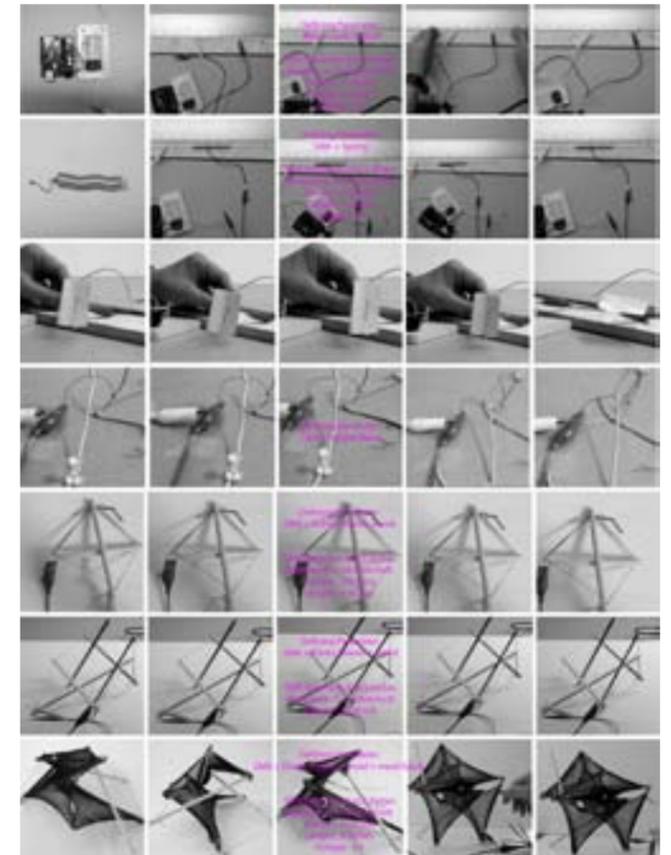
A type of world emerges whose material, technical, and architectural articulations—no longer simply objects, structures, or “building” but indeed electro-material environments at all scales—manifest themselves in a soft, perhaps insidiously holographic, manner, a world where everything flows seamlessly together in real time (Kwinter 1993: 227).

How best, then, to make a tensegrity structure adaptive like the human body?

Bill Gates once predicted that by the end of the first decade of the twenty-first century there would be nothing untouched by the digital realm (Leach 2012: 8). Arguably, this impact will be so pervasive by the end of the second decade that computation will hardly be noticeable any more. As such, computation would become a cohesive and integral part of the way people live by disappearing into the background. In other words, computers would be seamlessly embedded into the environment.

Moreover, as we shift from a mechanical to a biological approach, the properties of materials are likely to play an increasingly important role in the transformations of physical spaces such that they could move continuously in relationship to its users and their environment. We call materials that can be significantly changed in a controlled fashion by external stimuli, such as stress, temperature, moisture, electric or magnetic fields, “smart materials.” As Coelho notes, “Smart materials and their composites are strategically positioned to fulfil this desire by transforming input stimuli into controlled material responses, while presenting a wide range of material properties and behaviours” (Coelho 2008: 23). The implications of this are profound, in that such materials are likely to be used in an all pervasive way that will have a fundamental impact on the way that we live. As Trivedi argues, “The advantages of these materials that exhibit electromechanical properties are paving the way for the seamless integration of sensors and actuators into the environment, expanding the limits of where computation can be found and reshaping the ways in which we interact and communicate” (Trivedi 1998: 9).

There is already a vast range of smart materials. However, these can be reduced to three main categories⁵:

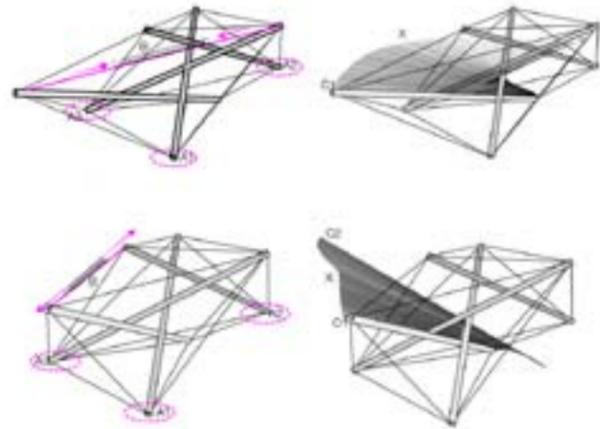


4 Experiments in the behavior of smart materials and studying dynamic tensegrity structures

1. Color changing materials
2. Light emitting materials
3. Moving materials

The intention behind studying smart materials is to embed them within a tensegrity structure whose inherent properties can be changed to meet dynamic external changes. One possible solution for creating a living system is to prototype and experiment with “smart materials” and define their behaviour and form based on different stimuli. Thus, there needs to be a constant process of back and forth negotiation between the computer and physical models in order to bring these ideas into reality. For this research, shape memory alloys (SMAs) have been chosen as they are one of the least expensive and most accessible of smart materials for designers and architects to experiment with. They are alloys that, after being subjected to various inputs, eventually revert back to their original shape. As their name suggests, SMAs have a “memory” of their original shape (Figure 4).

2 Material of Force Transmission



3 Simulation of Tensegrity Structure digitally and study of force distribution

Central to interactivity between a user body motion and the environment is the notion that for this process to happen effectively there should be a common logic of behavior shared by both user and the environment. If both the body of the user and the structure of the environment itself are governed by a similar logic of behavior, then the modeling of the behavior of one on the other will be all the more easy to engender. For example, as Michael Fox and Miles Kemp put it, one response might be to design a building similar to a body with a system of bones, muscles and fascias, and augmenting that body with a “brain” that knows how to respond in certain situations (Fox and Kemp 2009).

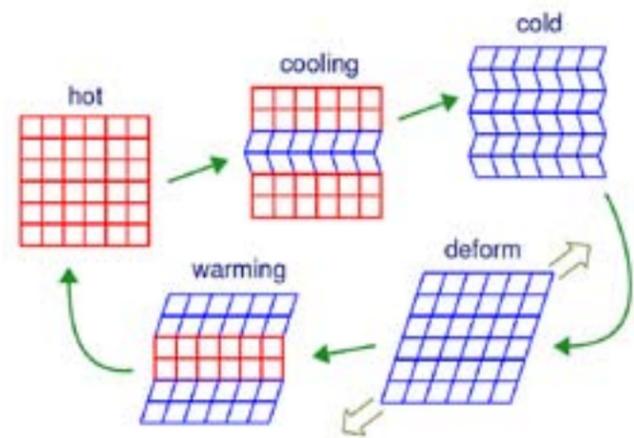
Such a response could be the use of tensegrity structures in that the body itself can be understood as a tensegrity structure. Tensegrity structures are, of course, nothing new.² What is new, however, is the potential for these structures to adapt and change their form. In this

As Sylvain Toru notes, the shape memory effect is based on a reversible, solid-state phase transformation between the high-temperature austenite phase and the low-temperature martensite phase. These two phases correspond to two different crystal structures: one is cubic and the other is monoclinic (Figure 5).⁵ Therefore, although this alloy is weak at lower temperatures, it contracts forcefully and can at high temperature lift up quite heavy materials depending on the coil diameter.

In other words, the diameter of the wires is one of the really important factors for actuation. As experimental research in MIT Media Lab shows, higher diameter wires have more pulling force than lower diameter wires.⁷ Additionally, higher-diameter wires have lower resistance and draw more power.⁸ The same logic is true for SMA springs.

But how might these new developments in smart materials open up the possibility of an adaptive tensegrity structure that might mimic the behaviour of any adaptive living creature?

We can already recognise the potential impact of such a system, in terms both of its capacity to behave in a predictable and controlled way, and in its ability to respond intelligently to various challenges. As Sybil P. Parker notes, “The main characteristic of any adaptive structure is that it should be capable of sensing and reacting to its environment in a predictable and desired manner through the integration of actuators and sensors. In addition to carrying mechanical loads, smart structures may alleviate vibration, automatically perform precision alignments, or change their mechanical properties or shape on command” (Parker 1994: 1998). Now imagine if we replace some of tensioned members in our tensegrity structure with SMA springs, which operate as “muscles” that can realign a structure within a constant overall equilibrium.



5 The one-way Shape Memory Alloy effect

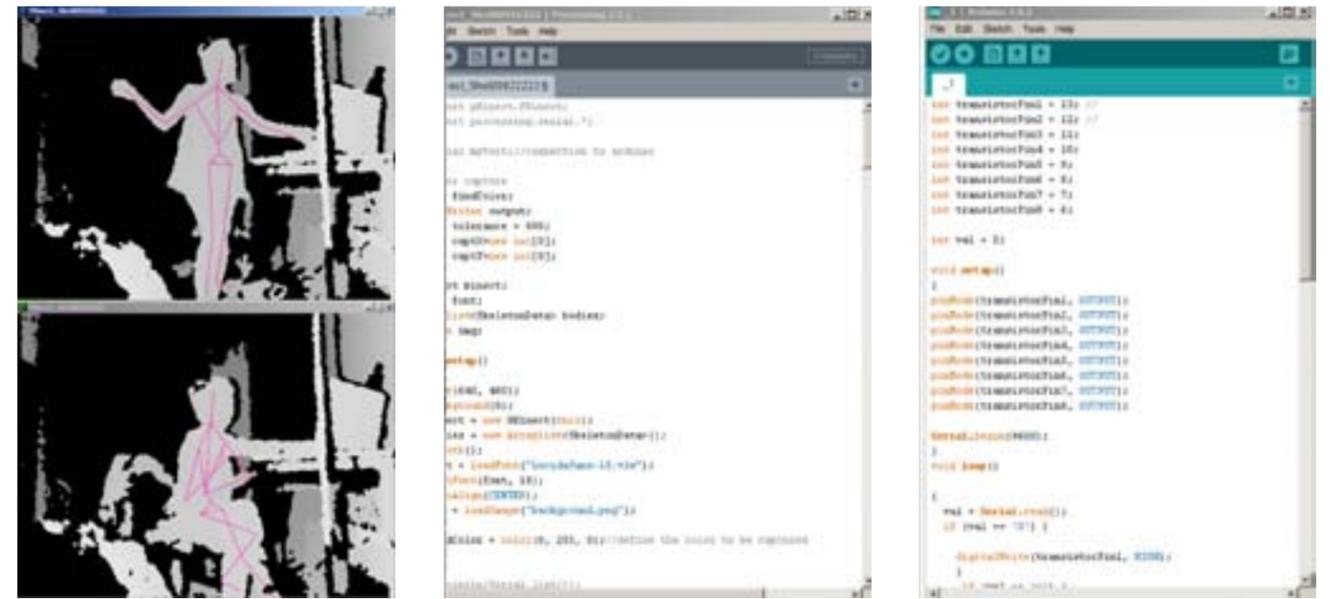
That equilibrium is maintained as other springs or expandable elements adjust their length to compensate for the initial movement, thereby reconfiguring the entire structure. Please note that in order to keep a tensegrity structure rigid, its members must be pre-loaded (Bronfeld 2010:7). This is why having elastic materials can help to calibrate the system in each moment. Of course, we have to distinguish between the varying behaviors of such materials. As Soong and Manolis observe, “Active structures consist of two types of load-resisting members: static or passive members, and dynamic or active members.” (Soong and Manolis 1987: 2300). In this sense, an “active” element of the structure breaks the equilibrium while the rest of the structure maintains dynamic stability in order to achieve the next phase of equilibrium. As a result, the structure moves. Similarly, in the Alloplastic Architecture project, SMA springs operate as “muscles” or active members, aluminium tubes as “bones” and textile fabric as “fascia” or passive members.

CONTROL

The next question is how to control the movement of the adaptive tensegrity structure.

In his movie, *Minority Report* (2002), Steven Spielberg presents a vision of the future that moves beyond the fantasies of science fiction to depict a technologically charged yet plausible future world. In fact, many of the devices that he envisions have since become a reality, as is the case, of course, with many other movies that have speculated about possible future realities, such as H. G. Wells, *Man on the Moon*, and the work of Arthur C. Clarke. However, what makes *Minority Report* so relevant from the point of view of this paper is that it predicts a device, the “spatial operating environment” interface, with which human beings are able to control their environment using bodily gestures in a manner similar to a conductor conducting an orchestra—a device that is now available commercially in the form of the Kinect motion-sensing device.

It would seem that *Minority Report* had an impact on the collective psyche in a way that science fiction shapes the future. As Jarrett Webb and James Ashley put it, “the film’s visuals immediately seeped into the collective unconscious, hanging in the zeitgeist like a promissory note” (Webb and Ashley 2012: 2). Moreover they began to resonate with a series of emerging concerns on the part of users, such that the film seemed to act as a catalyst for a series of subsequent developments. As Webb and Ashley observe: “A mild discontent over the prevalence of the mouse in our daily lives began to be felt, and the attention of the press and the public began to turn towards what we came to call the Natural User Interface (NUI). Microsoft began working on its innovative multi-touch platform surface in 2003, began showing it in 2007, and eventually released it in 2008. Apple unveiled the iPhone in 2007. The iPad began selling in 2010. As each NUI technology came onto the market, it was accompanied by comparisons to *The Minority Report*” (Webb and Ashley 2012: 2).



6 Experiments with Processing, Arduino and Kinect for Skeleton Tracking

But it was Kinect, perhaps, that responded most directly to the predictions made within the movie. Not only did it reconfigure the very nature of our interaction with technological environments, but not long after its launch, Kinect became famous worldwide, and its impact was truly remarkable. As Enrique Ramos notes, “Kinect was launched on November 4, 2010 and sold an impressive 8 million units in the first sixty days, entering the Guinness Book of World Records as the ‘fastest selling consumer electronics device in history’”. And indeed Kinect was the first commercial sensor device that allowed the user to interact with a console through a natural user interface (Melgar and Diez 2012: 23).

Technically speaking, not only does Kinect have an RGB camera, depth sensor and multi-array microphone, but it can also track body motion, sense hand/skeleton movement and recognize gestures. It does so through by using existing infrared based camera technologies developed to scan three-dimensional objects in space. As Adarsh notes, “Kinect is based on range camera technology by PrimeSense, which interprets three-dimensional scene information from a continuously projected infrared structured light. This three-dimensional scanner system called Light Coding employs a variant of image-based three-dimensional reconstruction” (Sundarand Kowdle 2011:7). In other words, the two depth sensor elements, the IR projector and IR camera, work together with the internal chip from PrimeSense to reconstitute a three-dimensional motion capture of the scene in front of the Kinect (Melgar and Diez 2012: 31).

Skeleton tracking is one of the functions of Kinect. The SkeletonStream produces SkeletonFrame objects and puts them together as an array to create a skeleton. It thereby defines a set of fields to identify the skeleton and describes the position of the skeleton and its joints. The skeleton tracking engine follows and reports on twenty points or joints on each user (Webb and Ashley 2012:6). The position of each joint is defined by X, Y and Z coordinates within a Cartesian grid. In fact, skeleton tracking employs a depth camera that uses an IR projector to record not the color of a surface but its distance of an object from the device. As Greg Borenstein comments, “Unlike conventional images where each pixel records the color of light that reached the camera from a particular part of the scene, each pixel of this depth image records the distance of the object in that particular part of the scene from the Kinect device” (Borenstein 2012: 6).

However, Kinect might be difficult to work with for architects without any consultants. Meanwhile, there are plenty of different ways to work with Kinect. For example, Kinect for Windows Software Development Kit (SDK) released in 2012 offers a set of libraries that can be added to programs. Alternately, Kinect SDK can be programmed with certain software such as C++, C# or Visual Basic. An open source programming language called Processing can be implemented for a more sophisticated result.

Given its range of capabilities, Kinect was chosen for the “Alloplastic Architecture” project. During the prototyping stage, the control circuitry of the tensegrity structure was simply programmed to cycle through a series of shape-changing animations in a sequence to create a wave pattern. However, once the Kinect sensor was added, the system became more sophisticated. From a technical point of view, the Kinect sensor captures the body of the user as a skeletal frame, detects its distance and position, and is therefore able to determine the exact position of the body in a Cartesian grid and send the information to the computer. Processing codes are sent through serial communication to the Arduino control board to actuate the SMA springs. In other words, the presence of the user informs which spring should be actuated and, as a result, the structure starts bending or repelling from the user.

Finally, a dancer was invited to interact with the structure and a video of the performance was recorded. As the dancer responds to the structure through her movements, the structure likewise responds to the dancer. What results is a bottom-up form of behavior, whereby the interaction of dancer and structure produce a series of unpredictable results. This is surely an example of emergence in operation (Figure 6).

CONCLUSION

This paper attempts to document the crucial questions behind the design of an interactive structure and analyze the decisions made within the design process. One of the main contributions of this paper is unraveling the fact that a physical environment can be designed to change its shape in order to accommodate various performances in the space based on user body motion. The paper also raises some interesting questions for the future. What would be a suitable structure demonstrating physical interaction with the dynamic world? How might we introduce SMA and other smart materials to be more comprehensively embedded in the environment resulting in an adaptive environment? And how might Kinect and other remote sensing devices be used more universally in order to enrich the way we interact with our surrounding environment?

Moreover, the paper also points to some interesting general questions about the changing role of design today. Not only do we find buildings beginning to operate in a more biological fashion such that even the design of components can be modeled on the principles of dynamic tensegrity structures that inform the human

body itself, but the very nature of design also faces a major overhaul. For a profession once dominated by a discourse of styles, we can detect a shift away from questions of representation and images and towards processes and material behaviors. Moreover, it is clear that these developments dramatically change the role of the architect. The architect no longer designs the final form but rather creates an initial state, introduces a set of controlled constraints and then allows the structure to be activated to find its form in real time. What results is the emergence of unexpected shapes. Does the advent of interactive architecture, therefore, not signal simply a shift to a more responsive way of handling the environment, but a radical challenge on the values that once informed the profession?

But perhaps the most interesting contribution of this project is to question the skepticism towards technology implicit within the philosophies of conservative thinkers such as Martin Heidegger, whose criticism of the potentially alienating effect of technology has helped to engender a negative attitude towards technology in general and in computation in particular—an attitude still prevalent in certain architectural circles (Heidegger 1993: 311-341). Far from being the source of alienation, the “Alloplastic Architecture” project shows that technology itself may actually combat alienation.

ENDNOTES

1. If the paper were to be grounded in hard science as opposed to science fiction, it would imply that even if an imagined possible future is currently fictional, it has a rigorous adherence to known science. In other words, we can extrapolate a possible future scenario based on what we know or what can be achieved today.
2. Buckminster Fuller coined the word “tensegrity” from two words: “tension” and “integrity”, and successive generations of artists, architects and engineers have developed the principle with an ever more sophisticated understanding of their behavior. The artist Kenneth Snelson built the first tensegrity structure.
3. <https://ti.arc.nasa.gov/m/groups/intelligent-robotics/tensegrity/pdf/tensegrity.pdf>
4. <https://ti.arc.nasa.gov/blog/irg/?p=713>
5. <http://www.designinsite.dk/htmsider/inspinfo.htm>
6. Toru , Sylvain. 2008. “Fast and Accurate Position Control of Shape Memory Alloy Actuators.” Master Degree Internship Report, University of Paris-Sud.
7. http://fab.cba.mit.edu/classes/MIT/863.10/people/jie.qi/flexinol_intro.html
8. <http://fab.cba.mit.edu/classes/MIT/863.10/people/jie.qi/>

WORKS CITED

- Borenstein, Greg.2012. “Making Things See: 3D vision with Kinect, Processing, Arduino, and MakerBot.” Sebastopol: Maker Media.
- Bronfeld, Avner. 2010. “Shape change algorithm for a tensegrity device.” Master of Science in Mechanical Engineering, TEL AVIV University.
- Brown, Gary.2002. “Freedom and Transience of Space (Techno-nomads and transformers) See Transportable Environments 2.” ed. Robert Kronenburg, Joseph Lim and Wong Yunn Chii. London: Spon Press.
- Chalam, V. 1987 . “Adaptive Control Systems: Techniques and Applications.” New York and Basel: Marcel Dekker, INC. Publisher.
- Coelho, Marcelo.2008. “Materials of Interaction: Responsive Materials in the Design of Transformable Interactive Surfaces.” Master of Science in Media Arts and Sciences, School of Architecture and Planning at the Massachusetts Institute of Technology.
- Fox, Michael, and Kemp, Miles.2009. *Interactive Architecture*. Princeton: Princeton Architectural Press.
- Fox, Michael. 2008. *Beyond Kinetic, Kinetic Design Group*. CITY: Cambridge, Massachusetts Institute of Technology, Department of Architecture.
- Heidegger, Martin. 1993. “The Question Concerning Technology in Basic Writings.” David Farrell Krell (ed.). New York: Harper Collins.
- Ingber, Donald E. 1998. “The Architecture of Life.” Scientific American Magazine. January 1998.
- Kwinter, Sanford. 1996. *Soft Systems*, in Brian Boigon, ed. New York: Princeton Architecture Press.
- Lanau, Torben. 1996-2008. “Design inSite.” <http://www.designinsite.dk/htmsider/inspinfo.htm>
- Leach, Neil ed.2012. “Urban Architecture (UA)”, No 97, p. 8.
- Melgar , Enrique Ramos and Diez, Ciriaco Castro. 2012. “Arduino and Kinect Projects: Design, Build, Blow Their Minds.” New York: Springer Science+ Business Media.
- Motro, René. 2003. “Tensegrity: Structural Systems for the Future.” London and Sterling. Hermes Kogan Page science.
- Parker , Sybil P. 1994. “McGraw-Hill Dictionary of Scientific and Technical terms.” 6th ed., McGraw-Hill.
- Qi, Jie. 2010. “How to make almost anything.” <http://fab.cba.mit.edu/classes/MIT/863.10/people/jie.qi/>
- Qi, Jie. 2010. “Intro to shape memory alloy actuation using flexinol.” http://fab.cba.mit.edu/classes/MIT/863.10/people/jie.qi/flexinol_intro.html
- Soong T.T. and Manolis G.D. 1987. “Active structures.” J. Struct. Eng. Vol. 113, No. 11: p. 2290-2302.
- Stach, Edgar. 2005. “Form-Optimizing Processes in Biological Structures. Self-generating structures in nature based on pneumatics.” Textile Composites and Inflatable Structures Computational Methods in Applied Sciences Volume 3: p. 285-303
- Sundar, Anandram and Kowdle, Adarsh. 2011. “3D INTERACTIVE INTERFACE USING A KINECT SENSOR.” Master of Electrical Engineering, Cornell University.
- SunSpiral, Vytas. “Tensegrity Snake Robot.” October 25 2012 <https://ti.arc.nasa.gov/blog/irg/>

SunSpiral, Vytas. “Distributed Control for Tensegrity Robots.” *NASA Ames Research Center, Intelligent Systems Division*. <https://ti.arc.nasa.gov/m/groups/intelligent-robotics/tensegrity/pdf/tensegrity.pdf>.

Tembak, Diana, Rashid ,Hafiz Md., and Handoko ,Wilson. 2003. “Adaptive Passive Control of a Tensegrity Structure.” Final Year Project, University of Adelaide, Faculty of Engineering, School of Mechanical Engineering.

Toru , Sylvain. 2008. “Fast and Accurate Position Control of Shape Memory Alloy Actuators.” Master Degree Internship Report, University of Paris-Sud.

Trivedi, Rohit. 1998. “Materials in Art and Technology.” Ames, Iowa: Trimet.

Webb, Jarrett and Ashley, James. 2012. “Beginning Kinect Programming with the Microsoft Kinect SDK.” New York: Apress, Springer Science+ Business Media.

Whittier, William Brooks. 2002. “Kinematic Analysis of Tensegrity Structures.” Master of Science in Mechanical Engineering, Virginia Polytechnic Institute and State University.

BEHNAZ FARAH has an undergraduate and two Masters degrees in Architecture. She is currently pursuing a PhD in iMAP in the School of Cinematic Arts at the USC where she is exploring the potential of interactive environments. Ms Farahi has also worked as an architect for SDA, and is the winner of the 2012 KAO International Award for Kinetic Art.

Ms Farahi has also worked with Professor Behrokh Khoshnevis on projects funded by prestigious NASA Innovative Advanced Concepts awards to explore the possibility of developing a robot to print structures on the Moon. She has also lectured and given workshops in several schools throughout the world, including USC, NUST and the Bauhaus.

Lorem ipsum dolor sit amet, consectetur adipiscing elit. Ut at massa et felis suscipit molestie sit amet et quam. Aliquam velit mauris, varius nec porta et, iaculis non lectus. Morbi viverra tellus in libero malesuada ut malesuada tortor pretium. Suspendisse sodales tincidunt est, vitae porttitor est fringilla eu. Nunc eget molestie ante. In porttitor dapibus pulvinar. Vestibulum in tortor adipiscing ante bibendum auctor. Aliquam purus ipsum, faucibus a pulvinar a, ullamcorper id nulla.

Aliquam in cursus odio. Pellentesque convallis pulvinar orci eget tincidunt. Praesent sollicitudin condimentum dapibus. In non felis tortor. Integer felis lectus, ultrices ac ornare nec, mattis a lacus. In fermentum imperdiet ultricies.

Phasellus felis lacus, tempus ac consequat a, vestibulum et neque. Aenean ornare ultrices risus, at vestibulum libero pretium non. Duis vulputate interdum ante, pretium suscipit nisl ultricies et. Vivamus quam dui, convallis vel tristique sit amet, accumsan eget nibh.

UNIVERSITY OF
WATERLOO


University of Buffalo
The State University of New York



The University of
Nottingham

acadia

ISBN 978-1-926724-02-7



9 781926 724027

Riverside Architectural Press