DESIGNING A RESPONSIVE MATERIAL SYSTEM WITH PHYSICAL COMPUTING

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Abstract. This paper focuses on an investigation to explore architectural design potentials with a responsive material system and physical computing. Contemporary architects and designers are seeking to integrate physical computing in responsive architectural designs; however, they have largely borrowed from engineering technology’s mechanical devices and components. There is the opportunity to investigate an unexplored design approach to exploit the responsive capacity of material properties as alternatives to the current focus on mechanical components and discrete sensing devices. This opportunity creates a different design paradigm for responsive architecture that investigates the potential to integrate physical computing with responsive materials as one integrated material system. Instead of adopting highly intricate and expensive materials, this approach is explored through accessible and off-the-shelf materials to form a responsive material system, called Lumina. Lumina is implemented as an architectural installation called Cloud that serves as a morphing architectural skin. Cloud is a proof of concept to embody a responsive material system with physical computing to create a reciprocal and luminous architectural intervention for a selected dark corridor. It represents a different design paradigm for responsive architecture through alternative exploitation of contemporary materials and parametric design tools.

Keywords. Physical computing; responsive material systems; adaptive architecture.

1. Introduction

In simple terms, physical and pervasive computing is about communication between the physical and digital worlds. This approach is not new in the field of ubiquitous computing, but is territory rarely explored in the world of
architectural materials and system design. While the previous design paradigm of cyberspace architecture threatened to dematerialise architecture, physical computing anticipates a new defence of architecture (McCullough 2004). Physical computing in architectural design has become a popular avant-garde phenomenon during the last decade, especially among architecture schools and newly established architectural practices. The accessibility and affordability of electrical hardware, such as Arduino microcontrollers, provide opportunities for non-specialists to design architectural prototypes with basic electronics and software. Open-source parametric software, such as Grasshopper and Firefly, create a user-friendly design environment, even for architects and designers without any knowledge of mechatronic or electronic engineering. The current accessibility of this form of design approach for architects and designers was unimaginable a few decades ago.

This study sought to examine whether physical computing can create a conversation between physical material data and external environmental data through a computing process, particularly within the responsive architectural design context. A core objective of this paper was to explore the idea of embedding physical materiality within computation to design responsive architecture. It discussed the potential for physical computational processes embedded in materials to investigate new possibilities for achieving a sensory, responsive and form-changing material system in architectural design. To explore this further, a rigorous and systematic design investigation was implemented. The investigation suggested that a design process with physical computing through constant feedback with designers would create the most effective responsive architecture. The outcome of this design investigation is embodied in a material system called Lumina. This newly developed material system is embodied in the form morphing architectural skin—namely Cloud—that serves as a responsive and luminous ceiling that changes shape and appearance in response to changing environmental stimuli and pedestrian movements.

2. Physical computing in architectural design

One of the first approaches that physical computing applied in architectural and engineering practice was Ove Arup’s model experiments on the roof shells of the Sydney Opera House during the 1960s (Sommer et al. 1994). These experiments tested and collected data from physical scaled models and sent them to a computer for analysis and processing. This innovative approach created a new set of possibilities for architects and designers to design architecture with physical models and digital data. This was considered
a pioneering use of physical computing in architectural design between physical and computation designs.

Three decades later, in his seminal book, *An Evolutionary Architecture*, John Frazer discusses some of his students’ works from the Architecture Association (AA) in London. He claims that evolutionary architecture should be responsive to evolving in not just a virtual, but also a real environment (Frazer 1995). Some of the works included in Fraser’s book are pioneering uses of physical computing in architectural design. The Universal Constructor developed by AA Diploma Unit 11 in 1990 is a significant example of these works.

Frazer and some of his students (from 1989 to 1996) at AA also cooperated with the late Gordon Pask. They related their work to cybernetic and architecture (Frazer 2001). These works included building new design tools and making models of intelligent responsive systems that went beyond the algorithmic approach to generative self-organising architecture, to investigate systems that can learn through the basis of feedback (Frazer 1993). Cybernetics in architecture began to appear in the 1960s, almost in parallel with the concept of kinetic and responsive architecture. Cybernetics is relevant to kinetic and responsive architecture because it typically requires a feedback and control system. A control system with feedback ability, including sensors and actuators, is considered a fundamental physical computing process that inevitably establishes cybernetics as a point of reference. There is also the possibility for cybernetics to be applied in responsive materiality. This approach served one of the main investigations of this paper.

During the 1960s, *avant-garde* architectural thinking flourished with provocative ideas involving flexibility, mobility, computers, prefabrication and robotics, as well as energy and resources (Frazer 2001). These ideas inevitably embraced the cybernetics concept, and it was no surprise that Gordon Pask became one of the pioneers who adopted the cybernetics concept in architecture. Pask was recognised as the source of inspiration for speculative cybernetics ideas in architecture during his teaching at the AA during the 1990s, particularly in terms of his contribution to the responsive architectural theory explored with physical computation technology. According to Pask in 1969, cybernetics was an architectural design paradigm that applies to the interaction between the designer and the system he or she designs, rather than the interaction between the system and the people who inhabit it (Pask 1969). This paradigm, proposed by Pask almost four decades ago, is still considered valid, especially for architects and researchers who investigate the design of responsive architecture with physical computing. It is thus important to consider how Frazer’s works and Pask’s cybernetics in architecture, conceived in the 1960s, relate to current research in responsive material
systems for architectural designs in today’s digital and physical computing technology. Frazer and Pask’s contributions are significant because they allow contemporary young architects and researchers involved with responsive architectural research to further their explorations. With current affordable and accessible electronics and materials, such as the Arduino microcontroller with plug-and-play programming software, designers and even architects can achieve Pask’s vision of an architectural design paradigm with current technology for more interactions during the design process between the designed systems and the designers.

This paper further explores the vision initiated by Pask and Frazer to investigate alternative architectural design possibilities with physical computing. By further integrating physical computing with materials, the outcomes of this research eventually form a responsive material system for adaptive architectural designs. With current material technological advancements and accessibility, do-it-yourself physical prototyping, and devices such as the Arduino microcontroller to serve as a tool to design, responsive material systems for architecture become achievable. The next section discusses the development of this approach with a simple, yet rigorous, process for designing an architectural responsive material system.

3. The development of a responsive material system

Countless contemporary design approaches adopt physical computing in responsive architectural designs with expensive and intricate mechanical devices and systems; however, few explore the simple alternative. Instead of refining the current popular mechanical approach with discrete motor, piston and sensing devices, this section anticipates a design approach for a responsive architectural system that exploits the material-based approach with physical computing. Recently, architectural researchers have begun to explore adaptive architecture with passive and active responsive materials and systems. This is included the experimental works of Achim Menges and Philip Beesley. While Menges and his team focus on the approach of programmed material performance to designing responsive architectural skin, such as the Hygroskin project work (Correa et al 2013), Beesley’s works move towards an active actuation and sensing approach by using several form-changing materials and an electronic control system (Gorbet 2010). Based on this context, this section takes an initial step to further investigate whether there is a system that integrates both passive and active approaches with physical computing. There is an opportunity to create a hybrid system that involves passive and active implementation to fully exploit the advantages of both approaches.
Table 1. The day-to-day materials to perform sensing and responsive capacity with a different design approach to form an integrated responsive material system.

<table>
<thead>
<tr>
<th>Materials</th>
<th>Sensing</th>
<th>Response</th>
</tr>
</thead>
<tbody>
<tr>
<td>Shape memory alloy</td>
<td>•</td>
<td>•</td>
</tr>
<tr>
<td>Silicone rubber</td>
<td></td>
<td>•</td>
</tr>
<tr>
<td>Glow pigment</td>
<td>•</td>
<td>•</td>
</tr>
<tr>
<td>Linear photo resistor</td>
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</tbody>
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In general, the intention to integrate physical computing and selected materials is to develop a multifunctional material system for designing an adaptive architectural skin. The development of this hybrid responsive material system—namely, Lumina—is conducted through a rigorous experimental process. Lumina is a synthetic material system in the form of modular triangulated skin. Its development process engages with physical materials, such as silicone rubber, glow pigment, linear photo resistor and shape memory alloy (SMA) (Figure 1). Their integration with physical computing allows sensing and responsive capacities to occur to perform kinematic actuation and illumination (Table 1). This approach explores the potential for materials that combine sensing, active and passive lighting, and form-changing responses for implementation in the design context of responsive architectural skins.

Figure 1. Left: Synthetic Lumina in liquid form. Middle: Moulding process with embedded SMA wires and linear photo resistor. Right: Drying Lumina with heating process.

3.1. SENSING CAPACITY

The Lumina material system is equipped with two fundamental sensing capacities: proximity sensing and lighting sensing. Proximity is sensed through capacitive sensing, and responds through tensional SMA wires embedded within the material for kinematic actuation. Light sensing detects the Lux
level of the surrounding environment and constantly sends the Lux data to
the Arduino microcontroller to trigger the appropriate response, either acti-
vating active light stimulation or not.

The sensing capacity of the Lumina material system begins with a simple
experiment to test the possibility to integrate various materials and physical
computing to develop a different responsive material system with fewer dis-
crete components, and to exploit the mechanical properties of materials. The
initial experiment integrates SMA wires with silicone rubber to test the po-
tential for sensing capacity and actuation purposes. This process uses SMA
wires as the initial sensing element to perform capacity sensing when a volt-
age is applied to create current. In this case, the SMA wire serves as the con-
ductive material that constantly sends variable data to the computer through
an Arduino microcontroller. The software environment includes Grasshop-
per and Firefly for Rhino™ to interface with the Arduino microcontroller.
This is the first step and trajectory to test the sensing capacity of Lumina.
The following subsections further explain the proximity and light-sensing
capacities of Lumina that were eventually implemented as the sensing sur-
face of the conceptual Cloud prototype.

Figure 2. Left: Lumina’s proximity sensing—no data reading. Right: Reading data from the
proximity of moving object (hand).

3.1.1. Proximity

Lumina responds through an active capacitive sensing. The integrated con-
ductive SMA wire and silicone rubber serves as a probe surface that uses
changes in capacitance to sense changes in distance to an object or person. It
senses the proximity of objects in the surrounding environment and responds
through transformation of the skin surface actuated by the SMA wire in var-
ious configurations. This sensing operation process, through the Arduino mi-
crocontroller and Firefly physical computing software, allows the material to
‘process’ external data and respond to them (Figure 2).
3.1.2. Light

A linear form of photo resistor is embedded in Lumina to detect the level of light in the surrounding environment. This light-sensing facility allows Lumina to constantly detect the light level and send the data to the Arduino microcontroller to process (Figure 3). The processed light data are a variable input to activate the heating process of SMA wires for active illumination. This process considers the responsive capacity of Lumina, and will be further discussed in Section 3.2.

![Figure 3. Left: Normal lighting condition, no data input. Right: The surface of Lumina performs light-sensing capacity with data reading.](image)

3.2. RESPONSIVE CAPACITY

In addition to the sensing capacity, there are two responsive capacities of Lumina: deformation and illumination. The deformation of Lumina is performed through tensional SMA wire as the actuators for the active transformation purpose that respond to the external data that are sensed by the linear photo resistor and the sensing SMA wire. In this scenario, the SMA wire not only performs as the actuator—as discussed in a previous subsection—but also serves as a capacitive sensor to detect the proximity of objects. The other responsive capacity of Lumina is the illumination function, which performs passive and active illumination that glows in the dark.

![Figure 4. Left: Lumina in its original state. Right: The deformation of Lumina is actuated by the heated SMA wires.](image)

3.2.1. Deformation
In addition to the active deformation actuated by the embedded SMA wire, Lumina is capable of performing passive deformation due to an elastic nature that cause it to deform when force is applied. This deformation is reversed once the force is removed, returning to its original state (Figure 4). This offers a potential new form of flexibility, adaptability and deformation by using the passive memory effect, especially in responsive architectural skin designs. While the active and passive form-changing capacities of Lumina are controlled by the Arduino microcontroller with its embedded sensing capability, Lumina is also able to transform in response to various changing environmental stimuli and site conditions.

3.2.2. Illumination

Besides silicone rubber and SMA wire, the fabrication of Lumina also integrates glow pigment to develop a passive and active luminous material system that glows in the dark. The passive luminous capacity of Lumina involves absorbing light energy during the daytime, and discharging this light energy after dark in order to produce the glow effect. When absorbing external heat energy, Lumina can also actively produce brightness beyond its passive luminous capacity (Figure 5).

Figure 5. Left: Passive illumination of Lumina. Right: Active illumination triggered by the heated SMA wires.

Figure 6. Left: Cloud in normal light condition. Right: Self illuminated Cloud in the absence of light.
4. Potential design implication of Lumina: Cloud

Derived from the relatively positive results from the development of the Lumina material system with sensing and responsive capacities—as discussed in Section 3—this section focuses on the potential design implications of this material system, and exploits its full potential in responsive architectural designs with physical computing. The design implementation of Lumina is a conceptual prototype—namely, Cloud—that functions as a reciprocal luminous intervention that is embodied as an architectural morphing ceiling (Figure 6).

![Figure 7](image)

*Figure 7. The heated SMA wires embedded in the surface of Cloud perform the animated luminous pattern.*

![Figure 8](image)

*Figure 8. Right: The sensing and responsive schema of Cloud. Right: The responsive system of Cloud is using a simple input-process-output system within the Firefly platform to control the sensing and responsive capacities of Lumina material.*

Cloud revitalises an existing, underused, dark, interior corridor through its physically responsive morphing and luminous effects. These effects are achieved through three responsive capacities: sensing, form changing and illumination. Instead of serving as a typical architectural lighting feature, Cloud performs a different role by offering an alternative animated lighting aesthetic with shadow play and responsive ambient illumination (Figure 7). These luminous effects create a mutable and malleable architectural lighting aesthetic that transforms the atmosphere of the existing interior space to induce a greater degree of social interaction. The prototypical Lumina and Cloud provide proof of the concept, and offer a platform to anticipate a different design paradigm of responsive architecture through an innovative integration of composite materials and physical computing with the simple input-process-output responsive system (Figure 8).
There is no intention of designing Cloud to serve as a conventional lighting device for the dark passageway. Despite the current limitation of its illuminating capacity, the outcome of Cloud anticipates a potential reciprocal urban intervention or annex for the exterior built environment. The future potential design implications of Cloud involve the structure serving as a retrofitted and heated ceiling that is responsive and luminous, for an existing tram or bus stop structure. In addition to providing ambient illumination, the kinematic and undulating surface of Cloud serves as a hanging ‘heating-blanket’ to provide a warm shelter to commuters during cold winter nights. With further research and new technological developments, this potential design implication is achievable and will be implemented as a reciprocal architectural feature.

5. Conclusion and future work

By reflecting on the outcomes of the design investigation of Lumina and Cloud, a new architectural design technique with physical computing has emerged to form a hybrid responsive material system that moves beyond contemporary digital design representation and visualisation. The direct engagement with materials and physical computing devices—such as form-changing luminous materials and microcontrollers—provides a viable alternative in the analogue and digital realm to the conventional design techniques of drawings or modelling. In a normal context, these tools serve as ordinary materials and devices with original functions or usages. By using a novel approach, they shift their roles to become part of alternative design tools used to design responsive material systems to adaptive architecture.

References


