Designing Resilient Buildings with Emergent Materials

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This paper looks at two distinct approaches to kinetic façades and smart building assemblies reminiscent of designs for the Institut du Monde Arabe and for Hoberman's Simon Center. The first approach uses Arduino microcontroller-guided kinetic components with a distinct assemblage of elements, each performing a dedicated function such as sensor, actuator, or logical processing unit. The second approach incorporates custom-designed smart materials-shape memory alloys (SMAs)-that not only complement or replace the need for electrically operated sensors or actuators, but also eliminate a microcontroller, since in this arrangement the material itself performs computational functions. The paper will discuss case studies that use physical computing and smart-material models as vehicles to discuss the value of each approach to adaptive design in architecture. Building on these observations, the paper looks into conceptual aspects of an integrated hybrid system that combines both computation approaches and unique opportunities inherent to these hybrid designs.

Keywords: *Adaptable designs, Arduino microcontrollers, Shape memory alloys (SMAs), Smart materials, Programmable matter*

INTRODUCTION

Material science and computation emerge as the two most critical and formative drives of current design practice. The impact of emerging smart material technologies with their unique properties is destined to redefine the built environment in the same way as it currently does within science, engineering, and product design. The ability to wire this new matter-interconnect into a broader network-and provide memory, anticipation, and autonomous operability would extend its potent qualities into larger structures such as a building or a city.

This paper discusses a number of design and research initiatives that explore this intersection of new smart materials and electronic technologies. In particular, it focuses on emerging practices that employ shape-changing materials and open-source electronic platforms.

Furthermore, this paper addresses a number of critical questions that frame current debate on adaptive façades and architecture. What is a conceptual framework for integrating smart technologies into context-aware and interconnected buildings? What are effective ways to interconnect electronic- and material-based information processing (computing)?

What are the opportunities and challenges of autonomous responsive façades and buildings?

GLOBAL CONTEXT

Buildings are a significant contributor to the human carbon footprint, and they are responsible for 34% of global energy consumption. The rapidly growing energy demands of the increasing population in developing countries will create an even greater energy demand, especially since some of the fastest-growing cities are located in the world's warmest climates (fig. 1). Alternatives to energy-intensive air conditioning systems are sorely needed.

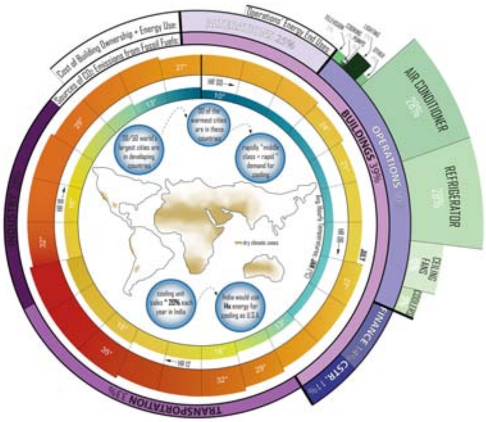

Figure 1
Joseph Ribaudo, New Jersey Institute of Technology | Temperature and Energy Data for India 2007/2010

Dynamic and responsive features in the architectural landscape hold promise for assisting in regulating the interior climates of the built environment and reducing the energy consumption of contemporary HVAC (heating, ventilation, and air conditioning) systems. Kinetic façade systems that can mitigate solar heat gain in buildings have been studied and might offer solutions to this problem of ever-growing complexity.

MECHANICAL KINETIC FAÇADES

Early designs of kinetic and adaptive building involved mechanized systems with some electrical and sometimes electronic controls. They were the direct legacy of the Industrial Revolution, which associated kinetic movements with mechanics and pneumatics.

Current state-of-the-art projects such as Hoberman's kinetic structures still build on this tradition and on occasions introduce exotic materials such as sensors and transducers. However, in their entirety, kinetic designs continue to apply industrial and mechanical thinking to architecture. While these kinetic practices represent a successful and effective lineage of design thinking, the future designs should also take a full advantage of currently available material, information technologies, and science.

Electronically controlled mechanical systems provide the ability to centralize control and monitoring. They are generally reliable, inexpensive, and easily maintained, particularly when made of modularized components. Standardization of elements is a critical part of the effective mechanical kinetic designs.

On the other hand, mechanically based systems require an independent energy source to power their operations and usually are executed in a purely actuating role; without harvesting energy and feeding it back into the system. This is a particularly significant limitation, since the nature of DC (direct current) motors (utilized by kinetic façades) would naturally lend itself to energy generation as well. Certainly, this would provide new challenges to designers, since most of current designs approaches do not easy allow for this double role. However, this would allow adaptive façades to optimize not only energy consumption but also energy generation.

The adaptive façade of the Institute du Monde Arabe in Paris (fig. 2) exemplifies the strengths and limitations of mechanically operated designs. While this was an early successful example of a kinetic shading façade, it also became an effective case study for what works and does not work with this approach. Placement of shading on the interior side of the glazing significantly reduces its effectiveness from the perspective of solar gains. While it prevents solar glare and controls the amount of illumination, it offers only minimal benefits for the reduction of heat gains. Once the sunlight enters the building, most of its energy is absorbed in form of heat, with little reflection to the outside.

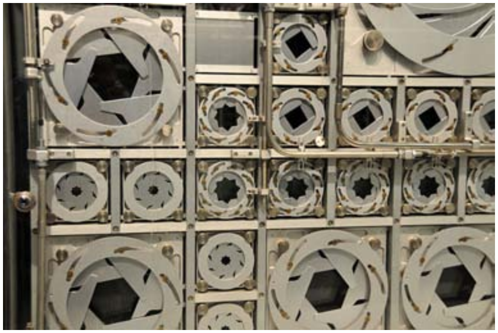

Figure 2
The detail of the adaptive façade of the Institute du Monde Arabe

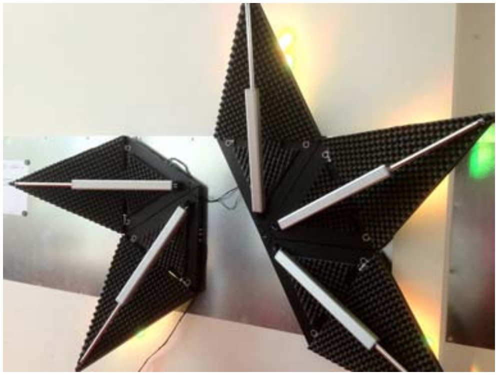

Figure 3
Components of the Hive System.

The tendency to place mechanically controlled screens on the inside-protected from the elements-is directly related to their reduced performance when exposed to weather conditions. This is due to both the mechanical nature of the system and its centralized structure with single actuators controlling larger façade areas. Finally, while mechanical systems have a relatively long life span, they tend to wear off faster than those made of non-mechanical parts.

INFORMATIONAL LAYER IN KINETIC FAÇADES

A new generation of adaptive façades such as Hive Systems [1] (fig. 3) use information technologies extensively to control individual building components and to share information in between. In this case, the façade design is a system of interconnected panels, with each of them working as a sensing and actuating element. Each component has an awareness of its surrounding panels and freely shares data with its neighbours. A significant advantage of this approach is its scalability. Removing an existing component (taking it off-line) or adding a new component (putting it on-line) is quickly recognized by the rest of the system, and these new elements are immediately incorporated into the entire assembly.

Additionally, the peer-to-peer communication approach provides another layer of reliability and resiliency, effectively functioning as a decentralized active organism. If any damage occurs to one of the panels, the remaining panels continue to function.

Another project utilizing open-source electronics is the ICT Media Building, in Barcelona, Spain. It uses a combination of pneumatic frit cushions and Arduino-based microcontrollers to control solar illumination and heat gains inside the building. Since the pneumatic panels are installed in a double-façade arrangement, they do not have the impediments of capturing solar heat present in the Institut du Monde Arabe building.

The strategy used in the ICT Media Building allows for individual addressability of each panel (fig.4) and thus for individual control, communication, and if need be, overwrite of its behaviour. These facilitate both localized and globalized controls. While this project does not have the interconnected nature of the Hive Systems, it could potentially follow a similar route due to the analogous underlying informational technology framework. The Soft Façade for Architects [2] project demonstrates transitional thinking in adaptable façade design where material performs in parallel with mechanical and electronic systems. In the project, a series of sophisticated pneumatically activated soft panels are deformed to produce various levels of wall opening apertures. While this approach stands in the direct contrast to purely mechanical solutions discussed earlier, and as such is possibly more reliable, it still uses material in a purely actuating role.

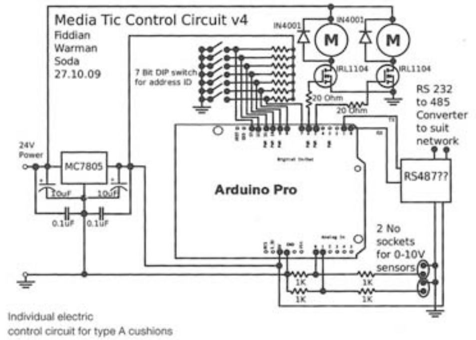

Figure 4
Controls for the individual cushion panel with Arduino microcontroller and the 7-bit DIP switch for ID address.

Figure 5
Smart Screen Prototype III Testing, Decker Yeadon LLC. The actuator design consists of a shape memory alloy spring (top) and a counter spring (bottom) that drive a piston in the middle of the actuator assembly. The piston moves the screen openings to align or misalign the openings in the screen.

KINETIC FAÇADE SYSTEMS WITH INTEGRATED SMART MATERIALS

Property-changing smart materials are a particular class of materials that can react to changes in their environment with a significant material response that originates at the scale of molecules, the nanoscale. These fascinating materials are engineered at the molecular level to respond to inputs such as photons of light, temperature differentials, chemical substances, magnetic fields, or electricity. The output that is generated by these materials can range from changes in volume, shape, or fluidity to emitted light, changes in colour, or electric currents.

Since these materials are not unlike microcontrollers that include programmable input/output peripherals, they have the potential to take over the function that these small computing devices have in contemporary kinetic façade systems. They have been demonstrated to assist in controlling ventilation, managing solar heat gain, and guiding daylight deep into outbuildings.

The Smart Screen by Decker Yeadon LLC is an example of a screen system that uses an artificial muscle consisting of shape memory alloys (SMAs) to control solar heat gain (fig. 5). SMAs can be engineered to respond to very specific activation temperatures by introducing impurities to the nickel-titanium alloy. At cold temperatures, the SMA can be deformed by mechanical means. Upon heating the metal, it will return to the original shape that it had before the subsequent mechanical deformation.

The Smart Screen actuator features a spring set that contains an SMA spring and a counter spring made of a regular material. At cold temperatures, the counter spring overcomes the force of the SMA spring, whereas at warm temperatures the SMA spring is stronger, causing the mechanism to return to its original shape. SMAs call for carefully conceived environments to ensure that the smart material is not heated or deformed excessively, so that the material can perform its tasks for millions of cycles without material fatigue. These actuators can act as sensors and motors at the same time and do not need any computing devices. They can help regulate solar heat gain through glazing solely driven by ambient room temperature.

By using a smart material motor as demonstrated in the Smart Screen setup, one actuator assembly can drive the entire screen system. But SMAs can also be evenly distributed in a façade system and react to changes in room temperature directly where they occur. By using muscle wires made of SMAs, this integration can be easily achieved.

In the screen design (fig. 6) by Adam Morgan (New Jersey Institute of Technology), a muscle wire can operate oculi akin to the façade design by Jean Nouvel for the Institut du Monde Arabe in Paris. A single wire drives a set of two openings.

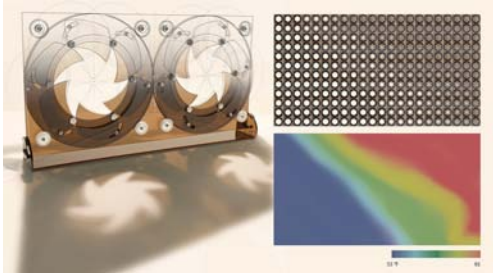

Figure 6
Screen Design by Adam Morgan, Option Studio, New Jersey Institute of Technology

Figure 7
Screen Design by Gayatri Desai, Option Studio, New Jersey Institute of Technology

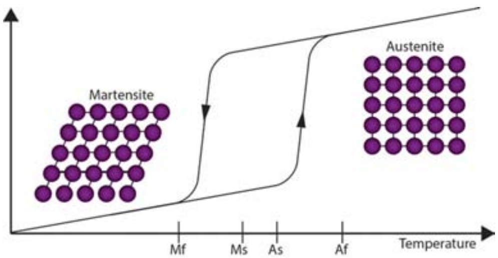

Figure 8
Hysteresis Loop in Shape Memory Alloys.

Digital thermostats that are instrumental in controlling HVAC systems are programmed to display a hysteresis that doesn't simply turn the heating or cooling systems on or off at a single specific temperature. In order to avoid a constant switching between on and off states, the thermostat is programmed to maintain a specific temperature range. Similar, upon heating, an SMA actuator will trigger a material response at a specific temperature and will go back to its original state at a lower transition temperature (fig. 8). This allows the material assembly to operate with a similar precision to that of the thermostat-controlled environment.

INTERCONNECTED SYSTEMS

The significant advantage of controller-based systems is their ability to interconnect into a broader system that can share sensory inputs and propagate information across the entire network. The neighboring cells can oversee the behavior of the individual adaptive components, and if need be, overwrite local actions with global directives. This is enabled by the individual addressability of each component-controller, as is the case with Hive Façade Systems and ICT Media Building. More importantly, this addressability parallels the conceptual framework of the Internet of Things paradigm with IPv6 protocol that will allow for individually addressing every element in the build environment.

The immediate consequence of the interconnected building components is the ability not only to share information but also to introduce performance anticipation into the building. Since individual components are aware of conditions in the neighbouring cells, they can preemptively adapt to emerging circumstances. For example, with increased solar gains being registered in one part of the building, spaces that are expected to be exposed to similar conditions within near future could be pre-cooled or pre-conditioned. Similarly, during cold outside-temperature periods, air humidity along the exterior building perimeter could be lowered to minimize curtain wall condensation before the outside temperature drops. This also points to the building's ability to subscribe to broader databases and forecasts to fine-tune its performance.

COMBINING MICROCONTROLLERS WITH SMART MATERIALS

The benefits of each approach, whether a kinetic façade element is driven by microcontrollers or by material motors, are intriguing. The computer-based model gives us an extremely high degree of control and lets us incorporate elements of machine learning. The system can evaluate information on the user, anticipate behaviours, and adjust its performance accordingly.

While the material-based approach resists being adjusted by a user, it offers an independent operation that can perform for millions of cycles without the need of an energy source. Through the combination of motors and sensors in one material, the actuators can be elegantly integrated into space-saving screen designs. Smart material-based assemblies are not vulnerable to computer failure or to the attacks of computer viruses or hackers. They are ultimately autonomous-including the lack of need for an outside energy source-and easily scalable. They often continue to perform in conditions where purely mechanical and electronic systems fail or demonstrate reduced performance.

New approaches can be contemplated in which the benefits of a microcontroller and a smart materials-based intervention can be combined. There are various strategies in which the two distinct approaches can be integrated in one façade system. The SMAs, for example, can be locally heated to their transition temperatures by running a current through the material. This would allow a microcontroller to take over and drive the kinetic functions. Another approach could be to disengage the mechanically based deformer that is essential in an SMA assembly. The decoupling mechanism could be controlled by a microcontroller to completely overwrite the material-based response.

CONCLUSION

The future adaptable designs will incorporate both smart material and information technologies, contributing to increased building performance and resiliency as well as to aspirations of zero-energy architecture. As we increasingly embed electronic chips into the built environment and every aspect of our daily lives, the question of reliance and of the required energy sources for these assemblies remains to be addressed. The shift from purely mechanical and electronic controls--energy hungry--toward smart materials-only active when the need arises-is an attractive alternative to the traditional design approach. It also provides a high level of reliability that will be necessary for future, more complex buildings.

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