Abstract. Historically, architectural design focused on adaptation of built environment to serve human needs. Recently embedded computation and digital fabrication have advanced means to actuate physical infrastructure in real-time. These ‘reactive spaces’ have typically explored movement and media as a means to achieve reactivity and physical deformation (Chatting et al. 2017). However, here we recontextualize ‘reactive’ as finding new mechanisms for permanent and non-deformable everyday materials and environments. In this paper, we describe our ongoing work to create a series of complex forms - modular concrete panels - using thermal, tactile and thermochromic responses controlled by embedded networked system. We create individualized pathways to thermally actuate these surfaces and explore expressive methods to respond to the conditions around these forms - the environment, the systems that support them, their interaction and relationships to human occupants. We outline the design processes to achieve thermally adaptive concrete panels, illustrate interactive scenarios that our system enables, and discuss opportunities for new forms of interactivity within the built environment.

Keywords. Responsive environments; Geometrically induced thermodynamics; Ambient devices; Internet of things; Modular electronic systems.

1. Introduction

Our research explores interactions between material form and its embedded electromechanical controls, while using human physiology and emotiveness as an activation of change in material character (Fig.1). Contemporary advances in technology shape interactions between organic and inorganic systems and their mutual formation. In order to rethink the role and effect of spatial interaction, both physical and human matter have to be open to design (Lally 2014). We are building series of complex architectural forms - using thermal, tactile and thermochromic responses guided by embedded distributed control system that - in near future will - change their affect and microclimate in response to thought. The current shift
in design thinking suggests new ways of shaping physical and human matter and their mutually perceptive capacities. We want to consider these new synthetic materials systems holistically, as a collective biological matrix that engages new forms of communication, feedback and sensory effects rooted in thermodynamics and direct communications of humans and their surroundings.

Figure 1. Test in thermochromics response, color surface effect induced by varying surface geometries and Simulation of projected visual and emotive response between environment and human perception of thermal and physiological comfort.

1.1. BACKGROUND

The relationships between temperature, emotiveness, human health and environments have been researched from more scientific angle (Nummenmaa et al. 2013). We also understand that there are effective relationships between individual thermal comfort and energy usage, color (Karlessi et al. 2009) and human perception (Matalucci at al. 2017). Weiser originally introduced ubiquitous computing and the notion of hundreds of interconnected computers in a single room in 1991. Enabled by miniaturization of computing but near-field communications, real-time localization, embedded sensor technologies, and advances in context-aware and personalized computing (Kortuem et al. 2010), this vision is largely realized (Abowd 2012). Today, though the IoT is described as having “one paradigm, many visions”, this multiplicity of interests spans distributed networks, context-aware computing, ambient and ubiquitous intelligence, tracking and monitoring (Rogers 2006) as well as hardware, software, human factors, network engineering and communications, data analytics, prediction, and more (Atzori 2010). Ubiquitous computing from an architectural perspective asking how smart and embedded software and hardware can enhance the experience and interaction with physical infrastructure (Picon 2018, de Waal 2014). This is the focus of our work. In particular we note Krueger’s definition of ‘responsive environments’ is one where “experience is controlled by a composition which anticipates the participant’s actions and flirts with his expectations.” Robles and Wiberg note the need to interface with computation at scale and through new
materials. They remark “open for examination is how the discipline of interaction design might move forward alongside architecture, product design, textile design, and materials science as part of a joint area for inquiry.” Yet to date little work has occurred in this way. Much of the work in interaction design for responsive architecture works with accessible materials: projections, programmable lighting and mechanical actuation. There is however a wealth of current interest in new material interactions as a means to achieve Krueger’s unexpected responses. For example, Devendorf explores computationally responsive clothing that create chromic responses as a novel textile display technology. Berzowska similarly explores conductive yarns and thermochromic inks blended with electronic components to create dynamic fabrics. While Yao, has explored pneumatic shape changing systems and biological methods to deform soft materials through environmental changes. Despite interest, almost all of this work focuses on small, object level interventions. We instead seek to apply them architectural scale.

1.2. PRECEDENT AND VISION

Our research project explores the division between humans and their environment by extending our prior work of variation in large scale concrete thermal mass structures (Cupkova et al. 2015) and surfaces to produce thermodynamic effects by embedding computing and mechanical controls to develop enhanced responsive and affective potential of a traditionally fixed material form (Fig. 2). We want to question the interaction of human occupation in space, its control of an immediate spatial character and explore new potentials for sentience and subjectively in reactive spaces. Such control shifts from physical proxy object as a mediator to being rooted in the human though and biometrics, while the fixed infrastructure is being activated and enlivened thus creating reciprocal effects between the user
and the space. Investigations to date from art, design, and architecture imagine reactive spaces as actuated physical infrastructure. We recontextualize ‘reactive’ as finding new mechanisms for fixed, permanent and non-deformable everyday materials and architectural forms to find evocative and expressive ways to respond to the conditions around them - the environment, the systems that support them, their interaction and relationships to human thought process. We work specifically with concrete because of its material permanence. Once cast or printed, the form is unchanged. However treated with thermochromic inks can be actuated with sensors from within without deformation or motion. Our research focuses on material features - characteristics of thermal diffusion, heat dissipation, surface effects; as well as technical and mechanical elements - how to embed intelligent systems within the infrastructure to activate and control responses.

1.3. CONCEPT AND CONTEXT

This work extends upon our research project on thermal mass geometry (Cupkova and Promoppatum 2017) that investigates effects of complex geometry on the process of passive heat distribution in thermal mass systems in buildings. It examines the premise that complex geometries can be used to improve both the aesthetic and thermodynamic performance of passive heating and cooling systems. The thermochromic effects added to geometric actuation of the mass, are electromechanically induced (Fig. 3). They play with the use of human physiology and affect as an activation of change in material character. Interactivity between this sentient object and perception explores the division between humans and their environment, while relying on thermodynamic behavior of complex surface geometry and change in radiant surface temperature.

Figure 3. Operational systems’ diagram showing the logic of control and effect scenario and Simulation of time based scenario sequence of electronically controlled nicrome wiring.
2. Design Process and Prototypes

2.1. FORM-MAKING STRATEGY

Surface geometries were digitally modeled to produce variation in surface curvature, depth and amplitude. The variation is related to heat dissipation rates, related to previous body of research on convection and surface geometry (Cupkova and Promoppatum 2017). We used sinusoidal curve formula as a base algorithm for generation of the pattern logic to test variable heights and amplitudes to create a dynamic surface that transitioned gradually over the course of three stages from low-amplitude, long-period curvature to high-amplitude, short-period curvature and a much more dynamic and flowing surface. This was done using a combination of third-degree and first-degree NURBS curves. To adapt the heat pattern to surface geometry we used gravity based flow simulation of the surface (Cupkova, Azel at al. 2015) to generate the pathway logic for heat wires (Fig. 4).

![Figure 4. Digital model of surface geometry with wire flow overlay.](image)

2.2. FABRICATION

Our prototype is a concrete cast piece with embedded electronics, consisting of nicrome wires and external control system. Our primary consideration for the fabrication of the test panel was to achieve a precise tolerance on the depth of embedding for the heated wire while maintaining a smooth surface finish. Precision was necessary in order to achieve a uniform speed of response in the change of the thermochromic coating. The panel was cast into a CNC milled MDF mold. We used projection to locate and place the wire pattern onto the mold and vacuum forming to precisely control the wiring layout embed within the final piece. The final product was then coated in thermochromic pigment. Before casting, the penetration points of the wires through the concrete were identified, and thin aluminum rods coated in wax were drilled through the vacuum-sheet into the main MDF mold. These were of a length such that, when positioned vertically, they protruded from the top of the mold assembly. The main concrete mixture was then cast into vacuumed form geometry. The wax was melted out of the final concrete panel in order for the wires to be threaded through. The thermal wires were placed into the panel’s front surface. This was then sealed into place with air-hardening clay to form a smooth surface on the panel (Fig. 5). A labeling system was used on the rear holes to identify each wire’s ridge and index. The final
stage of the process was the application of one coat of acrylic pigments in a gradient pattern, and several coats of thermochromic pigment on top of this. The heating of the wires at a uniform, small depth (1/16”) turns the thermochromic pigment clear at a very predictable rate, allowing for programmable pattern generation (Fig. 3). It is important to note that relatively few wires are actually being heated simultaneously - our generated patterns take advantage of the latency inherent in the heating process and cycle through the wires in each system, heating them each for a short period of time. This also allows a much smaller power usage than would otherwise be required to maintain the desired surface color at any given time. The next stage of our work involves development of detailed reactivites in response to various input types on the main panel.

2.3. ELECTRONIC CONTROL

To enable the actuation of the panel, the nicrome wires are connected to a microcontroller. This microcontroller can then control electrical current to each of the wires within the concrete. In the current interaction, 26 gauge nicrome wire is used with a 10 Amp, 12 Volt power supply. Nicrome is limited to a maximum length of 3 feet to allow for rapid reaction to supplied current, but lengths may vary from ½ foot to 3 feet depending on position and orientation. In cases of a longer length, the strand is typically independently controlled but shorter strands are often aggregated and controlled in series. The microcontroller (a Particle WiFi-enabled microcontroller) is used to receive a control signal from a remote source and can be directed to activate any of the nicrome wires (or groups thereof). In the current iteration, relays are used to switch power to the nicrome wire. To manage voltage and maximize effect, wires are individually actuated for approximately 200-600ms depending on the length of the wire. The surface effect then takes approximately 1-2 seconds to appear (Fig. 6). To achieve a patterned effect on a group of wires, the first wire is activated, and in turn each of the remainder. Patterns are sustained by repeatedly re-applying current to the wire.
2.4. INTERACTION

Because of the modular approach, our system for computationally controlled thermochromic surface has the potential to enable a wide variety of new interactions with the built environment. To illustrate the potential applicability of this work within architectural HCI contexts, we describe three scenarios that our interactive technique enables. All of these scenarios (Fig. 7) imagine the current work as fixed and permanent infrastructure within an indoor-building environment (i.e. organized as walls, ceilings or floors.) We imagine the system would be implemented as a series of modular panels, each independently powered, and coordinated with an embedded computation capable of wireless communications. We introduce these scenarios to posit potential for unique experiences and new forms of interactivity that it might be enable within the built environment.

**Ambient Animation:** The system could be introduced into the lobby of businesses, the walls of restaurants, meeting rooms or other similar spaces to create aesthetic experiences for the building occupants. The panels can create durational experience by iteratively heating the embedded nichrome wires and either sustaining that heat or allowing it to cool. In this way, it can create dynamic sustained or ephemeral effects that slowly reveal, evolve or progress over long periods time. **Playful surfaces:** If combined with real-time occupant tracking solutions (IR camera or a Microsoft Kinect), the occupants can then interact with and control a previously non-deformable material - concrete. As illustrated above, this would allow for an occupant to ‘paint’ in the patterns by moving through the space, by approaching the concrete panels or through other gestures made in proximity. **Occupant Navigation:** If combined with indoor positioning systems (iBeacon), we can imagine that the walls of a building might be able to identify users in the space and guide them to particular locations. For example, if Bob is a visitor to a building he might check in at the front desk. His cell phone or a smart lanyard could be provided allowing his location in the building to be tracked.
Then as he exits the elevator on his desired floor, the walls could respond creating a pattern that guides him to the right meeting room. **Human Response:** A common problem within shared workspaces is the thermal comfort and thermal preferences of building occupants. Our solution, not only allows for thermochromic effects to be produced, but adapts microclimates on the surface of the concrete panels. This in turn radiates heat into the surrounding area. Unlike current HVAC systems which uniformly directs conditioned air to a large area of the building, our panel system can adapt the thermal conditions in highly localized area. As such, we can imagine that a co-working space could be configured to the individual preferences of each person in the space.

**Figure 7.** Simulation of surface geometry warming sequence and proposed color-temperature relationship and two simulation of time based scenarios: Ambient field progression and Randomized point weight activation.

### 3. Future Work

The work creates a number of opportunities for future investigation. With the technique for responsive near-real time controlled thermochromic effects and thermal gradients (Fig. 8), an immediate next step for this work is to deploy the platform at full scale. We will next develop a series of modular panels that can be coordinated through wireless communications between in-built microcontrollers and deploy them to an indoor-location. This full-scale prototype will be used to develop and assess strategies for real-time human input into the responsive architectural system. These will include depth sensing with devices like the Kinect to trace the presence and location of building occupants and infrared cameras to adapt the surface effects based on thermal conditions of building occupants. Finally, we anticipate exploring practical applications of our computationally-controlled concrete in scenarios such as adapting indoor microclimates, developing aesthetic experiences for building environments and in delivering new interactive navigation and way finding solutions.
4. Conclusions

We present a method to create controlled thermal effects on the surface of concrete through a networked electronic system and offer a range of interactive scenarios and strategies in which this new mechanism may be deployed at architectural scale (Fig. 9). The intention is to allow us to explore relationship between responsiveness of built environment’s thermal gradients and the potential for aesthetic and haptic effects with what is traditionally a ‘non-deformable’ materials. By integrating electromechanical controls and thermochromics response directly into concrete panels we can provide individualized control of immediate physical space as well as it’s aesthetics. We anticipate this preliminary work will lead to a variety of future applications and explorations ranging from durational to interactive installations and to ergonomic configuration of indoor spaces through computationally controlled materials.

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