DYNAMIC ORNAMENT
Climatically responsive surfaces in architectural design

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ABSTRACT: In recent years, sensors and sensor networks have been broadly employed in buildings to monitor diverse aspects of the built environment. Sensors are commonly used to track indoor and outdoor climatic variables such as humidity, temperature, and solar radiation; and to recognize patterns in the activity of people. We propose that in addition to this common instrumental role, data gathered from sensors could also play an important aesthetic and cultural role in the design of engaging architectural spaces. We describe a design study that explores the use of sensor data as a means to qualitatively differentiate between spaces within the building, a role traditionally performed by architectural ornament.

KEYWORDS: Sentient architecture, thermochromic ink, sensor networks, ornament

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1. INTRODUCTION

The sensors used in this study are electrical devices that have been calibrated to respond to subtle changes in environmental conditions. Sensors are commonly used in buildings to monitor conditions such as temperature and humidity, as well as other qualities of indoor air such as levels of CO₂, CO and NO₂. The commercial availability of low-cost sensors combined with readily-available data networks has made sensing in buildings an obvious choice for control of HVAC or other building systems, as well as for a range of tasks related to building automation.

In this paper we propose that sensors could have an alternate life as the basis of an architectural ornament responsive to patterns of human activity. The sensors which have been embedded in building to serve a pragmatic role could also perform an aesthetic role as indicators of patterns in the activity of people. Such patterns can become the bearer of subtle cultural meaning related to the building and its use.

A sensor-based ornament offers the possibility of a dynamic, bottom-up expression of the character of a given space or aggregation of spaces that is not predetermined by the designer, but emerges from occupation and use. We have chosen the expression ‘dynamic ornament’ to convey this idea of an ornament that reflects its immediate surroundings by responding to dynamic qualities of the architectural environment.

1.1. Functions of architectural ornament

Architectural ornament has been defined by Sir John Summerson as “Surface Modulation”, and in its broadest definition ornament encompasses any surface treatment in architecture designed to realize specific aesthetic ends. Among these ends is the use of ornament as an articulate surface that embodies cultural meaning and informs the reading of the building as a whole. In pre-Modern buildings a shared social and cultural context provided a basis for the popular legibility of built form, and it was generally assumed that the building’s ornament would provide a rhetorical explanation of its function, its role in society as well as the beliefs and values of the people who built it (Kohane and Hill 2001). The representational function of architecture and the capacity of buildings of all types to communicate were taken for granted in the Renaissance discussion of the orders, grounded as it was on the premise of architecture as the built expression of a divine order. On the interior, fine distinctions between public and private, sacred and profane, servant and served spaces were often communicated through the use of ornament which abstractly conveyed differences between spaces and an understanding of their intended use. Ornament was used by the architect to articulate differences between spaces within the interior, and to suggest the suitability of a given space for a particular type of
activity. Architecture’s role as the primary repository and communicator of cultural memory was under attack before Victor Hugo penned Claude Frollo’s dramatic pronouncement in *Notre Dame de Paris*. If ‘Ceci tuera cela’ marked the death of architecture at the hand of Gutenberg’s printed book, the Enlightenment ‘crisis of representation’ provided a definitive close to the medieval prominence of architecture as the principal source of cultural understanding (Kohane and Hill 2001). The topic of ornament seemed to disappear amidst general antipathy during the Modernist celebration of austere surfaces, although many buildings of this period display an unashamed celebration of materiality and surface that can best be described as ornament in Summerson’s broad sense. Indeed, one of the most vehement Modernist critics of ornament, Adolf Loos, used surface materials in his interiors in a way that exemplifies the concept of ornament as an articulate surface that informs the reading of the building as a whole. The interior surfaces of the Muller House in Prague are clad with a rich variety of materials and surface treatments, each of which contributes to the definition of a particular moment in the unfolding of the *raumplan*, Loos’ elaborate system for the organization of the plan in space. Here, materials and material finishes are imbued with cultural meaning, and articulate the passage from one space to the next. The entry sequence is itself marked by a transition through four distinct zones, each identified with its own material cladding and surface finish. The porch, clad in travertine, opens onto a vestibule tiled with opaque glass panels, which in turn opens to the anteroom with its cream-painted wood and grid of recessed square panels; an opening off the anteroom leads to a cloakroom clad in burlap fabric (Kleinmann and Duzer 1997). There has been a resurgence of interest in ornament over the past decade, due in part to the availability of digital fabrication techniques which greatly facilitate the production of elaborate forms and surface finishes (Loveridge and Strehlke 2006). The production of new types of ornament has also been influenced by the availability of materials that are capable of change in response to digital information, such as thermochromic and electrochromic pigments which change color or become transparent in response to heat or electrical current.

1.2. Architectural uses of sensor data

The connection between human activity and measurable attributes of indoor air are well-established, and are commonly used to control building environmental systems based on changes in activity patterns. For example, CO$_2$ is known to serve as an approximate measure of the number of people in a room, particularly when compared with outdoor CO$_2$ levels, and can provide a real-time measure of the people in a given space assuming that the type of activity is known in advance (Leephakpreeda *et al.* 2001). Other measurable qualities of the environment can also be used to detect the presence or absence of
people: artificial light levels indicate when room occupation begins and ends, and temperature can give a rough indication of how many people are in a room at a given time. Some human activities also generate traces that can be detected by sensors. The use of photocopiers and laser printers produces ultrafine, nanoparticle dust (Keady and Halvorsen 2000), and laser cutters produce both smoke and dust allowing easy monitoring of their use. Taken together, these factors provide a subtle record of activity over time, and using a small collection of inexpensive sensors it is possible to construct a picture of human activity in a given space. Each type of activity creates its own atmosphere, and over time a unique signature emerges for each space based on the activities that tend to take place there. Sensors can be used to extrapolate this signature from a variety of indicators: temperature and CO2 levels provide a picture of the density of people within a space; noise, dust, and smoke register the operation of machines such as photocopiers, plotters, and laser cutters; and light records daily fluctuations in the use of artificial light as well as seasonal fluctuations in daylight. This paper proposes the use of environmental sensor data as a basis for the design of a new type of architectural ornament. The purpose of this ornament is not to communicate the current composition of indoor air – given the many factors involved this would quickly become a prohibitively complex undertaking. Instead, we propose to use a synthetic snapshot of indoor air at a particular moment as a means of distilling a unique signature for each space within the interior, and as the basis of an ornament that takes on a distinctive appearance in response to the atmospheric conditions where it is located.

Indoor climate was chosen as a subject for the design project because it sensitively registers spatial and temporal variations in patterns of activity, and because it is a pervasive and dynamic quality of the architectural environment (Banham 1969).

1.3. Dynamic ornament in building interiors

For the most part, the integration of sensors in buildings has been dominated by applications engineered for efficiency, with little concern for the impact of sensor data on the experience of architecture. The term dynamic ornament identifies an alternative paradigm in which sensor data becomes a springboard for the design of new architectural elements, introducing dynamic qualities of the environment into the experience of the building.

One role of traditional architectural ornament is the introduction of variable, fluid and dynamic qualities of nature into the building. If architecture has been defined since Vitruvius in terms of firmitas, that which resists nature and the decay to which all organic matter is subject, then ornament is a means of re-introducing the organic and fleeting into the heart of the architectural project. Unlike architecture itself as traditionally defined, ornament has the capacity to be life-like: to imitate formal aspects of living organisms and even to present the
artful illusion of motion and change (Figure 1). The data collected by sensors can be seen as analogous to nature itself: subject to daily and seasonal patterns, but also essentially unpredictable and variable. While the ornament of the past relied on artistry and illusion to convey the experience of motion and change, contemporary architects have access to a diverse array of responsive materials and actuated kinetic elements that can be used to introduce the variability of the natural world into the fixed universe of the building. Sentient architecture, the ideal of a building capable of change in response to its environment, is based in part on the desire to impart to architecture a fluidity more often found in the response of natural organisms to changes in their immediate environment.

**FIGURE 1. TWO EXAMPLES OF ORNAMENT AS AN ImitATION OF FORMAL ASPECTS OF LIVING ORGANISMS. LEFT: A GILDED BRONZE WALL LIGHT, FRENCH, ABOUT 1750. RIGHT: CAPITAL FROM THE CHAPTER HOUSE, SOUTHWELL MINSTER.**

Both are taken from gombrich 1984. Precedents for the current interest in a sentient architecture include the dream of the early 20th century avant-garde for an architecture capable of moving and transforming itself in response to the needs of its occupants and the ever-changing environment. The automated glass doors of Giuseppe Terragni's Casa del Fascio were designed as an integral part of the spectacle of Fascist display; and the elaborately adjustable screens, ladders and windows of the Maison de Verre permitted a careful calibration of the interior environment (Leatherbarrow 2005). One early example of a sensor-enabled dynamic building element conceived as ornament was Jean Nouvel's 1988 Institut du Monde Arabe, whose south façade would have been magnificent in its conception as a mobile expression of patterns of sun and shade, exaggerating and underlining the inherent variability of daylight that Nouvel has masterfully exploited in many of his buildings. The fact that the façade's 27,000 mechanized diaphragms ceased to function soon after the
opening of the building is almost inconsequential to the experience of the interior, which is quite remarkable even without their intended mobility, but is somehow telling of the building’s dynamic aspirations. To design a responsive architecture is to introduce the possibility that one’s architecture will not perform as it was intended to, including the chance of systematic failure. Still, this building presents an important example of a dynamic building element which was conceived from the beginning of the design process as a permanent element of the building, with a central role in creating the building’s iconic definition on both the interior and the elevation. Some projects from the world of installation art have also taken on the scale and permanence of architecture. Rachel Wingfield’s illuminated fabric installations include dynamic pieces that respond to their surroundings and offer the possibility of integration in the architectural environment. Her ‘Sound reactive wallpaper’ is a patterned surface that glows in response to ambient noise levels, and that becomes spatial in its wrapping of an interior (Underhill 2006).

2. CASE STUDY OF A DYNAMIC ORNAMENT PROTOTYPE

This paper presents a study in the design of dynamic ornament that responds to local climatic conditions. The ornament employed in this study consists of printed circuit boards (PCB’s) painted with thermochromic ink, allowing the generation of non-emissive wall patterns that appear to have been printed but are in fact dynamically-generated, slowly-changing patterns that respond to local sensor data. Although the largest panels built to date are 64cm x 76cm, these prototypes have been conceived as the first step toward the creation of an ornament at the scale of the room, an interactive wallpaper that engages the viewer not as an object but as an integral element of the architecture (Huang and Waldvogel 2005).

The goal of our project has been to create a surface that responds to its immediate surroundings, generating a unique pattern for each setting in which it is installed. We chose to use data about indoor air as a means of identifying a unique signature of each space in the building, one that is also subject to change over time depending on the activities that take place.

The prototypes described were completed between September 2007 and January 2009 by researchers at the Media and Design Lab of the Ecole Polytechnique Fédérale de Lausanne (EPFL).

2.1. Setup of the indoor climate sensor network

In our design study, two nearly-identical adjacent rooms in a recently-constructed (2005) computer science research building at EPFL were outfitted with a network of climate sensors. In the first step of the design process we collected minute-by-minute sensor data in each of the rooms over a period of four
months. One of the rooms was equipped with workstations for six people and was used primarily for quiet individual work, while the other room was used for group meetings and contained several machines used to print drawings and build architectural models (printers, plotter, laser cutter, CNC milling machine), as well as a small electronics workshop. In analyzing the data, we found that it was possible to identify patterns unique to each of the two rooms, and that the sensor data appeared in many instances to correlate with the activities taking place in each room. The sensors used in each room collected data on temperature, humidity, light, dust, cigarette smoke, volatile organic compounds, and CO$_2$. Sensors were grouped in pairs and connected to an AVR microcontroller-based Ethernet device (Socher 2008), which allowed us to poll each of the sensors every minute over the network and record its current state. Sensor values were stored in a MySQL database, and graphs were created using RRDtool (an open source data logging and graphing system for time series data). In order to better understand the relationship between sensor data and activities taking place in the rooms, a log was kept over several weeks recording the number of people in each room and the activities taking place. In this way it was possible to observe in a qualitative sense whether the sensor data reflected changes in human activity. For example, both the ambient air temperature and the level of CO$_2$ increased as people entered the room, giving an approximate measure of the number of people in the room at a given time. The cigarette smoke sensor responded consistently to the use of the laser cutter, probably because the hydrogen and carbon monoxide measured by the sensor are also produced by the combustion of paper products in the laser cutter. The light sensor gives a simple indication of whether the room is in use, based on whether or not the overhead lights have been turned on.

### 2.2. Design of the dynamic ornament prototype

Once we had a basic understanding of the patterns that could be observed using the sensor data, the next step in the design process was to find build a temporally-changing architectural ornament capable of reflecting these patterns. We first tried an ornament based on LEDs – this worked well as a simple indicator of the sensor levels, but despite our efforts to regulate the LEDs based on ambient light levels we found their brightness quite distracting. Both the rooms in our study were used (in part) for reading, writing, and other tasks requiring long periods of unbroken concentration, and we were dedicated to make the dynamic ornament an unobtrusive intervention in these environments. Avoiding distraction was also important because our goal was to build a surface that could be implemented at a large scale (the scale of the room, or even that of the building). Thermochromic ink is a commercially available material that changes color or becomes transparent above a specific threshold temperature. It is commonly used to produce novelty items like disposable
battery charge indicators and cups that display a message when their contents are too hot. Thermochromic ink has rarely been used in an architectural context or at an architectural scale. We decided in September 2007 to build a series of prototypes exploring the potential of thermochromic ink for the design of non-emissive, slowly changing building surfaces. Thermochromic ink is available for purchase in many forms: we chose a blue pigment containing microencapsulated particles which are colored at room temperature and become transparent at 40 degrees C, revealing whatever material is immediate beneath. Our goal was to selectively heat the thermochromic ink to reveal specific patterns, and we evaluated a range of materials and fabrication processes in terms of their ease of fabrication, heating efficiency and versatility in the creation of different types of designs. Thermochromic surfaces are typically created by embedding conductive wire within a substrate painted with thermochromic ink: when current passes through the wire it heats the ink and produces a color change that follows the shape and dimensions of the wire. Nichrome wire is often used because of its high resistivity, the ability of a material to translate a small amount of current into a large increase in temperature. Recently, researchers have found even more efficient materials than nichrome such as silver-Polydimethylsioxane (Liu 2007). We eventually chose to use PCB’s (printed circuit boards) to build our thermochromic surfaces: PCB’s can be quickly and inexpensively fabricated using well-established techniques, are relatively inexpensive, and are available in a wide range of sizes (the largest board we could easily build was 34cm x 40cm). PCB’s consist of an epoxy substrate with a layer of copper that is etched to create the desired circuits. The fabrication process affords a very high level of precision in the thickness and width of the copper lines, and we chose to use very thin lines (80 to 120 microns, the width of a human hair) because these would heat more quickly and produce a crisp line on the surface painted with thermochromic ink. When current is sent through these lines the copper heats: the rate at which this temperature change occurs and the temperature reached depend on the amount of current, the duration of the current pulse, the thermal inertia of the substrate, and the ambient room temperature. PCB’s can be built using many different substrate thicknesses: at 3.2mm, the epoxy base of the PCB is stiff and can be used to construct rigid assemblies or to build a load-bearing surface. At 0.1mm, the minimal thickness that we used in our prototypes, the material is strong and quite flexible. Prototypes built from the 0.1mm substrate can be used to wrap columns and other curved building surfaces (Figure 5). Another benefit of using PCB’s for our thermochromic surfaces was the ease with which the control system for the boards could be built-in to the PCB, or built on a separate PCB and connected with a cable to the thermochromic surface. Microcontrollers are easily integrated on the surface of the PCB, and can be programmed to regulate the current flowing through the copper lines underlying the thermochromic pig-
ment, turning on or off the figures inscribed. In our current prototype, the microcontrollers were programmed to turn the figures on and off based on readings from the indoor climate sensors. Once the copper lines had been etched on the PCB’s in the configuration we designed (Figure 3), the PCB was painted with a layer of white oil-based primer paint followed by 2-3 layers of the thermochromic pigment. When the thermochromic ink is heated, it becomes transparent and reveals the white paint underneath. White was chosen for the under layer to achieve a high contrast with the dark blue of the thermochromic pigment in its stable (room temperature) state. We explored two techniques for displaying patterns on the PCB’s: pixels and pre-designed shapes. The pixel surfaces allowed the display of simple raster graphics, while the pre-determined shape surfaces were capable of displaying highly complex vector graphics. To create pixels we drew a dense pattern of copper wires, packing a 1m length of copper wire into an area of 1cm² (Figure 2).

**FIGURE 2.** TWO ICON-BASED PROTOTYPES (THE FIRST TWO IMAGES ABOVE) AND A PATTERN-BASED PROTOTYPE (THIRD IMAGE ABOVE). THIS PATTERN PROTOTYPE EXPLORED THE USE OF OVERLAPPING FIGURES, EACH OF WHICH CAN BE INDIVIDUALLY ACTUATED.

Our largest pixel prototype included 256 pixels, each individually controllable, allowing the display of simple patterns or icons on the thermochromic ink surface (Figure 2). We also explored pre-defined shapes as an alternative to pixels: these offer the benefit of high image clarity and resolution, and the disadvantage that each board can only be used to display a limited number of shapes. We built several prototype boards containing an array of icons which could be individually turned on or off, a type of display that could be useful in a situation where explicit, non-verbal communication of information is needed (Figure 3). We also explored the use of abstract patterns in several prototypes: these consisted of geometric patterns that could be varied by turning on and off individual lines and shapes. Our current prototypes used a combination of icons (individually controlled, easily recognizable iconic figures) and patterns (abstract geometric shapes). We scanned a fabric pattern by Klaus Haapaniemi consisting of a vegetal ornament and bird, and inserted a number of recognizable figures into the interstices of the pattern (animals and insects). Finally, we created ~40 circuits by connecting elements of the pattern together, with the
intention that each circuit would be controlled individually to change the appearance of the pattern over time. While our earlier prototypes had been limited to the size of an A4 paper sheet for convenience in manufacturing, the current prototypes were constructed by joining four separate panels, resulting in a viewable surface of 64cm x 76cm – some space at the margins is taken up by soldered connections, which we chose to conceal with a frame (Figure 4).

**FIGURE 3. THE CURRENT DYNAMIC ORNAMENT PROTOTYPE: PCB SURFACE BEFORE PAINTING WITH THERMOCHROMIC PIGMENT, SHOWING COPPER LINES. ONLY THE THIN COPPER LINES BECOME HOT, AND THUS VISIBLE WHEN A CURRENT PASSES THROUGH THEM; THE THICK LINES EXIST ONLY TO COMPLETE THE CIRCUITS AND ARE REMAIN INVISIBLE ONCE PAINTED.**

![Figure 3](image1.png)

**FIGURE 4. CURRENT DYNAMIC ORNAMENT PROTOTYPE. THE DIMENSIONS OF THE VIEWABLE SURFACE ARE 64CM X 76CM.**

![Figure 4](image2.png)

### 2.3. Mapping of sensor data to graphical representations

The next step in our design process was to connect the thermochromic surfaces to the flow of data collected by the indoor climate sensors. One of our primary concerns was to accurately translate the indoor climate data into ornamental patterns in the environment, patterns which could be ‘read’ by an informed viewer as a representation of human activity. We were not interested, however, in visually representing the data in all its variety and complexity. Instead, our
intention was to simplify and abstract the sensor values into a graphical representation which would reflect patterns without literally displaying the data from each sensor. There were two reasons for this. First, we hypothesized that a complex and accurate representation of the sensor data would be far more distracting as a permanent element of the architectural environment than an abstract, simplified representation. Second, the information that we were interested in was the patterns in human activity, and we hypothesized that these are more clearly revealed in a long-term, cumulative view of the sensor data than in a minute-by-minute monitoring of the value of each sensor.

There were two steps in making the translation from raw sensor data to pattern: first the creation of a cumulative index of the sensor values, and then the mapping of this index value to a graphical representation. The first step was solved in a straightforward fashion by simply adding the values of each sensor at a given moment to create a cumulative picture of the sensor values. This cumulative picture precluded a detailed interpretation of the sensor values, but did provide a qualitative sense of the activity taking place in the space and the number of people present. As described above, each of the sensors responded to a different type of human activity, so a cumulative summary of the data gives an overview of the activity level without providing information about what types of activity are taking place. The mapping was accomplished by translating the cumulative sensor reading to a number between 1 and 40, and the illumination of the corresponding number of figures on the dynamic ornament prototype (which contains a total of 40 independent figures). Thus, as the cumulative measure of activity increases the pattern of the dynamic ornament becomes more dense, and the number of creatures increases (Figure 6).

**FIGURE 5. CURRENT DYNAMIC ORNAMENT PROTOTYPE. BECAUSE THE PCB SUBSTRATE IS VERY THIN (0.1MM), THE PANEL CAN EASILY BE USED TO WRAP CURVED SURFACES LIKE THIS COLUMN.**
3. DISCUSSION AND FUTURE WORK

In our design study, two nearly-identical adjacent rooms were outfitted with a network of climate sensors, with the goal of refining and evaluating the capacity of our dynamic ornament prototype to respond to and graphically express differences in the patterns of use specific to each space. As of this writing, the installation of the thermochromic panels in these two rooms is not yet complete. Although it is our hypothesis and design intention that the thermochromic ornament will take on cultural meaning through its representation of the unique signature of each space, we have yet to substantively demonstrate this idea. Plans for an evaluation of the dynamic ornament prototype during the coming months are being developed, and will involve more design iterations of the dynamic ornament and feedback from the people working in the two spaces on each of the iterations.

There are a number of disadvantages to the prototypes described here that we will address in the next design iterations. The dimension of our largest thermochromic panel is still small for addressing the scale of the room, and the panel itself is more an object than an integral element of the architecture. There are issues with power consumption and heat production that need to be addressed before these displays can be considered for permanent integration in the building. We also have not adequately addressed the desire for a display that can both become part of the background, and that can be ‘read’ as a legible expression of the unique character of each room within the interior. The prototypes described in this case study explore possible applications of thermochromic panels as a type of dynamic ornament. Initial data from our indoor climate sensor network suggest that inexpensive sensors can be an effective tool for recognizing differences between rooms or zones within the building interior based on patterns of use. The integration of dynamic architectural elements that respond to this information points the way toward new types of architectural ornament that are not completely determined by their designer, but that result from variable and largely unpredictable aspects of the environment.
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