Dynamic ornament: An investigation of responsive thermochromic surfaces in architecture

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This paper describes the use of environmental sensor data as a basis for the design of architectural ornament that takes on a distinctive appearance in response to the atmospheric conditions where it is located. Among the goals of the project were the identification of inexpensive fabrication methods that could be used to build responsive surfaces at the scale of a room, and the identification of material and tectonic strategies for integrating dynamic information displays in buildings. A series of prototypes were constructed to explore the benefits and limitations of thermochromic ink as a material for visualizing dynamic data, and a method is proposed for building thermochromic surfaces based on printed circuit boards (PCB's) that is cost-effective and allows the fabrication of large surfaces through tiling. The limitations of this method include high power consumption, a short lifespan and difficulties in controlling the surface temperature.

1. INTRODUCTION

Sensors are routinely used in buildings to monitor aspects of indoor climate such as temperature and humidity as well as other qualities of the indoor environment. In this paper we propose a type of dynamic architectural ornament that visualizes sensor data recording changes in the indoor environment. A sensor-based ornament offers the possibility of a dynamic, bottom-up expression of the character of a given space 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. The prototypes described here were designed to explore the potential of thermochromic panels as a representation of change in the indoor environment, measured in terms of the concentration of common airborne contaminants and aspects of indoor climate such as temperature and humidity.

In the project described here a series of functioning prototypes were constructed using thermochromic ink as a material for displaying data. In the following we introduce the concepts behind the project and describe the implementation of the sensor network and thermochromic prototypes.

1.1. Thermochromic ink as a responsive surface

Thermochromism is the ability of a material to change color due to a change in temperature. Thermochromic pigments have a large range of possible color, and sensitively register changes in temperature by changing color or becoming transparent at a particular threshold temperature. The change is in most cases reversible, and can be repeated over long periods of time without substantial degradation in the pigment's thermochromic properties[1]. The downsides of thermochromic ink include its sensitivity to UV light and the power consumption required to heat large surfaces. The UV sensitivity can be addressed by treating the surface with a UV-protecting material – without this measure the pigment loses its color in a matter of weeks when exposed to direct sunlight. The pigment is also sensitive to overheating and can easily be 'burned' if heated beyond a certain threshold temperature – with the result that the pigment becomes permanently transparent in the affected region.

Thermochromic ink offers a number of benefits as a material for information display. First, it is non-emissive and thus less distracting than LED or other emissive displays in an architectural environment: the contrast increases with the ambient light level, unlike light-emitting displays that have to compete with daylight. The graphic element can be made visible from both sides of the display, which can be molded in various shapes. The relatively low refresh rate (the surface needs several seconds to cool down) is well-adapted to the representation of data that do not change quickly.

There have been few implementations of thermochromic pigments in the production of responsive architectural surfaces. In a student project titled 'Not- So-White Walls', Dario Buzzini prototyped a responsive wallpaper consisting of a painted surface with thermochromic ink that could be actuated using a low-resolution grid of resistors that can be controlled computationally [2]. A number of projects have integrated thermochromic dyes and resistive wire to produce controllable color changing textiles [1][3][4]. The use of thermochromic pigments for information display has primarily been limited to very small high resolution displays[5] and larger low resolution displays such as those produced by Buzzini. There are a number of commercially-available architectural components incorporating thermochromic pigments, including architectural glazing that rejects unwanted solar heat gain while maximizing daylighting [6][7].

1.2. Sensing air quality

Sensors are commonly used in buildings to monitor indoor climate and the presence of contaminants in indoor air. 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.

Some activities also generate traces that can be detected by sensors. The use of photocopiers and laser printers produces ultrafine, nanoparticle dust[8], and laser cutters produce both smoke and dust allowing easy monitoring of their use. Taken together, these factors provide a record of activity over time, and using a small collection of inexpensive sensors it is possible to construct a log of activities in a given space. Each type of activity creates its own atmosphere: 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.

1.3. Responsive precedent

Automated building components have become a commonplace aspect of the everyday built environment. Examples include automated shading that reduce cooling loads due to solar radiation heat gain and dimmable lighting fixtures that respond to photosensors, reducing the brightness of artificial lighting when daylight is available[9].

In addition, however, to such practical applications responsive components and surfaces have also been used as a poetic and potentially subversive element in architecture. The concept of interactive surfaces as an expressive element of the building has been explored in numerous installations, mostly temporary, which have explored the architectural implications of materials capable of changing in response to their immediate surroundings. 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 becomes spatial in its wrapping of an interior[10]. Jeffrey Huang and Muriel Waldwogel have described how "the tectonic and psychological effect of our surroundings can be augmented, subverted, and estranged by animating wallpapers and introducing an interactive, possibly darker dimension into architecture."[11] The interactive surfaces that they have developed in a series of interactive digital art projects introduce an unexpected, subversive quality realized through a range of innovative material interfaces.

Another important function of recent responsive projects has been to emphasize material and tectonic considerations in the construction and integration of the visualization in the building. As computer interfaces have moved beyond the screen to objects and the environment, it has become an essential aspect of design to consider the materiality of the responsive interface[12]. Multiple projects such as the SpeakCup and Sprout I/O of Coelho and Zieglbaum have investigated the ability of particular materials to become part of the expressive expressive language of the computer interface[13].

2. BUILDING THE THERMOCHROMIC PROTOTYPES

The following prototypes were completed by the authors at the Media and Design Lab of the Ecole Polytechnique Fédérale de Lausanne (EPFL) between September 2007 and January 2009 as a proof of concept exploration of in-situ data visualization in buildings. 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

► Figure 1: Two versions of a surface consisting of four joined panels. Both use a highly flexible 0.1 mm epoxy substrate, and measure 64 cm x 76 cm.

of the room, an interactive wallpaper that engages the viewer not as an object but as an integral element of the architecture.

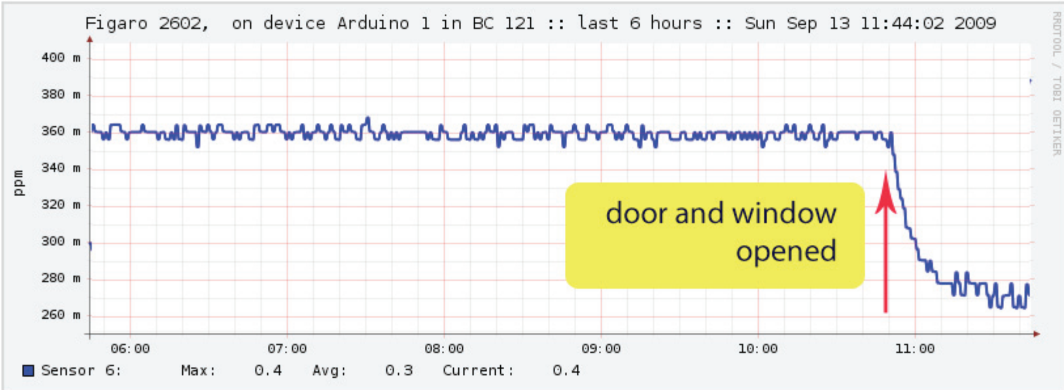
The goal of the project described here was to create an ornamental surface that responds to its immediate surroundings, generating a unique pattern for each setting in which it is installed. Indoor air quality was selected as an aspect of the indoor environment that is usually invisible and has a significant influence on comfort and well-being. Indoor air quality changes daily and hourly based on external conditions (weather) as well as the activity of people within the building. The thermochromic panels were used to visualize this change in indoor air over time.

2.1. Building the sensor network

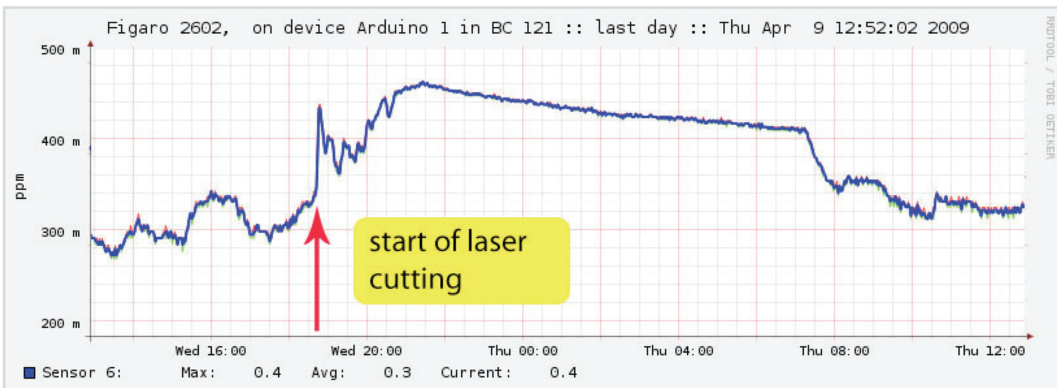
In our design study two identical adjacent rooms in a research building on the EPFL campus were outfitted with a network of indoor air sensors. In the first step of the design process we collected sensor data in each of the rooms over a period of four months. One of the rooms was equipped with workstations 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. In order to better understand the relationship between sensor data and activities taking place in the rooms, a log was kept over several months 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 sensor data reflected changes in human activity.

There were several types of actions that resulted in significant changes in the measured air parameters: for example act of opening a door and a window resulted in a sudden drop in VOC levels (figure 2), and the use of the laser cutter saw a sudden increase in VOC levels that persisted over 12 hours (figure 3). In addition, the light sensor provided a simple indication of whether overhead lights were turned on or off.

For the purpose of visualizing the data using thermochromic panels, we simply summed the average reading for each sensor in the room over one minute to get a number representing the unique climatic signature of a given room at a given time. Using this technique, we were able to identify in a very abstract way the differences between spaces in terms of indoor climate and the changes that take place over time. Because we were interested in identifying microclimatic differences between parts of the building over time, we chose not to consider the data from sensors whose measurements did not vary significantly from one part of the building to another. Humidity, for example, tended to be constant throughout the building at any given time so this was eliminated from the sum.



▲ Figure 2: VOC levels, showing the effect of opening a door and window in a conditioned room which previously had no windows or doors open (they were opened at 10:50).



▲ Figure 3: VOC levels over one day, showing the effect of laser cutting between 19:20 and 21:00. The VOC level did not reach its 'normal' state until 8am the next day.

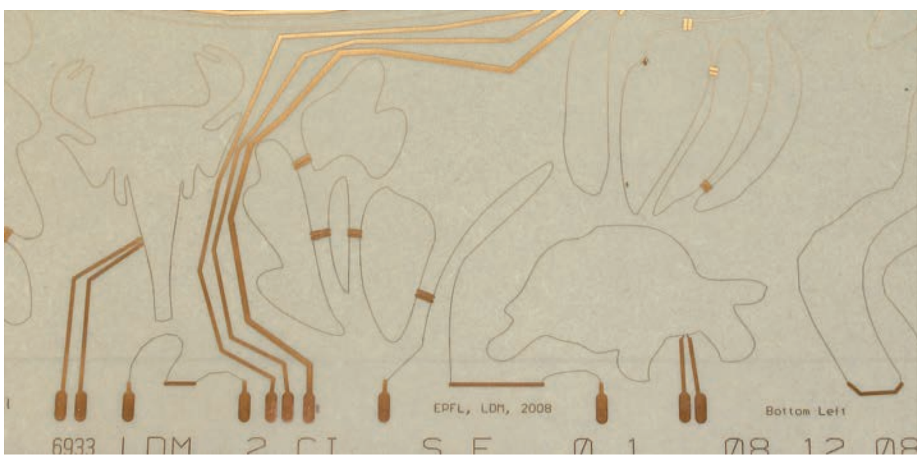
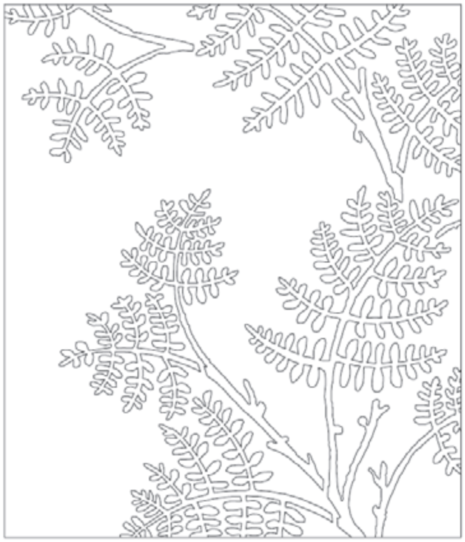


Figure 4: A panel before thermochromic paint was applied, showing the patterns outlined in copper. When electricity passed through the circuits thin wires would heat, producing a visible pattern on the painted surface, while thick lines would not heat sufficiently to produce a change in the paint.



◀ Figure 5: A panel based on a tracing of ferns, divided into eight circuits.

◀ Figure 6: Bird panel, loosely based on a fabric design by Klaus Haapaniemi.

2.2. Panel fabrication techniques

For the prototypes described below we used a thermochromic reversible leuco dye microcapsule-based ink which is blue below 40C and transparent above this temperature. We used this property of the dye to display patterns by selectively heating an ink-covered panel above the threshold temperature, revealing an underlying layer of paint. In all our prototypes a white under-layer was used for contrast with the blue thermochromic paint (figure 7).

► Figure 7: Applying thermochromic paint to a circuit board.

Our strategy was to ‘draw’ a figure using conductive material, and then reveal the figure by passing a current through the conductive material, selectively heating the ink. One example of this is figure 8: here a region has been heated with an underlying coil of conductive material that has the shape of an arrow. The Printed Circuit Board (PCB) was chosen as a means of selectively heating the thermochromic panels. PCB fabrication is a well-established industrial process, with extremely high levels of precision possible. The process involves the etching of a layer of copper that has been bonded to an epoxy plate; the thickness of both copper and epoxy can be selected at the time of manufacturing. Using this manufacturing technique, any number of circuits can be etched in nearly any graphic configuration. Using this technique it was possible to

► Figure 8: Example of a thermochromic panel – the arrow icon has been ‘turned on’ by sending a current through the underlying circuits, heating the thermochromic pigment locally and revealing the white paint beneath.

‘draw’ the patterns we wanted to eventually display on the thermochromic panels using CAD software, and then print these patterns in copper using one of several well-established techniques for producing PCB’s from a CAD file.

The advantages of this method include ease of fabrication (facilities are available worldwide); precision; the ability to create the design using CAD software, and generate gerber files which are used directly to fabricate the end-result; the few constraints in terms of the designs produced. The principal disadvantages are the limitations on the size of the panel imposed by the machines used for fabrication; and the cost. The maximum size of the copper plates varies based on the machines used; at the EPFL circuit fabrication shop the maximum was 23 x 30 cm. Copper does not have a particularly high resistance so the copper traces etched on the circuit board were specified to be as thin as possible: for the EPFL lab the minimum was 80-100 μm, roughly the diameter of a human hair; we used a copper thickness of 12 μm.

PCBs can be built using many different thicknesses for the epoxy substrate. At 3.2 mm, the epoxy base of the PCB is stiff and can be used to construct rigid assemblies or to build a load-bearing surface. At 0.1 mm (the thickness of a sheet of paper), the material is still strong but quite flexible. Prototypes built from the 0.1 mm substrate can be used to wrap columns and other curved building surfaces (figure 1). We also found that the thin (0.1 mm) substrate is better at heat-dissipation, allowing the patterns to be changed more quickly.

While our first panel prototypes were limited to the size of an A4 paper sheet for convenience in manufacturing, the final prototypes were constructed by joining four separate panels, resulting in a viewable surface of 64 cm x 76 cm - some space at the margins is taken up by soldered connections, which we concealed in one of the prototypes with a frame (figure 1).

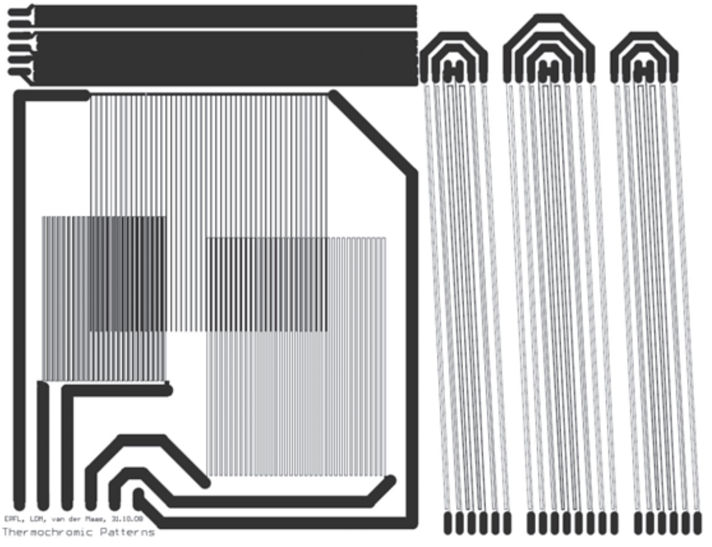
We went through several stages in refining our process for applying the thermochromic paint. In the earliest prototypes the paint was applied by hand with a paint brush: this resulted in an uneven surface finish, and the slight differences in the thickness of the thermochromic paint resulted in irregular response to heating across the surface (figure 7). Following this we used a spray gun to create a smooth, even coat of thermochromic paint across the surface of the panel (figure 9). In the last prototypes we used serigraphy as a method for applying the pigment: in this method the paint is applied using a machine process that assures an extremely even coat.

► Figure 9: Method of applying thermochromic paint with spray gun – Antoine Gagliardi of the EPFL Output Center.

2.3. Visualization strategies

Our first prototypes were used to test the design parameters of PCBs as a means of producing responsive panels with thermochromic ink. For example, finding the ideal width of the copper circuit traces requires consideration of multiple factors including speed of heating, line sharpness, blurring of adjacent lines into each other, and spreading of the line traces over time (figure 10). For some of the prototypes we took advantage of the fact that the heated region tended to quickly spread laterally, merging closely-spaced lines in what appeared to be a solid figure. For the later prototypes, we aimed for as thin and precise a line as possible, and

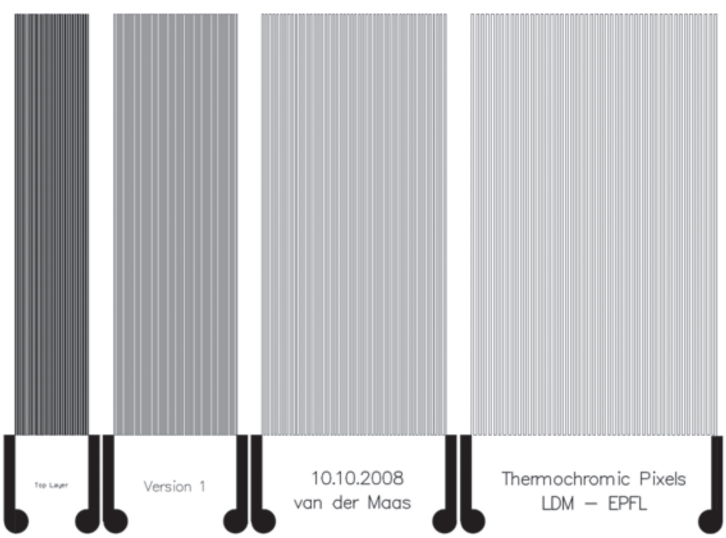
► Figure 10: Prototype built to optimize the thickness of the copper circuit traces.



needed to know the minimal allowable spacing of lines in order to avoid the visual effect of merged lines (figure 11). There was a necessary compromise between rate of heating and line thickness: the thinner the line, the faster the lines could be heated, so in cases where a thicker line was desirable we had to accept slower heating of the thermochromic ink or provide a higher level of power to the circuit.

Following these experiments we produced a series of prototypes exploring the use of pixels as a means of producing patterns. Pixels offer the advantage of flexibility in what is displayed – although increasing the resolution of the pixel grid greatly increases the complexity of the hardware involved in controlling a large number of individually-addressable circuits. The solution commonly employed to deal with this complexity is multiplexing, a method which allows the microcontroller to select a single pixel based on its column and row address. We chose to make pixels using tightly-packed copper traces (figure 13), placed so close together that when heated the circuits would blend together to form a solid shape. The largest pixel prototype (figure 12) consisted of 256 pixels in a 16x16 array. Each pixel was a square, 1 cm on each side, containing a 50 cm copper circuit. This surface was then painted with a coat of white paint, followed by two coats of thermochromic pigment, leaving the pads of the circuits exposed. We also produced several prototypes that used resistors as pixels – the smallest SMD resistors are about 1mm^2, and can be used to heat the overlying ink with a small amount of power. Commercially-available resistors are designed to not produce heat when used within their intended power range, but they can be made to overheat by applying more than the recommended power.

We tested this technique using tiny (~ 1mm^2) SMD resistors, a technique that seemed promising for the creation of a high resolution pixel-based display.

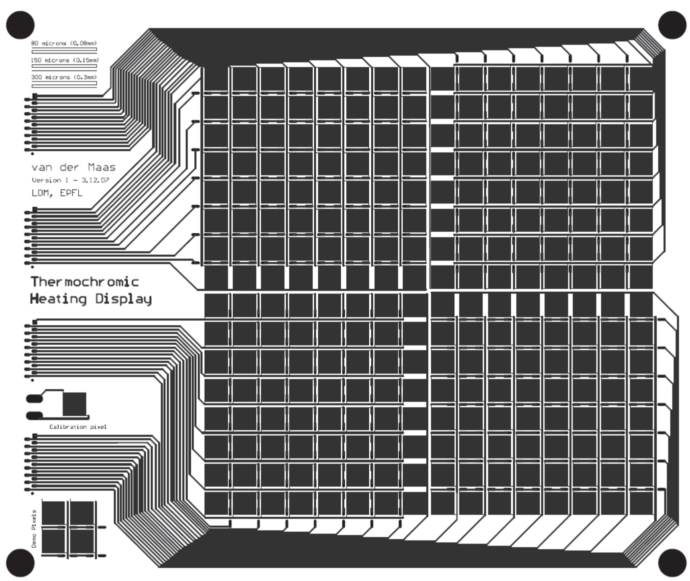


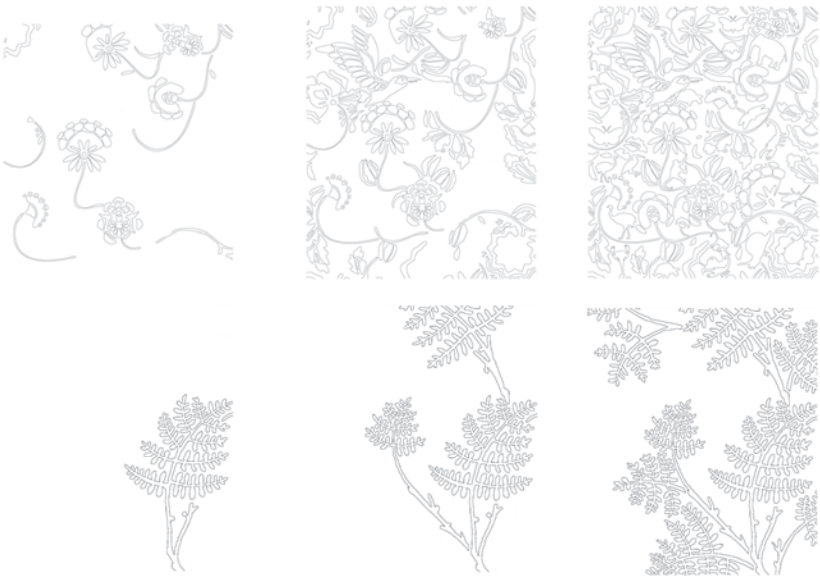
◄ Figure 11: Prototype built to optimize the spacing between each of the copper circuit traces.

Our final set of prototypes explored the use of patterns – figures formed by a single copper wire. The underlying copper lines can be extremely thin – as little as 80-100 μm. And, although there is inevitably considerable diffusion of these lines when their heat is transferred to the thermochromic surface, the resulting line is still quite thin, about 1 mm in width. Highly complex patterns can thus be displayed on the surface of the panel, and in the following prototypes we explored the possibilities for expression offered by this complexity.

Following the pixel display, we tried 'filled shapes' with several boards that used commonly recognizable icons to communicate information. We experimented with the spacing of the copper wires used to activate the filled shape, and found that the spacing had a direct effect on the color and brightness of the resulting shape (figure 11). To achieve the effect of an evenly-filled shape, in which the individual circuit traces were no longer identifiable, it was necessary to maintain a spacing between lines of 300 μm (0.3 mm), which meant that large shapes resulted in extremely long circuits, high resistances, and slow rates of heating. For these reasons, we decided that this technique was not an efficient use of the fabrication technique we had developed for the thermochromic panels. Our final set of prototypes explored the use of patterns – figures formed by a single copper wire. The underlying copper lines can be extremely thin – as little as 80-100 μm. And, although there is inevitably considerable diffusion of these lines when their heat is transferred to the thermochromic surface, the resulting line is still quite thin, about 1 mm in width. Highly complex patterns can thus be displayed on the surface of the panel, and in the following prototypes we explored the possibilities for expression offered by this complexity.

► Figure 12: A group of pixels from the 256-pixel display.





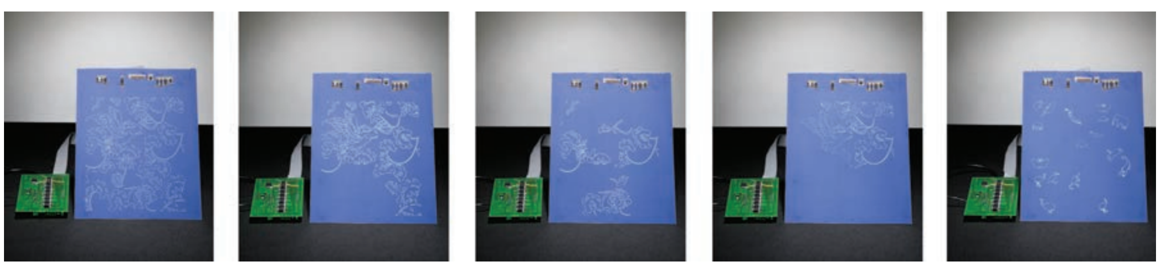
◀ Figure 13: Changes in the 'sensor index' are mapped to the variables of density and brightness in the thermochromic panels. Shown here is a transition from a low density pattern to a higher density in two different patterns.

For the first of these prototypes we scanned a fabric pattern by Klaus Haapaniemi consisting of a vegetal ornament and bird. Finally, we created eight 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 (figure 6). The responsive surfaces were built by painting custom circuit boards with a thermochromic ink which changed color in a predictable way when an electric current was sent through the circuit. In this way, it was possible to produce the appearance of slowly changing,

animated patterns on a painted surface. The panels consisted of 40 circuits which could be individually turned on and off as a means of changing the density of the pattern in real-time as the air quality sensor values changed.

The mapping of the sensor data to the panels was accomplished by translating the cumulative sensor reading to a number between 1 and 256. This number was then used to determine how many circuits on the panel to illuminate, and at what level of brightness. Thus, as the cumulative sensor

▼ Figure 14: Handheld panel developed as a portable object. This panel was enclosed in a box for interactive use in an exhibit.



index increases the pattern of the dynamic ornament becomes more dense (figure 13, 14).

Prototypes were built at several different scales anticipating different types of use. Seven prototypes were the size of an A4 paper sheet, and two panels had a display surface area of 0.48m^2 (0.74 by 0.64 m). We were able to build boards with a maximum dimension of 23 x 30cm using standard processes; larger panels could be constructed by tiling these boards together, and two of our prototypes were built with four boards each to form an apparently homogeneous surface of almost 0.5m^2. The A4 panels were designed to function as portable objects with the computational elements and sensors integrated in a box and provided interaction through a single button that activated the panel and revealed a pattern that represented current data recorded by the sensor (figure 14). The largest panels were designed for integration in the building (figure 1) and did not provide any means of direct interaction.

3. CONCLUSION

3.1. Limitations of thermochromic ink

We encountered two significant obstacles in our development of the thermochromic panels: the limitations on the size of the panels imposed by the fabrication process, and the difficulty of preventing overheating of the panels when left to run for an extended time. I will describe briefly how we overcame these obstacles during the project, and will describe our ideas for improving these aspect of the prototypes in the future.

The maximum size for circuit manufacturing at EPFL is 32 x 38 cm: for the largest of our prototypes we tiled four of these panels to create a single panel with a dimension of 64 x 76 cm. When painted the seam between the panels disappears; and, the technique is potentially unlimited in the number of panels that can be combined in this way.

An added complication is presented by the fact that voltage and current are significantly constrained by the power supply used. The power supply we finally selected for the thermochromic panels was rated for 36V 9.7A, or 350W (for reference a typical laptop power supply provides maximum 20V 4.5A, or 90W). We needed this much power to be able to quickly heat figures on the thermochromic panels – we could have reached the threshold temperature with much less power but it would have taken a longer amount of time to do so.

The problem of overheating is one that we encountered with all the prototypes. The control software used with the panels sends current through the circuits in pulses to avoid overheating, but with each pulse there is a slight increase in the temperature of the surface, a process that results in overheating if left unchecked. In the current prototypes we addressed this in two ways. First, tiny temperature sensors were attached to the panels and the current surface temperature was used to determine the current sent through the circuits, in theory avoiding the possibility of overheating. Nonetheless, we found that one temperature sensor was not sufficient to monitor overheating, which was often quite localized. A compromise was found by imposing a fixed period for cooling off after the panels had been turned on for at least ten seconds.

3.2. Future work

In the future we hope to produce larger display surfaces and have investigated the possibility of using serigraphy to print conductive traces on a substrate, a process that would bypass the PCB fabrication process and allow larger panels to be produced. Conductive ink for serigraphy is readily available and is often used for the fabrication of printed electronic components. Our intention for the next generation of thermochromic panels is to first print the conductive traces in a serigraphic process in which a screen is used to selectively apply ink to a surface, and then to apply the thermochromic ink using the same screen.

Such a technique could facilitate the use of entire interior walls as responsive thermochromic surfaces, capable of displaying local variation in the distribution of indoor air contaminants. For example, responsive surfaces located along a corridor could articulate changes in air quality and indoor climate experienced during the entry sequence of a building (figure 15). Similarly, in a deep room with windows open to the exterior on one side of the room but not the other, thermochromic panels could be used to visualize the gradation between exterior air and interior air.

◀ Figure 15: Proposal for an installation: panels located in a corridor visualize a gradual change in air quality and climate as one enters the building.

The purpose of the prototypes described in this paper has been to exploration the potential of responsive surfaces as a means of integrating dynamic information in buildings. The prototypes represent an effort to define a place in architecture for digital information and a suitable material and tectonic expression. Thermochromic ink has many limitations that make it impractical for permanent installation in the building, and we have used thermochromic paint as a substitute for more robust responsive materials which will surely become available in coming years.

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REFERENCES

1. Christie, R.M., Robertson, S. and Taylor, S., *Design concepts for a temperature-sensitive environment using thermochromic colour change*, Colour: Design and Creativity, 1(1):1–11, 2007.
2. Buzzini, D., *Not so white walls*, Technical report, Interaction Design Institute Ivrea, 2004. http://people.interaction-ivrea.it/d.buzzini/.
3. Berzowska, J., *Very slowly animating textiles: shimmering flower*, in Proceedings of ACM SIGGRAPH, page 34, 2004.
4. Shibutani, M., and Wakita, A., *Fabcell: fabric element*, in Proceedings of ACM SIGGRAPH, page 9, 2006.
5. Liu, L., Peng, S., Wen, W., and Sheng, P., *Paperlike thermochromic display*, APPLIED PHYSICS LETTERS, 90(213508), 2007.
6. Seeboth, A., Schneider, J., and Patzak, A.H., *Materials for intelligent sun protecting glazing*, Solar Energy Materials & Solar Cells, 60:263–277, 2000.
7. Fernandez, J.E., *Materials for aesthetic, energy-efficient, and self-diagnostic buildings*, Science, 315:1807–1810, 2007.
8. Keady, P.B., and Halvorsen, T., *A new tool for eliminating indoor air quality complaints*, Journal of Nanoparticle Research, 2:205208, 2000.
9. Sullivan, C.C., *Robo-buildings: Pursuing the interactive envelope*, Architectural Record, 194(4):p.148–152,154,156, April 2006.
10. Underhill, W., *Sunny-side up: Rachel Wingfield's textiles let the light out*, ID Magazine, page 71, September/October 2006.
11. Huang , J. and Waldvogel, M., *Interactive wallpaper*, in Proceedings of SIGGRAPH '05: ACM SIGGRAPH 2005 Electronic Art and Animation Catalog, pages 172–176, New York, NY, USA, 2005.

12. Vallgarda, A., *Giving form to computational things: developing a practice of interaction design*. Personal and Ubiquitous Computing, pages 1–16, 2013.

13. Coelho, M. and Zieglbaum, J., *Shape-changing interfaces*, Personal Ubiquitous Computing, 15:161173, 2011.

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