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Responsive, Dynamic Architectural Surfaces: From Conceptualization to Implementation

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Abstract— **In this paper, we present a case for the design and implementation of responsive, dynamic architectural surfaces as potential instruments to provide a structural function together with an aesthetic purpose and informative one. Responsive architectural surfaces are those than provide a dynamic structure—that is, it can morph or change in terms of its shape and content displayed on it according to different environment factors. These factors include how many people are around a structure and how they behave with and around it. In addition, environment information such air quality, temperature, noise level, sunlight quantity, and humility can all be captured, transformed, and returned in way the is perceivable by people, with the aim of highlighting different aspects of the information. An end goal, for example, may be to use these systems to raise awareness about a sensitive public issue (e.g., air and sound pollution level in an environment) in a subtle, implicit manner. In this paper, we describe 3 working systems, their purpose and technological features. In addition, we present a system we are currently developing. With these four example systems, we hope to provide a deeper understanding of what responsive, dynamic architectural surfaces can be useful for and their implementation challenges.**

Index Terms— **Responsive systems; Smart materials; Energy efficiency; Responsive architecture; Ubiquitous systems.**

I. Introduction

The main goal of this research is based on our past experience [8,13] to explore the use of architectural surfaces to communicate in a dynamic way and using different types of environmental information from the surroundings and biometric information from nearby people [2,3,4,5,6]. We aim to develop affordable artifacts and systems that serve two dual functions: architectural and informational. The first function requires the system to have a permanent, stationary role, while the second function will need the system to have the ability to be dynamic and responsive to the changes in the information it receives. Our focus is on dynamic architectural surfaces, or membranes. A dynamic membrane represents an approach to augment the capabilities of architectural structures by enabling them to sense their environment. In this way, they can capture different types of analog information and, through a transformative process, return the information back for people to see. At the end of this process, we want to reshape how people perceive their environment and to elicit a reactive and affective effect from the observers.

In this paper we provide a rationale for the need to have these dynamic membranes, describe challenges in their design and implementation, and propose some potential solutions. We will use some systems we have developed in the past and one currently under development to frame our discussions. The paper is organized as follows. In Section II, we examine related work, especially from the artistic and architectural domains. In Section III, we describe three dynamic membrane systems we have worked on. In Section IV, we present our work on a current system being developed. Finally, in Section V, we summarize the paper.

II. Related Work

Architectural surfaces are everywhere and are hence perceive with regularity by people. Often, these surfaces are simply empty, with no useful information displayed on them. Sometimes, they have some limited information on then, but it is often in a static form (e.g., graffiti or a poster). A direct relation can often be observed between human activities and what is manifested on architectural surfaces. These surfaces do not only serve as a means for human expression, they can be important instructions to communicate information to people.

Influential thinkers in the area of cybernetics, the study of regulatory, feedback based systems, their structures, constraints, and possibilities, such as Norbert Wiener [12], John von Neumann [11], and Gordon Pask [10] have considered buildings or their structural components as feedback, reactive systems rather static objects. Architects have also conceptualized buildings as dynamic, evolving structures. For example, John Frazer created a whole new lexicon towards an evolutionary architecture with many experimental projects with his colleagues to investigate fundamental form-generating processes and morphable structures [6]. Similarly, Cedric Price (cited in [2]), one of the first architects who actually formulated this dynamic model of buildings, proposed "The Fun Palace". Although never built, it was one of his most influential projects. The idea central to Price's practice was the belief that through the correct use of new technology the public could have

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unprecedented control over their environment, resulting in a building which could be responsive to visitors' needs and the many activities intended to take place there. The building constitutes an open framework into which modular, pre-fabricated elements can be inserted and removed as required according to need. For Price, time was the fourth spatial dimension, with length, width and height being the other three.

Oosterhuis [9] presents the design of a pair of buildings known as the "Salt-Water" and "Fresh-water" pavilions which incorporated numerous electronic sensors into their designs to gather information about both interior and exterior changes. Although the changes were mere virtual projections, the incorporation of computer sensing and display technology in the design of the buildings was a touchstone in the architectural discourse of computationally enhanced environments in which the building is loosely defined as an *Interface*.

Goulthourpe's system "Aegis Hypo-Surface" (cited in [2]) built in 2001 is perhaps the world's first reactive wall. The piece is a triangle metallic surface that has potential to deform physically in response to electronic stimuli from the environment (movement, sound, light, etc.). Driven by a bed of 896 pneumatic pistons, the effects are generated as real-time calculations. This project has potential for information to literally translate into form, it offers an entirely new medium, digitally dynamic yet materially tactile. Any digital input (microphone, keyboard, movement sensor) can trigger any physical output (a wave or pattern or word). In this Aegis has potential beyond that of a screen to being a fully 'architectural' (i.e. social, physical) interface, where activity (sound, movement, etc.) translates into form.

Another system, "Pixel Skin" [1], is a heterogeneous smart surface that could be used to generate low resolution images, low refresh rate videos or graphical patterns. The interactive wall uses shape memory alloys to actuate each of the 4 triangular panels. The simulation controls the pattern type in response to live weather prediction for the day. This project deals with finding a solution to contemporary architectural surfaces, where conventional windows have to compromise between providing a natural light source and climate protection versus facilitating advertising and information display.

Our research on responsive, dynamic architectural surfaces is inspired by the above work. In the next section we present three systems we developed. In the section after, we present an ongoing project with an expanding aim and discuss the complexity of implementing it.

III. THREE EXAMPLES OF AUGMENTED, RESPONSIVE ARCHITECTURAL SURFACES

In this section, we present three systems that are based on the idea of dynamic, responsive surfaces. "*Morphosis*", "*Life Speculatrix*" and "*Nausea Transformer*" [2,3,4,5,6] are working prototypes that physically respond to local and global external stimuli (movement, light and sound). That is, they "*interact*" spatially and temporally with the environment and its inhabitants. All the three systems have responsive membranes controlled by genetic algorithms which reconfigure their behaviours according to different stimuli and learn how to adapt themselves continually to the evolutionary properties of the environment. The dynamics of the materials in the three prototypes is produced by dozens of actuators made by Shape Memory Alloys (SMAs) and LEDs which react in real time to change the behaviour of the membranes, thereby providing a different visual and sensory feedback to people around them and eliciting different emotional responses from them.

A. *Morphosis*

One of the first prototypes we developed is Morphosis [5] (see Figure 1), a reconfigurable visual system, which is inspired by the manner in which an organism, or any of its parts, evolve and change form in a short lapse of time, triggered by some combination of external stimuli in the ever changing surrounding environment. It is designed as a model to be suitable for execution of a responsive architecture material and to enable the development of transformable architectural surfaces. Also, by developing Morphosis we wanted to investigate how the learning qualities of a material could be used to improve communication between buildings and its inhabitants. We then continued building upon this experiment to create other variations with the same design concept (see Figure 2). The several prototypes' behaviours are the result of complex system composed by sensors, microphones, webcams, shape memory alloys actuators, LED'S and a Genetic Algorithm (GA) component.

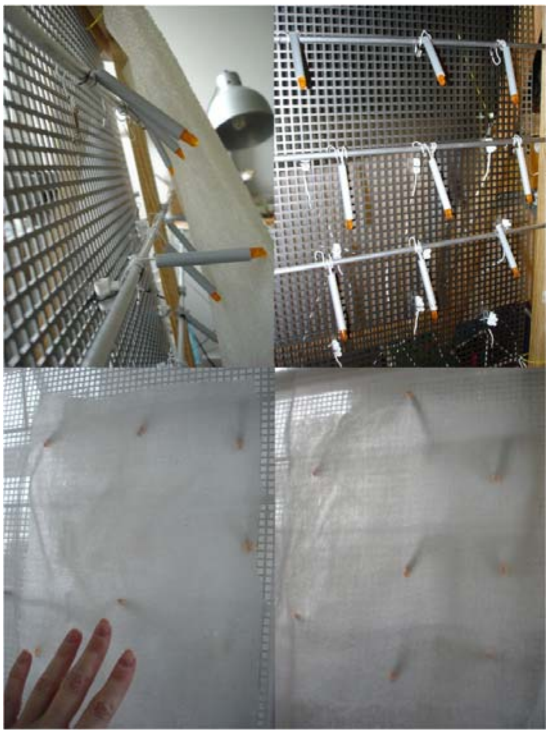

Figure 2. *Morphosis* prototype #1 with its SMA levers above and with membrane below.

Figure 2. "Morphosis" prototype #2.

The main sensory unit is a webcam and a video analyzing program that determines the "empathy" or "repulsion" regarding the current skin behavior by noticing at any given time how close viewers get to the wall. This is actually the Genetic Algorithm fitness function: how bright is the picture captured by the camera. By placing the camera looking down at an angle from the top of the wall, when a viewer comes into the field of view the images gets brighter and the fitness increases.

Four input devices inform the computer of the status of the surrounding environment: a webcam, a vibration sensor, a proximity sensor and a light sensor. These sensors are unobtrusively included in the wall and "feel" the environment informing the wall: (1) whether loud music is playing or someone is walking around (vibration sensor); (2) whether there is a rapid change in the ambient light levels (light sensor – web camera); (3) if someone approaches the wall in a touching distance (web camera). These inputs change the behavior of the membranes in shape, trigger sound, motion and light and can create random patterns on the surface, making the surface a responsive part of space, a lighting element, a functional architectural element and a performance piece.

The membranes start its learning process by responding to "empathy" or "repulsion" from the people around it. The environment feeds are inputs for the genetic variations. These inputs change the sound response behavior of the membrane, change its shape, and trigger motion and light, making the wall a performance piece. The membrane is always aware of its own shape at any given moment because the data is store centrally: the genome and each membrane pixel position. Therefore, when a fitness input is given (via web cam for example), the genetic algorithm knows the current behavior being exhibited by the membrane and thus knows how to correctly classify it.

B. *Life Speculatrix*

Life Speculatrix [6] (see Figure 3) takes inspiration on Grey Walter's "Machina Speculatrix", three wheeled, turtle like, mobile robotic vehicles built between 1948 and 1949. Even with a simple design, Grey demonstrated that his turtles exhibited complex behaviours. He called his turtles "Machina Speculatrix" after their speculative tendency to explore their environment. Life Speculatrix is a kinetic evolutionary physical skin based on digital environmental feedback retrieved through the webspace. RSS/Atom Environmental feeds, like pollution levels, climate features, sound, from around the world will affect its performance as it continually interacts spatially and temporally with the environment and their inhabitants. The fundamental idea is to create an online project as a living, evolving tangible experience.

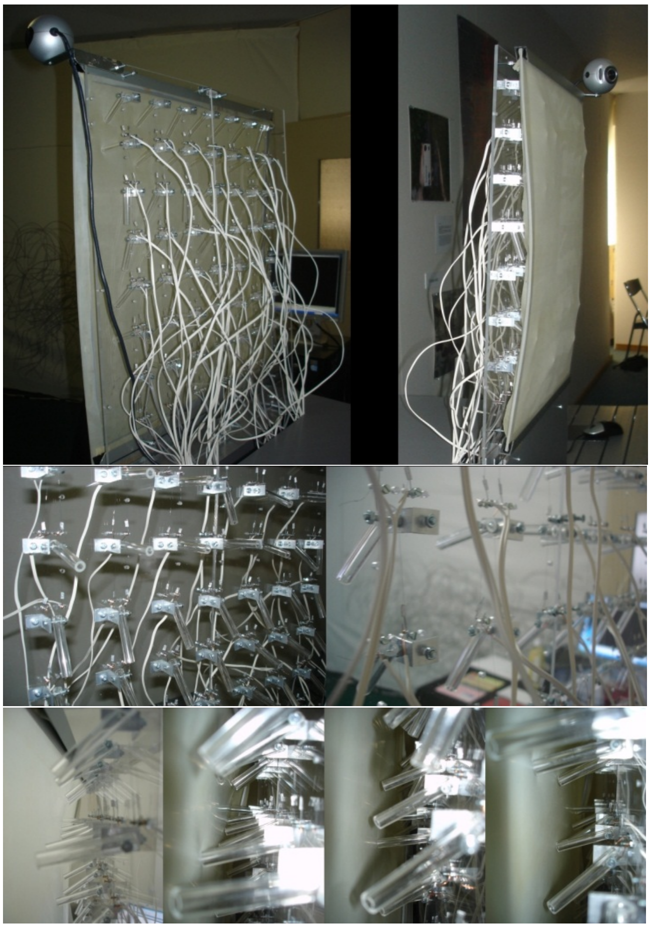

Figure 3. "Life Speculatrix" prototype changing the membrane's shape according to RSS pollution feeds.

C. Nausea Transformer

The word "noise" comes from the Latin word nausea meaning "seasickness", or from a derivative (perhaps Latin noxia) of Latin nocēō = "I do harm", referring originally to nuisance noise. Generally all non-musical sounds are considered to be noise. Noise is a complex concept and source material to deal with; it is an invisible architectural element with an undefined aesthetics. It deeply affects people and yet people feel very powerless to interact with or control it. The fundamental idea of Nausea Transformer is to turn noise into a reprocessed living, evolving and tangible experience, by interacting spatially and temporally with the environment and its observers. The purpose is to raise people's awareness to sound, in all its forms: speech, non-speech sound (sound pollution sources) or natural sound, and treat it like data with a corporeal dimension. We aspire to convey an embodiment to an often neglected "hidden dimension", by adding it to a phenomenology and a poetics of visual space.

Nausea Transformer [4] is thus a sound reprocessed machine that can unexpectedly create pleasant behaviours by recycling noise into pleasant sound, therefore promoting new interactive experiences to a nearby audience. In other words, it is a reconfigurable acoustic and visual system that records the environmental sound feeds in cycles of a certain time (i.e. 10 seconds), then filters that sound and delivers it to the audience with a physical response. The dynamics of the system, materialized as a responsive wall, is made of robotic levers, a latex membrane, sound sources and LED's which react in real time to change the behaviour of a membrane (Figure 4). The system, creates an evolutionary set of rules for what it considers a "perfect sound environment" and reacts accordingly with a sound source and a physically manifestation. If, for example, the system receives "disturbing" levels of sound, it reacts in "resentment" with a louder cacophony feedback. Simultaneously, it exhibits a physical relation creating "noisy" patterns on the surface through its actuators. If the input harmonizes with the set of rules of the moment, the output can be musical, pleasant and/or humorous. A pleasant sound is defined by low amplitude (not very loud) and by a small difference in frequency between two consecutive samples averaged for a number of samples. The membrane will try to find a behavior that will lower the "noise" (or sound level) made by the viewers by attracting their attention towards it. This is a similar approach to the one previously described for using a webcam.

IV. AIRQ WALL: "A WALL THAT TELLS WHAT YOU ARE BREATHING"

A. Purpose and aims

The idea behind AirQ is to explore architectural systems that can adapt and transform themselves in response to the constant change of the conditions of our surroundings, in particular air quality (see Figure 5 for a conceptual representation of the system). We want to develop a system which can achieve three goals: (1) to improve the energy performance of existing glass-curtain facades; (2) to increase social engagement on the subject of air quality; and (3) to provide a better ambiance to nearby people by informing them the conditions of the environment (e.g., noise and humidity levels, temperature, etc.) using subtle changes in LED light-based displays. The issue of deteriorating air quality is important in many places (e.g., in developing countries such as China and India), and it is this very pertinent to raise awareness on this issue. In addition, in places where air pollution is serious, production of energy is a key contributor. As such, AirQ will fit suitably to be used in these environments.

Figure 4. "Nausea Transformer" actuators changing the membrane shape according to sound input.

AirQ is more challenging to develop than the three systems described earlier. We want AirQ to be a self-sustaining system. That is, it can monitor air quality but with a self-harvest capacity to power itself. The system will be composed of a matrix of units. These units are moveable and detachable components of a glass-curtain wall. They are double sided and have two complementary components on each side: one to harvest solar energy; and the other to display ambient light of different types to provide information about the indoor air quality. In this way, the surface will (1) harvest solar power, (2) control the amount of light coming in, and (3) provide subtle information about air quality levels and other environmental conditions.

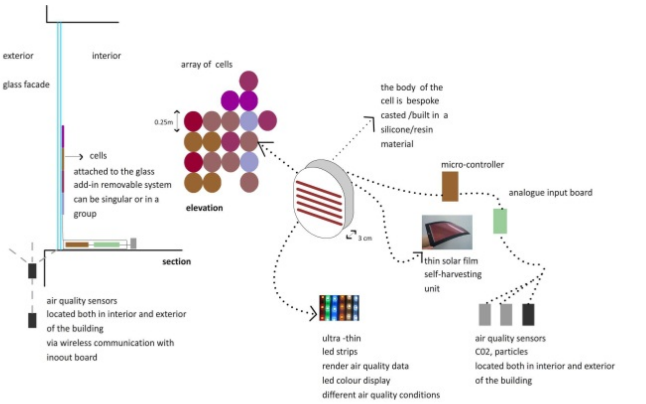

Figure 5. A conceptual diagram of AirQ as a dynamic curtain wall which on one side can capture solar energy and on the other side can provide pollution and other environmental information to people by changing its LED colour and pattern display.

The system will reacts locally and remotely to light and air quality data being sent by sensors wirelessly. The solar harvesting unit powers the display surface of the unit. The cells are designed in a matrix where visual patterns will be displayed against "an environmental performance criteria framework" simulated and evaluated according to multiple environmental and social criteria including thermal comfort, day lighting quality, air quality, variable privacy and dynamic visual effects. The design methodology focuses on the performance requirements through a 1:1 experimental prototyping and evaluation within a glazed surface in a university campus building in China.

B. *Implementation*

To implement the system envisaged, there are several technical and hardware issues that need to be considered.

1) *Topology of the communication network*

Given that we need to capture different environmental data, different sensors will be required. These sensors will have to be connected one receiver. To minimize the amount of physical elements we need to use, we are opting to use wireless components. In this case, the receiver will have to be a transmitter so that it can send the data collected from the sensors. Given that there will be several wireless transmitters (e.g., groups of xBees), we need to have a suitable topology for the network. We have chosen to adopt a Mesh tree network for the system (Figure 6). In this network, there is one coordinator which has to be placed at the right position and distance so that the signals from the transmitters are able to reach it. About six other routers are deployed in the network to relay the signals.

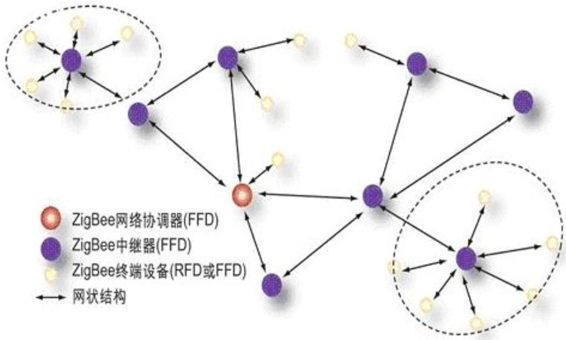

Figure 6. Mesh tree communication network of components adopted for the prototype.

2) *Hardware components*

Coordinator. The coordinator consists of an xBee module, an adapter for usb-xBee connection, and a cable connected to our server (see Figure 7). Our server is a processing center for collecting and sending management commands for the end user device.

Figure 7. The xBee wireless component serving as the coordinator

Control Board. The control board is one of the main parts of the system. We have chosen an Arduino-based controller board. It performs the control and coordinating function for the other devices. Slotted on top of the Arduino board we have placed an xBee-shield to connect the other xBee transmitters with the arduino board (see Figure 8).

Figure 8. The control board with an xBee-shield attached

The onboard program reads the data from the sensors and compares the data with onboard parameters. After the comparison, the program decides what LED lights to turn on/off and their value (see Figure 9). The hardware set up is shown in Figure 10.

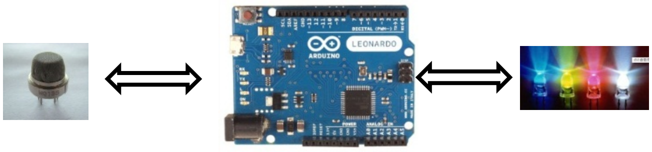

Figure 9. The traffic of data and the components involved in the process: (left) a sensor; (center) the Arduino board; (right) the LED lights. The arrows indicate the flow of information between the components.

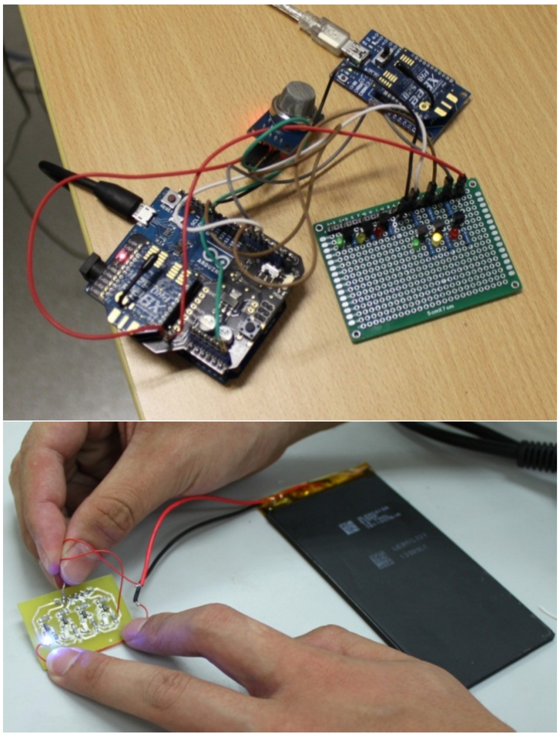

Figure 10. The hardware set up for the prototype.

C. *Discussion and future work*

A small scaled system with its separate connected individual components is working according to our designs and plans. It can capture pollution, noise, humanity, and temperature data at the same time. In addition, the lights are responding to the different parameters set in the program and are able to provide a variety of responsive color patterns and degrees of light intensity.

We are currently looking at the energy aspects of the system. As stated, we want our system to be energy efficient and also to be as green as possible. In terms of energy efficiency, we are looking into components that are simple and with low energy consumption. At the software level, we are attempting to design efficient algorithms and make smart use of its hardware components. For example, although the energy consumption of xBee modules is low, one can further reduce its energy use by leveraging its sleep mode. When used properly, power usage can be further reduced.

In terms of making our system as green and environmentally friendly as possible, we are in the process of attaching small, portable, and efficient modular film solar panels to our working prototype. We aim to find an optimal solution so that the number of solar panels is keep to a minimum, yet we can obtain a stable and reliable quantity of energy which is enough to power our full fledge system.

As this research attempts to address pertinent issues of energy performance and air quality monitoring, which is very much on the agenda of sustainable problematics of contemporary societies for both developed and developing, we seek answers to the following research questions: (1) Can real time sensing technologies be used effectively for energy efficiency in existing glazing facades? (2) By integrating air quality monitoring and its visual manifestation in buildings, can we provoke new types of social and collective engagement with issues of sustainability? And (3) how can real-time, responsive sensing technology become a source of inspiration, a conceptual framework for designers and engineers to build upon?

The first question is technology-centered, and the last two are more people-centric and require examination of the people's perceptions, feelings, and opinions. To obtain answers for the last two questions, we need to exhibit the system to people and obtain their subjective responses to it. Once a complete, full fledge working system is in place, we will have it on permanent display intermittently during 2 months in total in a series of fine-tuning sessions in a glazed surface in selected private places (e.g., offices) as well as a public area of buildings (e.g., hallways with high traffic) at a University located in a medium size Chinese city. An evaluation period involving observation and questionnaires is applied to collect information about performance and users' response.

V. SUMMARY

In this paper, we have attempted to make an argument for the use of responsive, dynamic surfaces in architectural structures. Architectural surfaces are all around us, but are non-responsive and serve only a structural/functional/decorative purposes. Our goal is to add an additional dynamic dimension to these surfaces by leveraging the power of embedded sensors and computing technologies. By adding this dimension, the usefulness and utility of these surfaces can be expanded. Some uses can be based on improving the aesthetics of the structures. Other uses can be about raising awareness on certain issues. Three working example systems are described in this paper. A further system that is currently under development is also presented to highlight the implementation issues and propose some hardware and software solutions. It is hoped with this paper that researchers from different areas, such as architecture, computer science, and engineering, can work together and study deeper further applications for these dynamic architectural surfaces to make better use of such rich and widely available resources in the form of "augmented architectural functional walls".

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