Toward Responsive Atmospheres
PROTOTYPE EXPLORATION THROUGH MATERIAL AND COMPUTATIONAL SYSTEMS

Kathy Velikov
University of Michigan
RVTR

Geoffrey Thün
University of Michigan
RVTR

Mary O’Malley
University of Michigan
RVTR

Colin Ripley
Ryerson University
RVTR

ABSTRACT
The Stratus Project is an ongoing body of design research investigating the potential for kinetic, sensing and environment-responsive interior envelope systems. The research emerges from a consideration of our attunement to the soft systems of architecture – light, thermal gradients, air quality and noise – paired with a desire to develop and prototype envelopes that not only perform to affect these atmospheres, but also to promote continual information and material exchange, and eventually dialogue, between occupant and atmosphere. Stratus v1.0 included the construction of a modest prototype using simple open source technologies, aimed to explore the formal, operational and technological possibilities, as well as potential operability and control conflicts, as part of the first phase of thinking around these questions. It deploys a distributed approach to structural, mechanical and communications systems design and delivery, where localized response is prioritized. The project works to reclaim the environmentally performative elements of architecture – in this case, specifically, interior mechanical delivery and interface systems – to within the purview of the discipline, as territories of material, formal, technological and experiential innovation and exploration. This paper will describe both the development of the current prototype as well as future research and investigation trajectories. The Stratus Project begins by situating itself at the crossroads of the disciplinary territories of architecture, technology, environmental control and cybernetics. Through the use of computational technologies and in collaboration with researchers in the fields of computer science, mechanical engineering and materials science, this project aims to advance the development of responsive environmental design and performative building skins.
With the transition from the 20th century to the 21st, the subject of the cultural sciences thus becomes: making the air conditions explicit.

(Sloterdijk 2009, 84)

There have been several instances in the history of the 20th century when architects, who are much more accustomed to thinking that they design buildings, realize that they are in fact designing systems and environments (Pask 1969, 494). This realization begins to shift both the thinking about the role of architecture, as well as the structures that are designed. Reyner Banham’s Architecture of the Well-Tempered Environment was first published in 1969 and outlined an alternative history of modern architecture, one read through a context of the development of its mechanical systems - heating, air conditioning and plumbing - as opposed to formal or structural advancements. Banham’s text might also be understood to be positioned within an operatively critical mode relative to some of the leading radical edge of architectural discourse and experimentation at that time, one that was focusing its attention on system over object and on the mediated environment over form. These included the numerous membrane dome projects of Buckminster Fuller, Yves Klein’s “Air Architectures” from 1959, Banham and Dallegret’s own “Environment Bubble”, from their seminal 1965 article “A Home is Not a House”, Cedric Price’s experiments into inflatable structures and infrastructures, Archigram’s “Living Pods” and nomadic architectures and Coop Himmelblau’s “Heart Space”, “Pneumatic Living Unit”, and “Cloud”, proposed for the 1972 Documenta V.

These shifts in disciplinary priorities can partially be attributed to the rapid advancements and proliferation of mechanical systems for buildings (Gideon 1948, Banham 1960). Particularly, the domestication of air conditioning after WWII may have had as profound an effect on architectural development and form as the elevator did in the previous century, since the role of providing interior comfort conditions no longer resided within the building envelope. Once the envelope was freed from its traditional role of environmental mediator, its presence and necessity immediately began to be questioned, leading to numerous speculations in architectural form where the building envelope was rendered as the thinnest possible of membranes, or, in some cases, not even present at all.

Coincident with the development of mechanical air conditioning was the development of air-cleaning and particulate purifying equipment. First developed by the US military, HEPA filters became common in buildings in the 1960’s, addressing the increasing incidence of what is commonly known as “sick building syndrome” catalyzed by sealed interior environments and airborne toxins produced by industrially manufactured building materials (Gissen 2009). In our modern world, as Peter Sloterdijk points out, the air is no longer something that can be taken for granted (Sloterdijk 2009, 6). In an era of poison gas, radioactivity and germ warfare, and not to mention smoke, pollen, exhaust, dust, volatile organic compounds as well as radio frequency waves, wireless signals, and noise, the right to breathe is no longer inalienable. “Safe”, a 1995 film by Todd Haynes, chronicles a woman’s descent into aerosol-based environmental hypersensitivity, which eventually makes it impossible for her to exist in contemporary society. Cities now produce their own aerial territories of modified atmosphere, which are sometimes legible, as in the case of cities like Los Angeles or Beijing with their notorious smog clouds, but are more often invisible, until brought to our attention, as is the case in recent projects such as Nerea Calvillo’s “In the Air”, or the “Nouage Vert” project by the interactive artists HeHe.

Our current machine age may be defined as one of ubiquitous digital inter-connectivity, accompanied by ever more powerful and versatile technologies as well as a deeper understanding of complex systems, materials, feedback processes and an increased consciousness of the extended ecological interrelationships between buildings, humans, and environmental systems. The current generation of high performance building envelopes are comprised of sophisticated assemblies combining realtime environmental response, dynamic automation, advanced materials, embedded sensing, controls and intelligence. While many of the recent efforts in responsive and adaptive building envelopes have been focused on energy performance and light management, few have approached the management and design of the air environment as an element to be addressed by the emerging digital communications, sensing and control technologies.

2 The Stratus Project

The Stratus Project (Figure 1) is an ongoing body of design research in environment-responsive, dynamic envelope systems that develop continual information and material exchange, and eventually dialogue, between breather and atmosphere. The work is explored through prototype testbeds

Figure 1. Stratus v1.0 (left) surface operation study; (right) stratus v1.0 prototype detail

Figure 2. The Stratus Project v1.0 installed, January 2011
supported by institutional and government funding. The ambitions of the research are to develop the concept of adaptation beyond sense and response regimes toward the design of instrumental interiors, or "second skins" that sense, adjust and mediate air conditions, including the development of intelligent sensing that would enable custom configuration of spatial volumes and user preferences over time.

The fully realized system will develop a series of immersive layers, from a sensing, breathing and energy scavenging ground plane to a deep enveloping soffit, considering the material design, performance and experience of both that which is sensed - surfaces, atmospheres, thermal gradients and light - and that which lies beyond our sensory capabilities - aerosols, energies, transmission and radiation waves.

Stratus v1.0 (Figure 2) was constructed as a 2.4m x 4.0m working prototype and exhibited at the gallery of the University of Michigan Taubman College of Architecture and Urban Planning. The prototype mobilizes smart surfaces and responsive technologies in the development of a thick suspended ceiling that produces a light and air-based architectural environment using distributed technologies and systems to sense and respond to occupant energy and movement flows and to produce envelopes of intimate and collective space.

From the perspective of building science, the Stratus Project is concerned with mediating indoor air quality and occupant comfort, and with providing live air quality information to the occupant in both analog and haptic ways. The research aims to advance the development of responsive, or adaptive architectures; architectures that include realtime sensing, kinetic climate-adaptive components, smart materials, automation and the ability for user-interactive characteristics such as computational algorithms which operate under the principles of second-order cybernetics (Dubberly, Pangaro and Haque 2009), wherein both user and system are capable of shaping an unlimited set of performance outcomes so that both "learn" over time. What follows, is a more detailed account of the development of its elements and performance from this first phase of research.

2.1 STRUCTURE

The structural foundation of Stratus is a flexible tensegrity weave that organizes and supports its operational components (Figure 3). A tensegrity-based system was selected for its lightweight and stable properties, as well as for its perceived elasticity, and capacity to deform as a textile. The overall structure allows controlled deformation across all dimensions without failing or disturbing the attached components. The cable strut system used for the constructed prototype consists of 210 individual tensegrity units, and is adapted from a system developed by mathematicians Wang and Liu (Wang 2004, 86-96). Each is comprised of three rods connected with elastomer cord, which was selected over a more rigid cable, or wire, to enhance the overall flexibility of the system. The individual units are woven together to create a complete array.

Woven into the tensegrity structure is a distributed array of sensors, actuators, lights, micro-fans and light-diffusing fabric panels. On the underside of the structure are located the "breathing cells": individually actuated cells that form a translucent, light-diffusing skin that open to allow thermal conditioning and air extraction.

2.2 BREATHING CELLS

The breathing cells comprise the primary visible surface of the Stratus Project (Figure 4). Each cell is made from a single die-cut piece of translucent vinyl, folded and taped into form, and attached to a laser cut acrylic substructure. Vinyl was chosen for its visual depth, high diffusion properties, and workability, however we are exploring more environmentally benign materials for this application. The cells are designed like scales, to provide a tight continuous surface across multiple formations of the ceiling plane when closed. The acrylic substructure consists of two main parts – the cell frame and the motor platform – and provides consistent details for support, mechanical motion, and mounting to the tensegrity fabric. A micro-servo motor is mounted into each motor platform to open and close the cell. Like standard servos, these micro-servos will rotate to a specific angle based on electrical signals received from the control board. Each motor draws only 0.75 watts of power. Rotating the servo to 90° pulls the cell closed while rotating to 0° opens the cell. Motion is triggered by input from the temperature sensor; when the temperature threshold is exceeded, the cells open to create ventilation and airflow, closing them again when excessive heat is relieved (Figure 5). The next stage of physical explorations will explore closer material and geometric integration between the cell and support/
actuation mechanism, as well as investigations into materiality and performance of the cells (such as, ability to seal, surface qualities, chromatic response).

2.3 CIRCUIT AND SENSOR ACTUATION

The distributed electronics platforms house low-power temperature sensors with a -40°C to 150°C detection range that output analog voltage proportional to the ambient temperature. When the circuit is first powered up, the microcontroller takes 100 readings from the temperature sensor every 5 milliseconds and generates an average of these readings to determine the ambient air temperature. The control program for the Stratus Project was composed in the Arduino programming language (a Wiring based language similar to C++). It uses the baseline measurements to establish a temperature threshold, which governs the actuation of the cells and the operation of the fans. Once Stratus is in operation (i.e. in its “loop”), the program calls on a number of subset programs to control the separate systems of lighting, cooling, and cell activation. Custom Boolean logics generate feedback loops that inform Stratus when it is in an active cooling state or a passive state, and a similar structure is used to track light intensity levels in relation to occupancy. Tracking the operation of the servo actuators mitigates electrical interference that could disrupt the analog sensors. The program employs a modified Variable Speed Servo Library (http://www.arduino.cc/cgi-bin/yabb2/YaBB.pl?num=1276899740) to choreograph the movements of the cells within each circuit and minimize conflicting signals (Figure 6).

Passive Infrared (PIR) sensors distributed throughout the weave detect changes in infrared radiation levels across a 20’ range. Using infrared insures that only motion created by occupancy will trigger operation. The sensors are nested in openings between the cells, and control the lighting in each module. This location permits a direct sight-line to movement in the space, but also brackets the detectable range to an area immediately below the module, in order to achieve personalized response. Working in conjunction with the breathing cells, distributed 2.5watt micro-fans provide localized, focused heat relief for occupants. The cooling fans are mounted via wire stand-offs above the electronics platforms (Figure 7).

The cooling fans respond to input from the temperature sensors; when the ambient temperature exceeds the established threshold, the fans turn on at full power until the temperature is reduced. The fans are outfitted with blue LED indicator lights that turn on when the cooling fan is active, providing ambient cues to the occupants (Figure 8).

Figure 4. Breathing cell array
Figure 5. Fluent® model of airflow velocity relative to spatial and cell configuration
2.4 LIGHTING

Low-energy high-brightness lights illuminate and track motion within the space. Each light contains one 0.5 watt 4000 K white LED module with a diffuse distribution and 30-lumen output. The lights are wired in parallel in groups of six, one group for each module. The lights respond to the input from the PIR sensors: when activity is detected within the adjacent area, the lights begin to fade on. If activity continues, the lights continue to fade on until they reach full brightness, at which point they remain on until activity ceases. When no motion is detected in the immediate area, the lights fade off at the same rate until they are completely off.

Stratus v1.0 contains a dense layer of elastic nylon fabric woven into the tensegrity structure. In the first prototype, this layer contributes to light diffusion. In the next iteration, this textile will carry applied Phase Change Materials (PCMs) that we anticipate will contribute to regulating the interior microclimate of the space. The fabric layer in the tensegrity fabric is designed to maximize its exposed surface area in order to provide as much absorptive PCM area as possible. Future tests will examine the ambient impact of PCM fabric coatings at varied densities.

2.5 AIR QUALITY / AIR DESIGN

In addition to the modules that control lighting, cooling, and cell movement, additional circuits control an array of extraction fans. These circuits consist of an Arduino microcontroller, a CO2 sensor, and six extraction fans. In this application, the CO2 sensor has been outfitted with a prefabricated circuit that allows the user to manually set a threshold level for CO2 concentration. When the threshold level is exceeded, the sensor outputs a digital signal to the microcontroller. This triggers a bank of six extraction fans wired in parallel from an external power source. These fans are intended to displace stale air and permit the movement of fresh air into the space.

The current sensor/response regime for Stratus v1.0 experimented with cooling and CO2 responses to air sensing. One of the goals of the project is to attune attention to the immediate air-based environment and to the physical conditions that produce it. Running concurrent to the operation of the air environment modifying apparatus, a custom graphing program provides visual feedback on atmospheric conditions to the occupant. This program also employs an Arduino platform to intake data readings, which interfaces with a Processing-based animation. While the visualization program could provide relatively accurate real time temperature readings, tracking of CO2, VOC, and humidity levels were presented more relatively than quantitatively, tracking variation over time rather than specific parts per million levels or percentage humidity with the intent of this information being more accessible to non-expert inhabitants.

It is an ambition to develop further ways to affect the ‘design’ of gaseous agents, especially in response to airborne pollutants, and to investigate further ways in which Stratus itself might be able to register and communicate information, either biologically or electronically, providing to the breather a consciousness of their own agency within the air environment.
2.6 Spatial Shift

The base tensegrity structure and the overlapping tessellation of the cells of Stratus v1.0 were designed to accommodate movement and undulation in the vertical configuration of the ceiling and the current structure has been outfitted with six small, high-powered 12V DC motors controlled through a single Arduino that can displace the structure up to 600mm off plane (Figure 9). This area of research anticipates applications across a range of spatial configurations and interior programs by providing dynamic, flexible, and responsive lighting, thermal, ventilation, and acoustic systems. Each system could be tailored and adjusted independently to provide optimum support for a range of activities while minimizing overall energy draw. The adjustable displacement of the soffit creates a stratification of thermal space, which reduces the amount of air to be conditioned when a space is unoccupied, limiting energy devoted to inactive spaces. Lighting levels can be calibrated from low ambient levels to high task requirements both through digital dimming controls and through adjusting the distance between the light source and the illuminated surface, allowing higher illumination levels where needed while keeping energy density well under one watt per square foot. Similarly, thermal comfort and ventilation systems could target individual bodies and occupation density. Central heating and cooling elements would condition the air to the appropriate temperature, while the breathing cells and microfans activate only in occupied zones to deliver the desired effect of cooling with air speeds as low as 0.1 m/s.

3 Evaluation / Projection

The Stratus Project is a multi-year body of research and development. The first prototype allowed for the exploration of a preliminary tectonic testbed of the system, utilizing relatively simple and crude component design, circuits, controllers and actuators. The value of this first prototype was in the development of the distributed and layered system, as well as a demonstration of its possibilities (although, due to the limitations of the gallery installation of the v1.0 prototype, the actual effects on air composition or user interaction could not be evaluated with any degree of accuracy). However, this prototype has been particularly successful in securing more substantial funding to continue development on the project. In addition to several areas of further research described in the context of the text, two primary areas will be explored in the next phase: micro-control and responsiveness.

3.1 Micro-Control

In collaboration with Dr. Jerome Lynch and Dr. Robert Dick at the University of Michigan, the next iteration of the project will deploy more robust generations of Micro Electromechanical Systems (MEMS) and Wireless Integrated Microsystems (WIMS). Specifically, we are looking to incorporate distributed wireless sensing networks utilizing the low power Narada wireless nodes capable of processing raw measurement data directly in the network, eliminating the need for a centralized server to process and aggregate data. Powering the wireless sensor and actuator network could rely on energy harvested from thermal gradients at the building envelope via distributed thermal electric generators (TEGs), making the operation of Stratus a net-zero energy installation. Further
exploration of Multi-agent Systems (MAS) could enhance the intelligence and performance flexibility of Stratus. "Agents" are software abstractions that are capable of perceiving their environment through sensing, and then acting upon that perception through actuation based on a rational decision process of embedded intelligence. Multi-agent systems are particularly attractive for providing control for ubiquitous networked assemblies such as Stratus, as they represent a scalable control approach well suited for a decentralized sensor and actuator network.

### 3.2 Responsiveness

The term “responsive” has often been used interchangeably with interactive and adaptive, and most simply, has been described as "how natural and artificial systems can interact and adapt" (Beesley, Hirosue and Ruxton 2006, 3). Negroponte proposed that: “The manipulative environment is a passive one, one that is moved as opposed to one that moves. In contrast, responsive...means the environment is taking an active role, initiating to a greater or lesser degree changes as a result and function of complex or simple computations” (Negroponte 1975, 132-3). In a responsive milieu, rather than the designer predetermining system responses to user inputs, the system could measure reactions to its outputs and continually modify its actions according to these responses so that user and system are able to shape an unlimited set of outcomes. One of the goals of the Stratus Project is to develop computation that includes algorithms which allow the system to self-adjust and learn over time, both relative to environmental variable conditions and to occupancy patterns, preferences and habits, exploring how the system could operate through second order cybernetics. It is anticipated that through this approach, inhabitants might develop more sensible and cognitive relationships between their own actions, the buildings they inhabit, and the larger environment and might also be able to better understand their impact and agency within the air-based environment.

The possibility of user-controlled responsive atmospherics is of course exhilarating and terrifying, liberating, yet confining. As a ‘soft’ system, the air environment enters the contemporary territory of biopolitics, making questions of agency less readily resolved, politics more nuanced, and ethics more complicated. The Stratus Project both approaches and yet defers the question inferred by Sloterdijk — who designs the air? The air environment evolves out of the decisions and actions of many different actors and the agency of the individual within the collective environment is, at best, difficult to discern. Negotiating this territory is, of course, one of the responsibilities we take on as designers.

You are on life support, it's fragile, it's technical, it's public, it's political, it could break down — it is breaking down — it's being fixed, you are not too confident of those who fix it. Our current condition merely relies on our more explicit understanding that this tentative technological system, this “We support,” entails the whole planet — even its atmosphere.

(Latour 2006, 106)
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