Nervous Ether: Soft Aggregates, Interactive Skins

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ABSTRACT

This paper describes the authors' exploration and experimentation with cellular pneumatic aggregates for kinetic, environmentally responsive envelope systems. The work is situated within the history and technology of pneumatic structures, biological paradigms, the agency and aesthetics of material, information translation, and the tension between performance and affect within responsive environments. The paper elaborates on the physical and computational development of novel pneumatic systems, experimentation with their interactive capabilities, and a recently completed installation, *Nervous Ether*, a pneumatic spatial envelope that operates as an instrument to register and communicate remote environmental information while also developing affective interaction with inhabitants.

Introduction

Our work aims to develop material and cognitive dialogue between built form, humans, and the environment via experimentation with prototypes for responsive envelopes that engage the soft systems of architecture, such as light, thermal gradients, air quality, and acoustics [1]. We are currently exploring the formal, material, and operational possibilities of cellular pneumatic aggregates to function as deep building skins, imbued with environmental response, interaction, and intelligence. *Nervous Ether* is a full-scale prototype that operates as an instrument to register and communicate remote environmental information, while also generating specific effects within the immediate, inhabitable environment. The project aims to apply the agency of air and information in order to spatially and physically materialize the immaterial into a palpable, sensate environment (Figure 1).

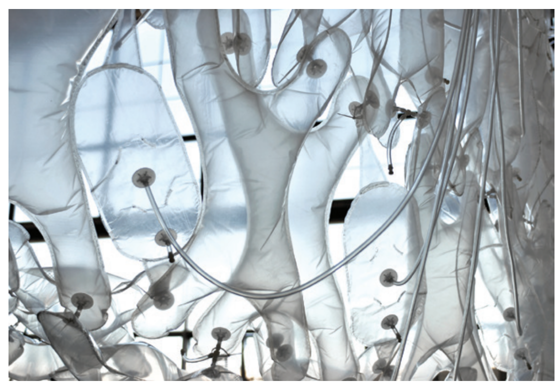

Figure 1. *Nervous Ether*, first prototype installation, 2013. © 2013 RVTR.

Explicit and Implicit Knowledge: Performance and Affect

Equally interested in the performative aspects of responsive environments and their affects, we explicitly operate within a ground that supports and navigates both of these realms, as well as their often-divergent discourses and histories [2]. In his recent book *Ambient Commons*, architectural and media scholar Malcolm McCullough describes two models of cognitive production, whose similarities and differences become useful to articulate our intentions [3]. One is the empiricist model of scientific knowledge-making and representation. Through acts of framing, distinct sets of data are foregrounded while others are pushed into the background. Symbols governed by logic—spoken or written—organize and structure data into knowledge, which is then represented and communicated. Knowledge produced in this way is called *explicit*: action occurs after thoughtful deliberation. McCullough, however, identifies the contemporary

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urban dweller as existing in a milieu characterized by an excess of data, constantly connected and exposed to digital information flows, living in a continuous cloud of ambient information [4]. These data oceans foster forms of information processing that are cognitively different from a systematic empiricist approach, which can be understood as being more closely linked to what Michael Polanyi has called *tacit knowledge*: knowledge that is acquired through the body rather than the mind [5]. It occurs through physiological processes and is created within specific situations. It does not need to, and sometimes cannot be, translated into semantic symbols. We may call this kind of tacit and situated knowledge *implicit knowledge*: action is reflexive and immediate. Both models are useful for us to define the building blocks and vocabulary for responsiveness in a more detailed fashion. Our research looks at responses resulting from empiricist inquiry while also exploring ways of knowledge-making that lie beyond the scientific realm. We aim to develop architectural constructs that simultaneously support instrumentality and affinity, performativity and affect, explicit and implicit knowledge, technological optimism and the uncanny.

The title of the work is derived from the history of physics, wherein philosophers and scientists have speculated on the existence of a "nervous ether," a material atmosphere that is a conductor of the vibrations of heat, light, sound, electromagnetic impulses, and mechanical frictions [6]. In the late 19th century, the physicist John Tyndall theorized that the "transported shiver of bodies" of the cosmos and the stars could be intimately felt within our own physical bodies and consciousness [7]. More recently, philosopher Michel Serres has argued that "we inhabit a kind of informational weather," volatile and intermingled [8]. Within the contemporary context of data oceans that can be registered, collected, and communicated via the increasing ubiquity of electronic devices, we speculate once again on the material embodiment of ambient information. The *Nervous Ether* project combines embedded intelligence with computation to develop an architecture of soft aggregate bodies, sensitive to frequencies and periodicities, and to situated and extrinsic energies that are also spatial, experiential, and performative propositions in and of themselves.

Pneus

Architecture is a material practice. Its core disciplinary questions of form, embodiment, aesthetics, meaning, and experience are all rooted in the physical world. Contemporary discourses of material ontology prompt us to think about both the agency of matter, as well as its bioethics and biopolitics [9]. What are the consequences of privileging a seemingly immaterial substance such as air for architectural matter?

Air held captive by a membrane in tension is one of the basic structural principles of living organisms. In the 1970s, Stuttgart's Institute for Lightweight Structures (IL), under the directorship of Frei Otto, devoted a major part of its research toward exploring the intersection between building and biology, with the aim of identifying and understanding biological models for engineered systems [10, 11]. One of the primary areas of investigative focus was the *pneu*, a neologism defined as "a system in which a layer stressed only in tension envelopes a medium" [12]. Across the four years of collaborative exchange among engineers, architects, biologists, and zoologists following the 1973 Biology and Building symposium, Otto radically declared the pneu "the essential basis of the world of forms of living nature," and regarded it as the fundamental material system to be explored by designers seeking to develop lightweight structures shaped by and adaptive to external forces [13].

Pneus also occupy an aesthetic category of forms that Otto and his colleagues identified as residing in the realm of "taboo." They write: "We can only state without comment that in man the signals of repulsiveness, beauty, and sexuality are given by the characteristic structural form of the skin strained by internal pressure, that is the pneu" [14]. While the IL avoided elaboration on the receptive characteristics of pneus, within artistic practice and discourse there has been a far deeper investigation into the simultaneous attraction and revulsion that defines the aesthetic category of the formless, and the uncanniness of "the dismantling of the body into so many part objects" [15]. As Reyner Banham observed, physical responses to and of pneumatic structures are visceral, intimate, and sympathetic to the human body [16].

We explore air itself as a physical and spatial material, which through pneumatic control and containment within membranes can initiate kinetic transformations for the dual purposes of environmental adaptation and dialogue. Instead of a firm protective wall against an inclement environment, we propose an architecture that would become a malleable extension of the human skin, constantly adapting to ever-changing conditions. In favoring flexibility over firmness, this responsive architecture challenges traditional architectural values. It advocates for an architecture whose main virtue lies not in Vitruvian "firmitas" but in its ability to be *in-firm*; not to resist change, but to embrace change as its ally.

Biology and Technology

Advancements in the design of membrane structures have been facilitated by the evolution of synthetic polymers, first developed in the early decades of the 20th century, and with the majority of these new materials appearing in the period between the 1930s and 1970s [17]. It is not surprising then that the 1960s and 1970s were a time when interest in the structural, performative, and aesthetic possibilities of captivated air peaked. Architecture witnessed a surge in large-scale inflatable and air-supported structures, as well as visions for new forms of inhabitation, such as Fuller's climate dome for Manhattan or Frei Otto's City in the Arctic [18]. While these architectures focused on the technological potential of membranes, activist architects and artists frequently championed the ephemeral bubble as counterpoint to rigid political and social climates. Projects by Coop Himmelb(l)au, Ant Farm, Haus-Rucker, and Utopie explored the notion of hermetic spheres separating the stale or polluted air of the postwar years from the societal and technological utopia inside [19]. However, experimentation with dynamic pneus for architectural applications analogous to the packed, cellular membrane systems appearing more frequently in nature and documented by the IL was relatively minimal.

Recent advances in the material science of membranes and co-polymers—particularly the development of the environmentally stable and recyclable material ethylene tetrafluoroethylene (ETFE) and its approval for permanent building applications in the 1980s—have spurred a renewed interest in membrane-based architectures [20, 21]. The design of these irregular and elastic forms is being made increasingly possible through maturing computational tools for simulating nonlinear structural systems and form-finding software [22]. Inflatables were also recognized early on as being the most appropriate materials for responsive architecture, due to their ability to "exhibit motor reflexes through simple controls" [23]. The current generation of smart and ubiquitous technologies expands the capacity for control and environmental adaptation within architectural envelopes [24]. Contemporary artists and designers are renewing experimentation with membrane installations, often imbued with intelligence and interactivity, such as Tim Hawkinson's *Überorgan*, Michael Fox's *Bubbles*, Tomás Saraceno's various *Clouds*, and the work of Peter Hasdell and Patrick Harrop, among others [25].

In this technological context, our explorations take on the formal and aesthetic potentials for cellular pneumatic foil-based envelope systems to be developed as thick, sensing, kinetic membranes that, like biotic skins, must perform multiple, sometimes non-aligned, functions

[26]. Our research engages two formal and performative territories of cellular pneus: aggregation and actuation. In both cases, the exploration begins with the study of biological models, whose abstracted principles inform digital and physical models and prototypes (Figure 2).

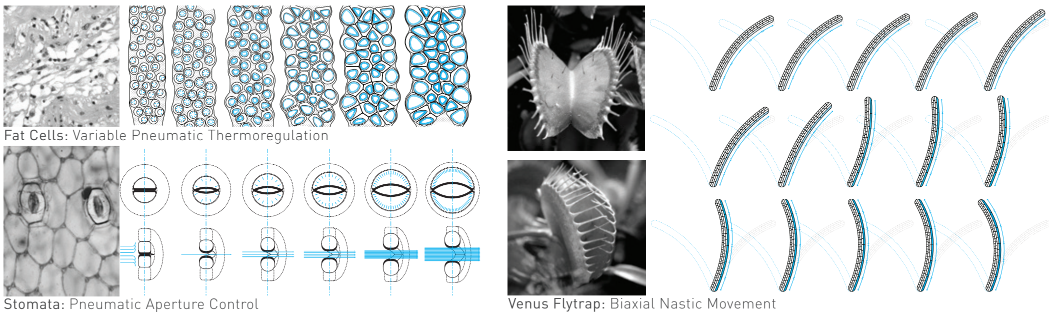

Figure 2. Biological studies for pneumatic thermoregulation, aperture control, and nastic movement. Photos: Fat Cells, © 2008 Yale Rosen (via Attribution-ShareAlike 2.0 generic license); Stomata, © 2013 AJ Cann; Venus Flytrap closed and open, photo courtesy of Amy Snyder, © 2011 Exploratorium; Venus Flytrap showing trigger hairs, © 2006 Noah Elhardt.

Adaptation to severe changes in temperature is one of the most basic imperatives, biologically and architecturally. Though adipocytes (fat cells) within mammals are understood to act primarily as energy stores, they can also provide variable thermoregulation through variation in the lipid content of their highly elastic membranes [27]. Within an architectural material system, pneus can inflate and deflate to vary their capacity for thermal insulation across an aggregate assembly; architectures might become "chubby" and sealed in winter, "skinny" and more porous in summer. To explore the regulation of airflow through a pneumatic envelope, we look to the stomatal complex of plants. This offers a model for aperture control within a packing system of variably sized pneus that constitutes an alternative to frame-reliant façade operation in buildings, while limiting thermally bridging elements.

It is a characteristic of pneumatic systems to deform, sometimes quite radically, when under pressure. Nastic movement is a term that refers to physical, non-directional responses of plants to stimuli. In contrast to the complex skeletal-muscular system of movement in animals, this mode of movement occurs through a unified action resulting from turgor (water pressure) changes within specific cell geometries. Studies of the Venus flytrap, whose movements (thigmonasty) occur more rapidly and radically than in other plants, have demonstrated that the double-curved geometry of the leaves could be responsible for the speed and force of closure [28]. This principle demonstrates a sophisticated model of adaptation with low energetic cost and has been guiding our experiments with geometries for pneumatic actuation.

Simultaneously, we have been exploring systems for aggregation of cellular pneumatic composites. Whereas the most common form of pneumatic aggregation is the Weaire–Phelan structure of packed bubbles and foams, we are pursuing alternative aggregate structures utilizing compound forms to produce self-binding and self-supporting assemblages. Our physical studies have focused on developing novel nested-weave structures that take advantage of the deformation capabilities of free-body pneumatic cells to self-compress and maintain the integrity of the assembly (Figure 3).

The non-linear and elastic properties of pneumatic structures necessitate combinatory approaches for computational simulation, development and design. Even simple cell models require constant iterative comparison between the digital simulations and physical tests to predictively anticipate performance. Our computational explorations move between the animation programs of 3D

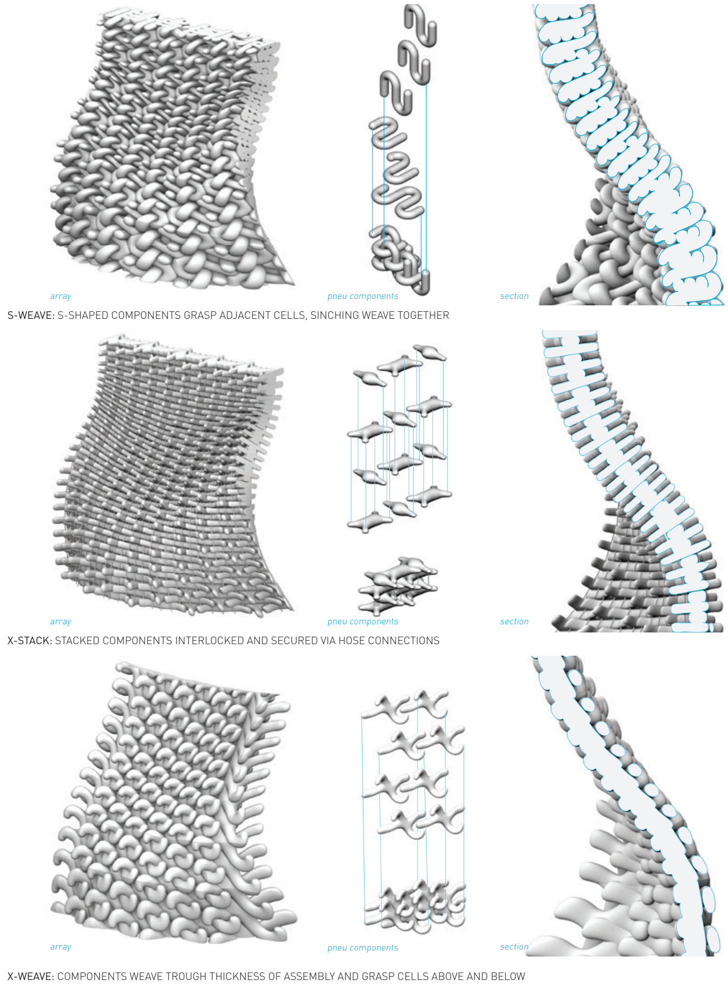

Figure 3. Computational models of different types of nested arrays. Top to bottom: "S-Weave," "X-Stack," and "X-Weave." © 2014 RVTR.

Studio Max and Maya 3D and physics-engine-based modeling in the Kangaroo plug-in for Rhinoceros. All of these platforms have limitations in the extent to which they can reliably anticipate material collisions in pneumatics or simulate a consistent relationship between elastic deformation and real-world air pressurization. Preliminary cell models are physically prototyped to assess conflicts, performance, and fidelity to the computational environment. Three-dimensional scans are fed back into the computer models and used to refine the inflation algorithms. A suite of modified fluid dynamics and energy modeling software (ANSYS Fluent, Window7, and Energy+) is utilized to simulate internal convection and thermal transfer within the aggregate systems. Our physical prototypes are constructed using 4mil LDPE thermoplastic foil welded with a defocused laser cutter, which allows for rapid prototyping and assessment of differentiated forms.

Nervous Ether

The topology of *Nervous Ether* is developed through a tessellated array of tetrahedral pneumatic cushions. Two pneumatically independent layers of cellular cushions intertwine to create a membrane weave that is hung and tensioned (Figure 4). The array is inflated to a constant air pressure, forming an open framework, or platform, that supports a variety of actuatable membrane components and response modalities that can be integrated with the structure and air supply (Figure 5).

The *Nervous Ether* installation responds to two types of data inputs: atmospheric and human, mapped in loose zones of encounter within the array. In the past several years, environmental sensing has become almost ubiquitous, with countless weather, seismic, and ocean-current sensor nodes streaming continuous information. This information can be queried by anyone with an internet connection through sites such as those operated by Weather Underground and the National Oceanic and Atmospheric Administration. In the installation, sensor inputs feed variable data through the Grasshopper and Firefly plug-ins for Rhinoceros modeling software, which then translates the inputs to an Arduino micro-controller. The Arduino in turn controls air supply through an electropneumatic regulator and manifold, translating the environmental data into variations in air pressure and supply to the system (Figure 6). For this prototype, we used two local sources of atmospheric data that had relatively high fluctuation rates: barometric pressure and wind speed in the San Francisco area. Barometric pressure was registered in the movement of the ovoid-shaped cells: the greater the barometric pressure, the faster their pulse. These were situated in a field within one portion of the array. Wind speed was translated to control the movement of the S-shaped cells that lined the bottom edge of the array: the faster the wind speed, the longer the interval that the S-cells take to fill. The translation was not meant to be didactic, but rather an ambient register of these specific data streams, taking the environment's proverbial pulse and communicating it intuitively to inhabitants. The gentle, stochastic flexing and relaxing of the cells create a sense of breathing and soft quiver.

Figure 4. ***Nervous Ether*, first prototype installation, 2013. © 2013 RVTR.**

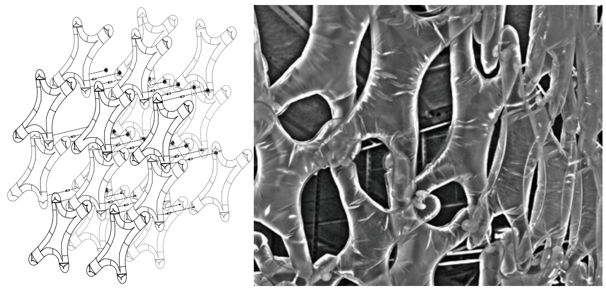

Figure 5. ***Nervous Ether*, first prototype: Drawing of tessellated weave topology (left); photograph of installation at night (right). © 2013 RVTR.**

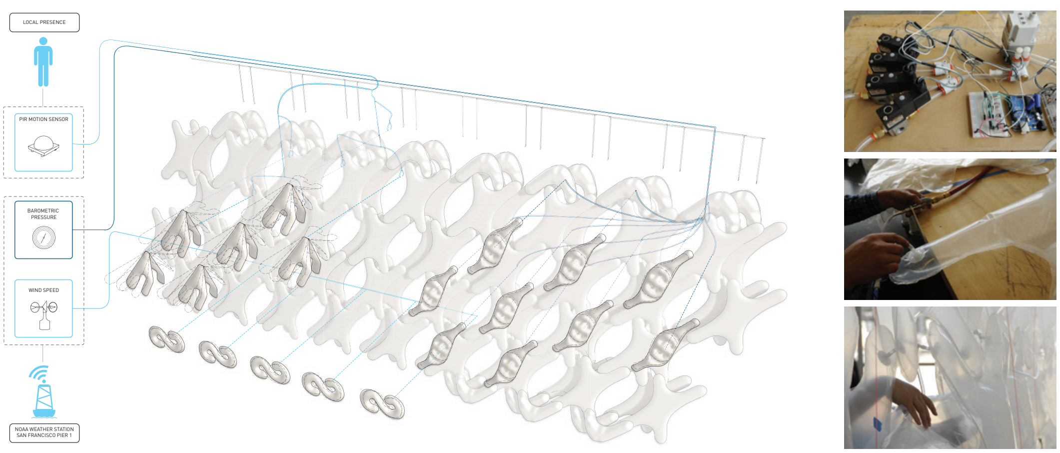

Figure 6. ***Nervous Ether*, first prototype: Data inputs, response logics and array components: tetrahedral, ovoid, S and wing pneus (left); Arduino-controlled pneumatic regulator (top right); testing of pneu components (middle right); approaching the array (bottom right). © 2013 RVTR.**

A second category of response was aimed at developing human interaction with the system, moving towards an affective environment. As visitors approached close to the structure, a series of motion-sensor-controlled wing-shaped cells suddenly filled with air and moved perpendicularly outward, like hairs standing on a person's skin. These cells were located in a second field and required that visitors be in close proximity to the array to trigger the sensor, so that activated cells were likely to make physical contact when kicking out. *Nervous Ether* was what we termed an "anxious" material system, which became further agitated, beginning to shudder, when approached.

Figure 7. X-Weave array installation: continuing prototype research on nested aggregate geometries. Photo: Christina Kull. © 2014 RVTR.

Projection

In this paper we have charted the historic situation and our early explorations of interactive pneumatic material systems that operate both instrumentally and affectively, in dialogue with environments and humans alike. In subsequent work, we are continuing to evolve the second iteration of physical prototypes for tightly nested geometries coupled with actuatable components (Figure 7). As the precision of system assembly improves, we aim to develop actuations that may shape thermal regulation and air through-flows across the system. The composite, interconnected nature of these structures makes system self-awareness critical. Airflow must be balanced across the entire system, and there may be many possible sequences and combinations of action to achieve a desired environmental performance. While the introduction of AI to evolve the control logics over time may enhance the efficacy of response regimes and the operation of the skin, it also opens up new models for how the built environment might learn to engage inhabitants. Through these experiments, we are moving toward developing a vocabulary for a responsive architecture that is not only functionally optimized for regulatory parameters such as climate control or energy use, but also one that might develop relationships with human inhabitants that are based on attraction, empathy, or even playfulness [29]. In the words of Nicholas Negroponte when speculating on intelligent environments in 1975: “Maybe a house is a home only when it can appreciate your jokes” [30].

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