Toward a Pedagogy of Material Systems Research

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INTRODUCTION

At one time, in the words of le Corbusier, architecture was described as the "masterly, correct and magnificent play of masses brought together in light." Now our attention is turned far more intently to the processes of formation and production that define these "masses"—which are increasingly understood as thickly layered assemblies with very specific material characteristics and environmental behaviors. They are not just in light, they shape and control it, as well as energy, air, humidity, acoustics, and with increasing frequency, information. Not only are we developing a deeper understanding of the characteristics and behaviors of materials themselves, but also we are now able to synthesize entirely new materials—polymers, composites, fibers, smart, and energy converting materials. This, combined with the increasing sophistication and pervasiveness of computationally driven design and fabrication technologies, has radically changed the design, composition, and modes of production of everything from clothing to cars—and architecture is trying to catch up.

The term *material system* intends to encapsulate the multifaceted aspects of a spatial architecture and the means by which it is formed. Christopher Alexander shapes the term *system* into an architectural context referring to the "unselfconscious process" as the manner by which architecture is continually and concurrently defined by its interaction with culture and environment (1964). This expands the notion of architecture and form as a dynamic entity that encapsulates activity as well as physicality. Materiality serves as the medium by which formal relevance, as a reflexive engine to social and contextual pressures, can be determined. Where form is defined as performing and responsive, its nature emerges via material's behavior in relation to a specific and specialized environment (Menges 2008). A material's behavior is articulated as a direct repercussion of the processes of formation. The *material system* poses a perspective that necessitates both the study and execution of material formation, in simultaneity with the measure of contextually responsive behavior.

Designing within this paradigm requires the forming of new tools, skills, and methods, which serves as a primary focus for the Master of Science in Material Systems (MSMS) program. The program fosters an understanding of materials—physically and also chemical-

Mobius Rib Knit Installation (Sean Ahlquist, University of Michigan, 2014) ly—as well as the logics, processes, and machines that give them form. The program is also based in a deep engagement with computational tools that extends beyond form-finding and fabrication logics to encompass material behavior, systemic performance, and integration with communication and sensing technologies. The work is based in an understanding that material itself, intrinsically, has the capacity to compute, process, and exchange information with its environment. Design methods are put forth to engage matter's own computation and its informational exchange with environment. A design framework emerges where iterations move rigorously between digital and physical modes of experimentation evolving operational prototypes through filters of measure and evaluation.

The specification of such performance emerges from the both the formation, articulation, and manipulation of existing and bespoke means of fabrication, manufacture, and assembly. In addressing a scope that spans from the details of making to the prototyping of application, content is borne of faculty-driven research initiatives which sample from the fields of tooling, computational design, material behavior, and responsive architectures. The confluence of these topics take place through the curriculum of the MSMS program, engaging the students in forming and executing multimodal design methodologies developing new materials and fabrication methods with priority on the advancement of materially and spatially adaptive architectural systems.

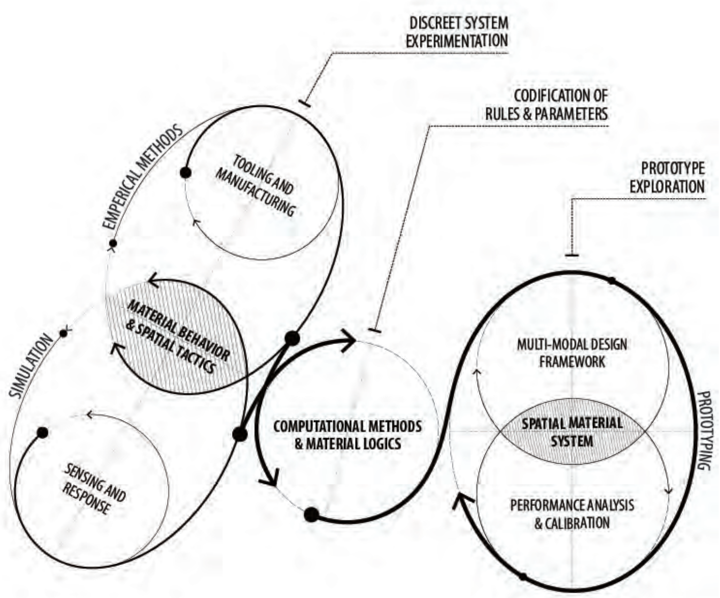

Figure 1: Extensible design framework for research in material systems (Sean Ahlquist, 2014)

Key to a pedagogy that supports the study of material systems is a framework for computational design thinking and sequences of experimentation at ever-increasing levels of complexity (fig. 1). This framework defines the critical foundation of material system research at the generation of system logics through empirical methods and studies through physical experimentation and observation. As mentioned previously, the term *computation* is not explicitly confined to the domain of *virtual* methods. The factors that drive a specific material behavior are most readily deducible through iterative exploration of physical simulations. It is rather through abduction (rule + result = case) that the rules exhibited in the physical precedents serve more exhaustive virtual means. Prototyping encapsulates the design space as a proving ground for methods of study as well as a generator for new vocabularies in material form and spatial performance (Coyne 1990). This is posed as a scalar framework where layers of material performance and spatial complexity can be engaged through continual embedding of parametric rules, tacit material knowledge, and calibrated responsiveness.

RESEARCH AGENDA ON DEVISED SKINS

Framed under the primary theme of the program *Devised Skins*, design methods are focused on the intimate control of material formation to realize material systems that operate as structural, spatial, and contextually-aware architectures. Within this framework, we explore the textile as both a literal deployment of fibrous conditions parametricized for specific multi-capacitive performance and a figurative expression of interlaced multilayer systems. Such a premise demands an expansive knowledge from the direct forming of heterogeneous materials (as opposed to the destructive manipulation of homogenous materials) to the comprehension of behavior in interaction with other material elements and in the presence of contextual (environmental) pressures. This necessitates embedded and evolving expertise from multiple disciplines for the deployment of critical relationships between material formation and system operation.

Within *Devised Skins*, research is approached through a drawing together of diverse and conflicting concerns in the context of specialized knowledge. The distinct primary research specialties of each director can be broadly summarized as (i) tooling in the discovery and articulation of material attributes and behaviors (ii) computational design methodologies, and (iii) embedded sensing, response, and environmental mediation. Collectively, these three territories constitute overlapping domains of concern, each replete with their own modalities, methodologies, and theories to which students are exposed in the development of their design research projects over the course of a one-year program. The involvement of external advisors in engineering specialties, material science, information systems, computer science, and advanced manufacturing methods complements these intra-disciplinary priorities with interdisciplinary perspectives and knowledge. Rather than the transmission of an isolated perspective and single stream of technique, the combinatory model delivers a broader approach that enables students to customize their inquiry enabling a learning experience that is scalable and transportable to future research and practice challenges. We imagine, then, the development of post-professional specializations as an opportunity for a depth of exploration, in shaping extensible methods of interdisciplinary research and forming specific knowledge of operational material systems that foster new ways of drawing together as well as drawing forth.

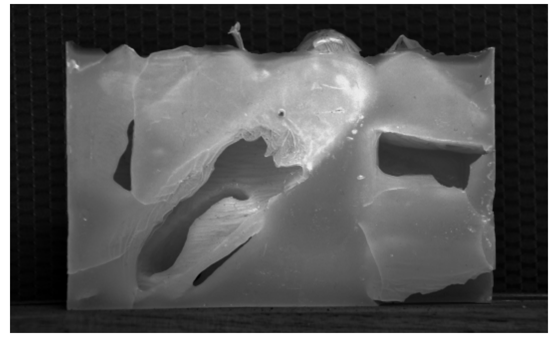

Figure 2: Wax forming studies (Lauren Bebry, Master of Science in Material Systems—Assistant Professor Catie Newell, University of Michigan, 2013)

Material attributes, behaviors, and tooling

Fundamental to the design of more complex assemblages is the comprehension of innate material behaviors and their specific and individual computation and response to environmental pressures. Strictly linked to specific qualities of matter, each element of a system can be defined by its own attributes. These underlying properties range from physical qualities (including strength, elasticity, and tactility) to environmental responsiveness (of conditions such as thermal, humidity, and pressure changes) and finally more atmospheric and appearance-based attributes (emission of light, smell, and electromagnetism). Further, materials must also be understood through qualities inflicted by manufacturing processes such as the cut direction of wood, the pour of steel, or the thickness of glass. Defined by this myriad of properties, it can be argued that a material, with such capacities, is already a system: responsive to its surroundings through its own innate physical, behavioral, and immaterial characteristics.

The endeavors of the MSMS program maintain close design sensitivities towards the attributes of a material and its environment. This extends into manipulation of multiple materials, and the resultants of their system assembly. For example, in the Physical Attributes Core course, and as an underlying component in all subsequent research pursuits, students are presented with a research practice that demands a hypersensitivity to material attributes in designed-based decisions. Within the course, students are asked to develop a tool for the manipulation of a material and its environment. With the ambition of altering material systems *during* their production, the design of such a specifically focused tool presents a method that necessitates a direct coordination between all attributes of the system—making, form, and performance. Each material, either as the subject of study or a part of the tool, must be coordinated to align behaviors and intentions. The course is taught in a work-

Figure 3. Kinetic PETG system (Steven Beites, Master of Science in Material Systems—Assistant Professor Catie Newell, University of Michigan, 2013)

shop setting that fosters experiments harnessing and agitating material attributes while simultaneously aiming at the formation of typical building components with the expectation for atypical resultants, pressing students to project larger structures and implications on space. An early exercise by Lauren Bebry collapsed misaligned cooling temperatures of ice and wax to formulate a system of production for amorphous apertures that are otherwise formally complex spatial maneuvers (fig. 2). Under an entirely different technique, Steven Beites worked closely with the physical and immaterial qualities of a translucent PETG (fig. 3). Experiments worked back and forth to demonstrate a collapsing of material attributes with mechanized operations of production and assembly. Friction, light emissions, and patterning were coordinated alongside the tooling paths and pressures of a knife cutter, and the resulting performances of a motion-activated screen wall. These endeavors succeed in setting-up forms of practice and inquiry attuned to attributes at various stages of a manufactured material system.

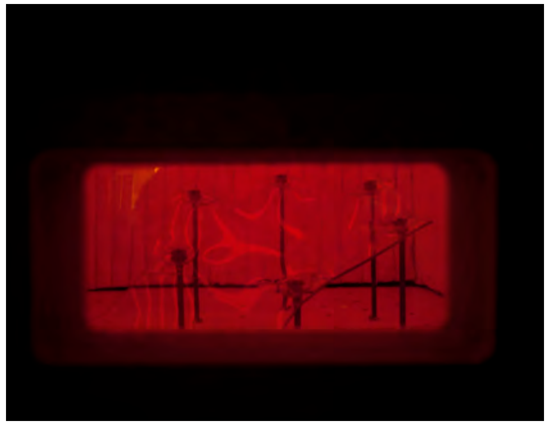

Figure 4: Custom pin-mold kiln (Wes McGee and Catie Newell, 2011)

This research practice is based heavily on the continuing research of faculty members in the MSMS program focusing on the manipulations of physical and immaterial attributes through the development of tooling and fabrication techniques honed to the properties of a specific material. The work of Catie Newell and Wes McGee challenges existing modes of working with glass across a range of applications and scales, interrogating the connections between craft and the explicit control offered by custom developed manufacturing processes and tooling. This research began by questioning the de facto application of glass as flat pane that reinforces the ubiquity of sheet materials throughout contemporary building tectonic systems. Such ubiquity remains a reflection of the industrialization of architectural products, whereby traditional materials have been modified and compressed into standard sheet goods and then fabricated using subtractive technologies. Arguably this has both driven and been driven by a lack of feedback between material properties and the design process. This research instead demonstrates an alternative methodology whereby material and process constraints are integrated into the design process through experimental and computational techniques, developing a feedback loop between design intent and materialized formal attributes. The related design projects represent a multimodal approach to design research, encompassing the latent materiality of glass as an amorphous solid, overlaid with an explicitly controlled, empirically verified process which seeks to advance the performative capabilities of the material both spatially and visually.

Figure 5: Glass Cast: catenary slumped glass panes at Research Through Making exhibition at the University of Michigan (Wes McGee and Catie Newell, 2012)

Integral to the larger body of research was the development of a digitally controlled, reconfigurable pin-mold embedded into a kiln. Articulated with 99 pins and hexagonal tiles, the kiln facilitates the formal alteration of flat sheet stock into geometrically defined curvatures (fig. 4). Developed and integrated with a parametric modeling plug-in to provide manufacturing constraint feedback directly into the design process, the equipment and software developed as part of this research is tied very specifically to particular material attributes and modifications, providing the potential for continuously variable formal output, while reducing the waste associated with dedicated molds. The fully integrated methodology includes feedback on the formability of specific geometries, material properties, and direct machine control of both the forming kiln and the post-form robotic abrasive waterjet trimming of panels. The research as resulted in three full-scale installations exploring the material and immaterial behaviors and relationships between glass and the physical and thermal environment of the kiln: Glass Cast (fig. 5) demonstrates formal curvatures as achieved through catenary slumping in coordination with tests of temperature and duration (McGee, Newell, and Wilette, 2012); Specimen is a spatial enclosure and amplification of the inherent light effects and different grains of reflection as provided by the created forms (fig. 6); and most recently, Displace is a study in material and optical distortions as captured in mirrored glass pulled and distorted through a studied pairing of the initial geometrical forms with an exaggerated heating cycle.

Figure 6: Specimen: catenary slumped glass panes and light installation at The Not Yet exhibition for SiTE:LAB (Wes McGee and Catie Newell, 2012)

Topological description, structural action, and materiality

Material systems are shaped by the inextricable relationships of material make-up and assembly. This poses a unique challenge in terms of methodology as the critical design variables are dependent and indeterministic until the whole of the system is addressed and activated. To parse this complexity, a material system can be broken down by the definitions of topology, structural action, and materiality, with exploration of system behavior occurring across several modes of design between physical form-finding, spring-based simulation, and finite element analysis (fig. 7) (Ahlquist et al 2014). *Topology* allows for the componentry of the system to be addressed by count, type, and association, without the need for considering geometry. *Structural action* implements the conditions of internal and external forces. In the case of material-formed lightweight structures, pre-stress, such as tension, compression, and bending-active behavior, is the primary agent. The definition of *materiality* is two-fold. This embeds data of fundamental material properties. In the case of textiles, it involves defining bi-directional (warp and weft) performance as a tensile surface or in bending as a part of a composite matrix. Additionally, the functions of *materiality* include constraints of material formation, and methods for the translation from computational data to material assembly.

Managing both inherent properties and variable relationships for the behavior of a material system, a distinct set of design modes have to be engaged, shifting

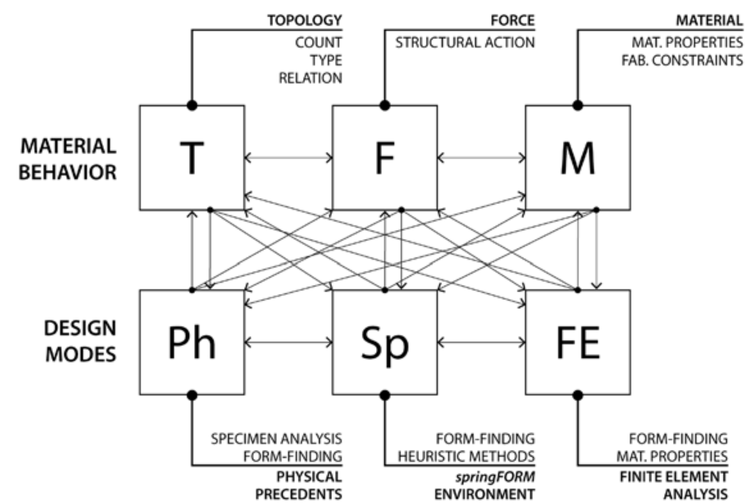

Figure 7: Components of behavior and modes of design (Sean Ahlquist, 2014)

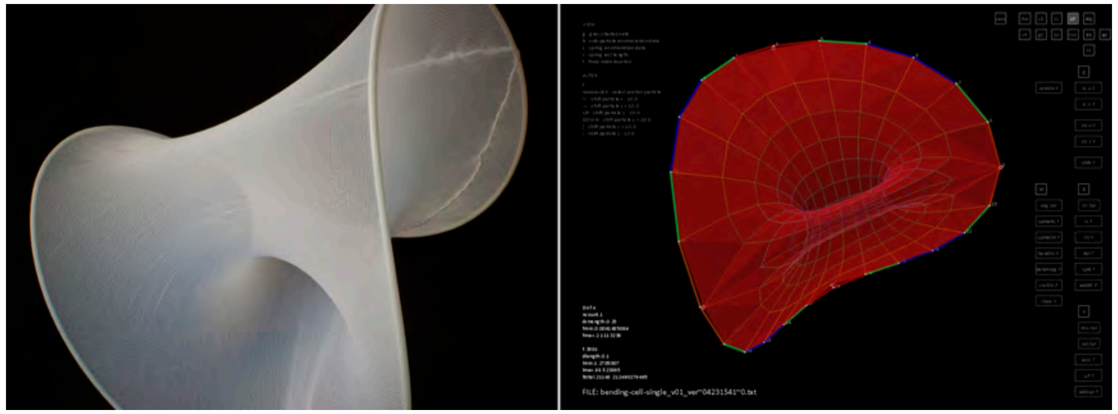

Figure 8: Physical model compared to spring-based simulation in springFORM (Processing, java-based) software (Sean Ahlquist, 2012)

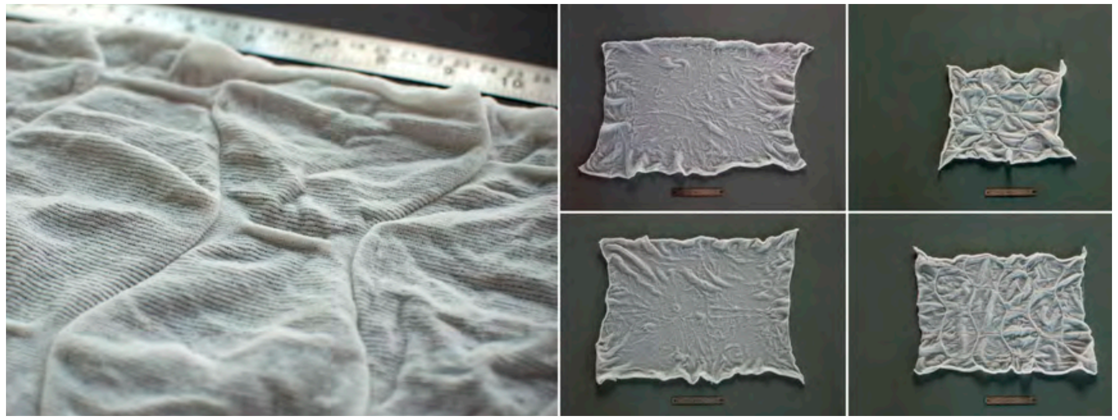

Figure 9: Custom knitted textile with differentiated structures, significantly varying material size and performance (Sean Ahlquist, 2012)

between physical and computational exploration. This is a multimodal approach where methods are sequenced to form a fluid design framework. No single method is considered robust enough to manage the entire design space of a material system. It has been shown that the sequencing of methods can be predicated upon the topological complexity of the system (Ahlquist et al 2013a). As complexities in count, type, relation, and resulting behaviors increase, the ability to resolve form (equilibrium) through physical study is limited, as all facets of topology have to be more precisely *pre-planned* before engaging model assembly. Such coordination is often not possible without a great degree of prior practice and intuition. When topological complexity advances, behavior is more easily resolved and understood through a spring-based computational environment. This has been developed as a material-behavior based modeling environment in the *springFORM* software, a program developed in Processing (Java) as a part of the doctoral research of Sean Ahlquist. Once topology becomes fixed and resolved, finite element analysis (FEA) serves to define the exact mechanical description. It is important to note that ratios of force distribution are still variable within this environment, meaning FEA is still an active mode of design in resolving force to reshape form.

Aspects of this methodology are exhibited in the ggggallery installation in Copenhagen, Denmark, by Sean Ahlquist. The material system is termed a textile hybrid, where equilibrium form is generated at the balance of a tensile surface and the stiffness of a continuous glass-fiber reinforced polymer (GFRP) rod. The semi-toroidal form is studied comparatively through physical and digital simulation (fig. 8). The structure utilizes variegated knit textiles designed specifically for the project, in close collaboration with textile designers and knit manufacturers near Stuttgart, Germany. In examining a series of isolated knit samples, the complexity in behavior is obvious. In Figure 9, the samples all have the same number of loops, but because of changes in knit density (stitch/loop length), quite different textile size and behavior is produced. These facets of behavior are encapsulated within the diagram in Figure 10 (left), where variations in density are strategically placed in order to accomplish the large structure with only two textile parts—a cylinder and a four-side panel. The elasticity of the yarn is maximized and density minimized in the cylinder textile to enable a 16-foot static boundary to stretch to over 40 feet. The result is an architecture with minimal structural exertion into the gallery space and maximal spatial presence, as shown in Figure 10 (right).

As a part of the MSMS Capstone, Tom Bessai continued the study of bending-active structures by studying beams composed of GFRP rods with extremely minimal cross-section. Through study primarily of physical models, a method was developed in order to produce a large spanning and cantilevering structure within the Research Annex for the Taubman College of Architecture.

Sensing, response, and environmental mediation

> *Life is made possible by membranes. Part of their function is to provide a surface on or from which interactions and reactions can occur and be controlled… In all cases, plant and animal, the skin is specialized not only as a covering but also as a selective barrier to passage in both directions of mechanical, physical, and chemical stimuli such as force, heat, water and volatiles. Since this single layer has to perform many different functions, it is inevitable that there will be conflict between the various requirements. We make the assumption that in biology these conflicts have been largely resolved by evolution, and that we can benefit from the abstraction of concepts from these natural structures into a form that can be integrated into our own technology.* (Vincent 2009: 3)

Adaptation has been frequently identified as a characteristic fundamental to the pursuit of sustainable design. Within living and social systems, adaptation allows for fitness relative to external conditions, efficient energy usage, and resilience to changing conditions over time and through disruption. Like the biotic skins described by Julien Vincent, architectural skins are more than simply wrappers and can be considered quite literally as complex membranes capable of managing energy, material, and information exchanges, while adapting to variable environmental conditions. Integrated with other building systems, they can be designed to operate "as part of a holistic building metabolism and morphology" (Wigginton and Harris 2006: 3). One of the ultimate goals of this aspect of the work is to reclaim the environmentally performative domains of architecture, almost entirely relegated to engineering professionals, to within the purview of the discipline, as territories of material, formal, technological, and experiential innovation and exploration. In order for this to occur however, collaboration with engineering, material science, and computer science is required from the outset, and it is fundamental for designers to learn to collaborate productively with other disciplines, as well as industry specialists, as part of an exploratory design and research process.

In the recent research undertaken by faculty and students in the Material Systems program, this question is being explored through the development of thick, sensing, and kinetic skins comprised of integrated as-

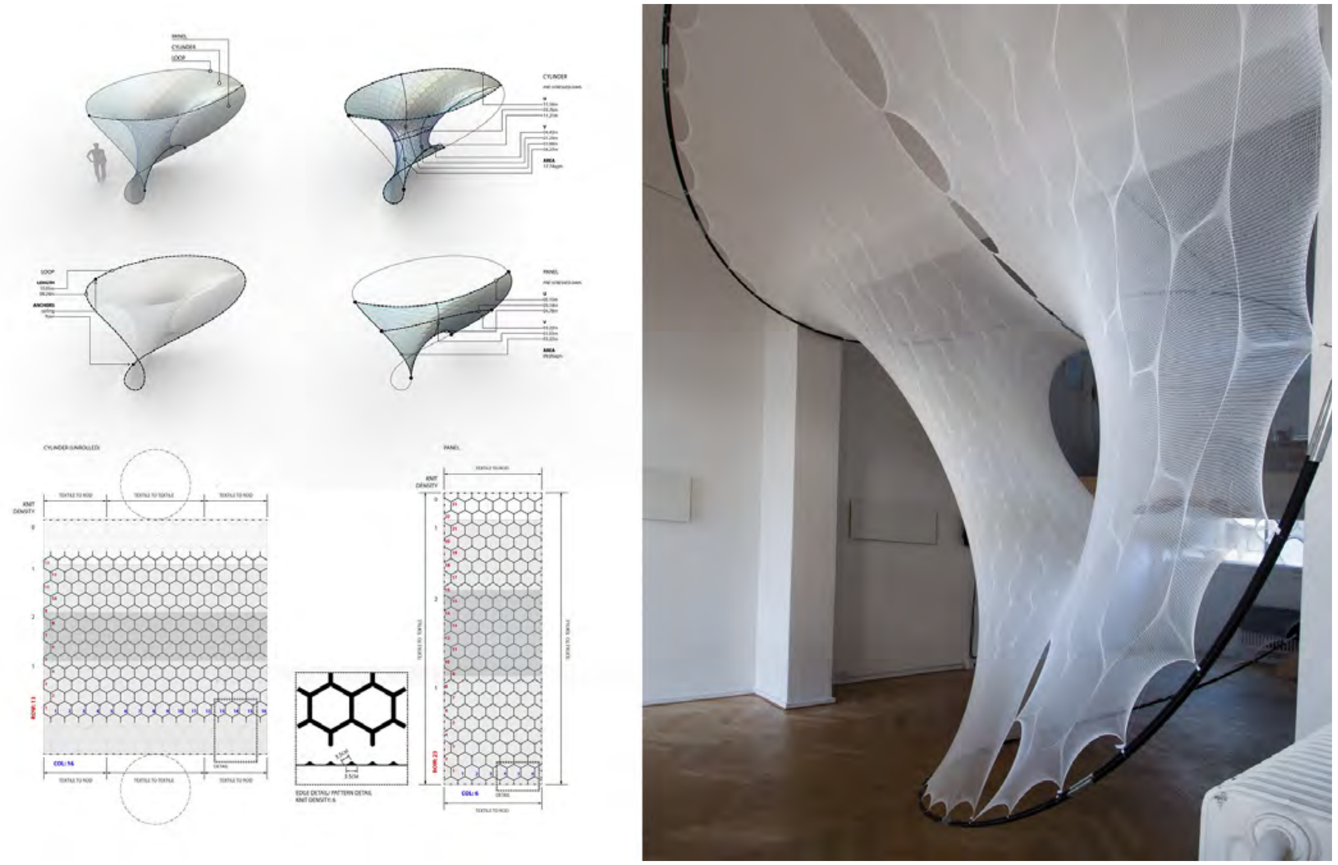

Figure 10: Semi-Toroidal Textile Hybrid installation at ggggallery in Copenhagen, Denmark, composed of GFRP bending-active boundary and two tensioned textile elements (Sean Ahlquist, Institute for Computational Design—Professor Achim Menges, University of Stuttgart 2012)

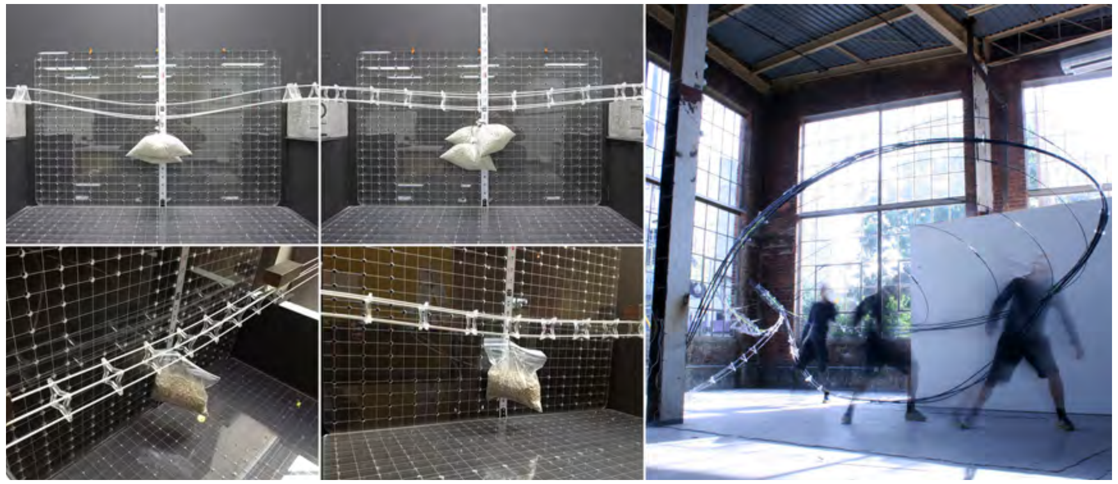

Figure 11: Variegated bending-active beam structure (Tom Bessai, Master of Science in Material Systems—Associate Professor Geoff Thün and Assistant Professor Sean Ahlquist, University of Michigan, 2013)

semblies of performative and interdependent layers and components. These serve individual as well as cumulative environmental functions, and are designed to adapt to variable environmental conditions while also developing responsive behaviors relative to human interaction. The work is explicitly integrative, advancing each project through a design ecology that operates through feedbacks between simultaneous research in lightweight deployable structures, new materials, logics of manufacture, and the integration of sensing, actuation and control technologies. The physical development of performative full-scale prototypes is also fundamental to this research. While computational simulations are able to model the anticipated performance of a specific component, the performance of the composite system is too complex to be predictively modeled. Further, human interaction and resulting immaterial effects requires the development of full-scale operational prototype installations.

The work of student Delia Guarneros explored the possibilities for 'texegrity' systems (structural systems based on tensegrity which utilize textiles in place of the tension members), to operate as kinetic skins capable of controlling light penetration (fig. 12). The research involved iterative experimentation with textegrity geometries, modeled both physically and computationally, that could achieve desirable results when actuated. The system's operation could be controlled by both integrated light sensors, as well sensors that detect human presence and negotiate the conflict between shading and view paradigms within the system. The work of Steven Beites explored the use of shape memory polymers (SMPs) as thermo-sensitive actuators for use in kinetic facade systems (Beites 2013). Due to the capability of SMPs to elastically deform at one temperature threshold, and to return to a memorized shape at another temperature, they allow for the possibility of adaptive architectural components that can be actuated without the use of mechanical components or external energy inputs. Steven's work involved exploratory research into methods of manufacturing SMP forms through injection molding, as well as their integration into a prototype skin system with deployable openings (fig. 13).

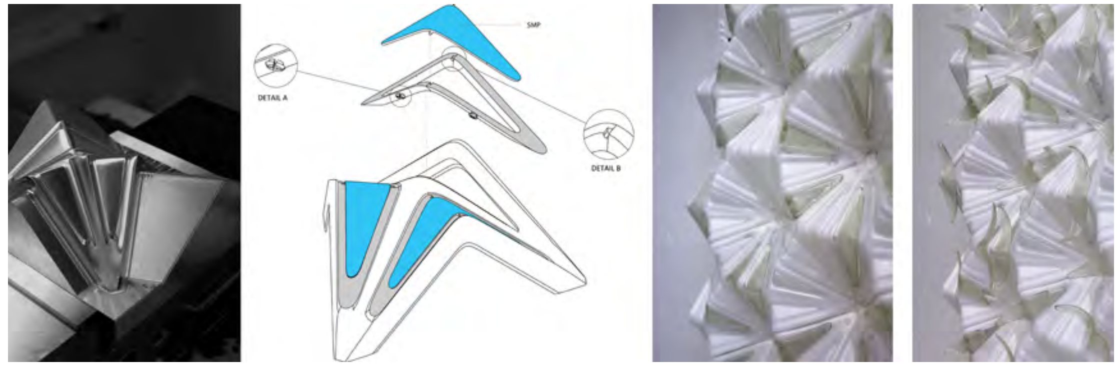

Figure 13: Transformable shading system using shape memory polymer (SMP) (Steven Beites, Master of Science in Material Systems—Associate Professor Geoff Thün and Assistant Professor K. Velikov, University of Michigan, 2013)

The Stratus Project, led by faculty Kathy Velikov and Geoffrey Thün, develops a distributed interior envelope system that modifies atmospheres while attuning our attention to the air-based environment and to the physical conditions that produce it (fig. 14). It is comprised of a deep suspended textile: a 'thick' surface consisting of a tensegrity weave whose nylon tension members provide deformational flexibility for spatial transformation, while also supporting a network of physical elements and technologies. The system senses movement, proximity, temperature, humidity, CO2, and airborne pollutant levels, and reacts according to individuated occupancy triggers and processing algorithms to modify comfort conditions. Light-based communication informs occupants of reduced air quality, so that this new skin also operates as an interface through which individuals might develop more sensible and cognitive relationships between their own actions, the spaces they inhabit, and the larger air environment (Velikov, Thün, and Ripley, 2012). Resonant Chamber is a subsequent prototype for an interior envelope system focused on transforming the acoustic environment through an integrated system that develops a spatially dynamic rigid origami surface comprised of acoustically specific material assemblies and electro-acoustic technologies (Thün et al 2012). This work builds on the North House prototype, a fully functional test bed constructed at the scale of the house, which combines a nested hierarchy of interacting systems, consisting of a high performance environmentally-responsive kinetic envelope, intelligent solar-powered HVAC controls and an interactive interface aimed at producing co-evolutionary behaviors between building systems and inhabitants (Thün and Velikov, 2013). Their most recent body of research in this area explores the architectural possibilities for lightweight deep skins based on biological models of densely networked assemblies of cellular pneus (i.e. tension-active membranes) that are capable of dynamic and variable performance primarily through the use of air pressure (fig. 15).

Figure 12: Texegrity transformable structure (Delia Guarneros, Master of Science in Material Systems—Associate Professor Geoff Thün and Assistant Professor K. Velikov, University of Michigan, 2013)

CONCLUSION

The work shown here has elucidated upon an approach and design methodology for the effective design, instrumentalization, and deployment of *material systems*. Such is being explored through the research by faculty and students involved with the Master of Science in Material Systems (MSMS) program at the University of Michigan. While the framework has been striated between studies of material formation, structural form-finding and responsive media, the research seeks to more exhaustively cross-pollinate these fascinating aspects of spatial and material phenomena. The stream of research, termed *Devised Skins*, moves through three stages—(i) *Topology, Materiality and Form*, (ii) *Sensing, Feedback and Transformation*, and (iii) *Performative Spatial Systems*—in order to foster the expansion of design considerations and performance as the research develops. Current studies have examined the repercussion of exploring topology and material behavior in the forming of lightweight structures. This has produced unique knowledge in the forming of textile- and composite-based structures that exhibit high degrees of controllable elasticity. In the next phase, this performance will be charged with means for sensing, feedback, and responsiveness, utilizing inherent flexibility as a way for geometric transformation avoiding the use of mechanical and kinetic means. This will involve, among other studies, the use of an industrial flat-bed weft-knitting machine, newly procured as a part of the FabLab at the Taubman College of Architecture and Urban Planning. With the concluding phase, we will compile the methods and material knowledge to study the possibilities for responsive spatial systems. Moving beyond the study of wall systems, this will engage projective imagination of material systems that engage the *extra-systemic*—the contingencies that lie outside (and interfere) with the tuned operation of a spatial, responsive material architecture.

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Figure 14: The Stratus Project installed at the University of Michigan, demonstrating operation of breathing cells and fans to dynamically adjust air temperature and pollutant levels (Assistant Professor K. Velikov and Associate Professor Geoff Thün, University of Michigan, 2011)

Figure 15: Nervous Ether installation undertaken through a workshop at the California College of the Arts, composed of a cellular pneumatic tessellated weave that registers and communicate remote environmental information through changes in inflation (Assistant Professor K. Velikov and Associate Professor Geoff Thün, University of Michigan, 2013)

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