Methodological Approach for the Integration of Material Information and Performance in the Design Computation for Tension-Active Architectural Systems

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Abstract. As computational design processes have moved from representation to simulation, the focus has shifted towards advanced integration of performance as a form defining measure. Performance, though, is often assessed purely on the level of geometry and stratified between hierarchically independent layers. When looking at tension-active membrane systems, performance is integrated across multiple levels and with only the membrane material itself, defining the structural, spatial and atmospheric qualities. The research described in this paper investigates the integrative nature of this type of lightweight structure and proposes methodologies for generating highly articulated and differentiated systems. As material is a critical component, the research focuses on a system-based approach which places priority on the inclusion of material research and parameterization into a behavior-based computational process.

Keywords. Material behavior; material computation; system; gestalt; tension-active system.

INTRODUCTION
Architectural design processes have been increasingly tailored to foster more thorough and precise considerations of context in the generation and specification of form. Here, context is not simply the physical elements at the boundaries of an artifact but refers to the interwoven composition of material, environment, and functional intensities. This is reflected within current computational platforms, as well as organizational frameworks, which attempt to embed the variants and invariants related to a building’s materiality, its internal spatiality, and its external relations within a cohesive process structure. By in large, these design frameworks function through strategies which place primacy upon geometry. Geometry is formed in response to a limited number of contextual conditions, and in subsequent steps tested against the remaining internal and external criteria. Such a stepped approach often resolves itself in systems of interconnected but autonomous layers; interconnected as geometry, but autonomous in their operation and function. With the design of each hierarchical layer, its preceeding layer is ‘frozen’
in the overall geometric configuration. Of course it is understandable that such a stratified process is necessary. The complexity of inter-relating all aspects of form and performance is intense to the point that evaluation of a precise nature can typically only occur once externalized from the iterative and generative design process (Kalay 1991).

Nevertheless, the trend is clearly to expand, through computational design frameworks and processes, the spectrum of inputs and measures being considered. At the same time, the effort of measure within the design process seeks increasing precision. Computation, since its introduction to architecture as a digital format in the 1960’s, has intended to relieve the struggle, as stated by Nicholas Negroponte, in managing complexity in large scale relationships alongside small scale constraints in their particularity and seeming trivialness (Negroponte 1969). A vast array of computational techniques have been implemented to, in the least, visit this realm of multi-scalar design and attempt to find equilibrium between the micro and macro relationships of form and performance. Parametric modeling, information modeling, and recursive (evolutionary or swarm) algorithms are examples of such techniques. Ultimately, though, there is a more fundamental question of how information beyond geometry is embedded, coordinated and increased, with the most critical aspect being the latter. In design, where the formulation of the procedures, requirements, possibilities and subsequent solutions work in a transformative manner from abstract to precise, the framework for process must encapsulate the same progression (Aish 2005). Understanding the system to be produced and the system by which it is developed are two synchronous but separate conditions. The first is a specific expression of principles, while the second is a search and discovery of opportunities within an evolving set of principles. Examining tension-active structures, one must evoke a concept for understanding architecture in its physicality as a dynamic system – assembly of surfaces defined by lightweight materiality and equilibrium of tension forces – and process as a system for the complex resolution of form and performance – inter-relating the structuring of doubly-curving surfaces, materialization, spatiality and environmental description of thin membrane material (Ahlquist & Menges 2010). Computationally, this can be accomplished in a process which balances embedded knowledge with simulated behavior. It exposes a process by which material study can be combined with computational means to develop a robustness, which produces viable results within an agile design environment, functioning with a high level of manipulability in a constrained design space. Ultimately, through the search of expanding information and precision it is intended that new principles and consequent innovative results can be achieved (Miller et al. 2002).

SYSTEMS OF SYSTEMS
In expanding the influences which define and activate architectural form, the methodological approach which generates such form reaches beyond a pure study of technique. The broad exposure of computational programming and parametric modeling techniques to architecture has established deftness in the ability to both invent and resolve complex geometric relationships. The development of libraries, such as Robert Woodbury’s Design Patterns [1], thoroughly defines the concepts and applications for the construction of associative models. The question lies in the broader understanding of how architectural systems function, and what arrangement and execution of techniques can most adeptly relate to aspects of how systems are materialized and how they perform within their specific contexts of function and environment. Developing a conceptual and methodological approach for the integration of form and performance means there must be an intimate understanding of what constitutes a system and the procedures by which they can be simulated.

The term system has many definitions and it is, by no means, foreign to architectural design processes or the activation of architecture as a physical artifact. When we define a system as the intertwining of information and operation resulting in particular
phenomena, then we can quickly jump to the understanding that achieving a precise series of phenomena requires accuracy in the descriptions of elements and interactions which underlie the entire system. This is the acute challenge in architectural design when expanding the scope of systems inclusive to the design process. In relation to Negroponte’s statement of the designer’s ignorance to large scale complexities and avoidance of small scale conditions, a system is exactly the resolution of global relationships and local specificities.

Ludwig von Bertalanffy addressed the complexity of systems and the failure of processes which tried to understand them through investigating elemental units in isolation. When dealing with issues of organization in “systems of various orders”, he surmised that the study of only local events will not explain the entirety of the phenomena (1969). In seeing systems as universally striving for a particular homeostasis, Bertalanffy proposed a cyclical feedback mechanism, as shown in Figure 1A. Handling the complexities of relationships at the elemental level, he defines three distinctions: number, species, and relations, as described in Figure 1B, where case 3 deliberately shows that relations are a critical aspect in defining system components.

This is a descriptive mechanism by which the elements and operation of a system can be deciphered and partitioned to ultimately be re-integrated and tested. It does not portray the manner in which each aspect of the system is particularly characterized. If we view form in this manner as a system, the elemental units are its component parts which are organized, not by hierarchically independent layers, but through integrated pressures based upon the influence of material reactions and environmental response. Christopher Alexander states this clearly as form being a continually dynamic result of pressures in material and environment. Modulation or the discovery of an equilibrium state between the active agents which inflect upon material conditions defines an architecture. Yet he also distinguishes between the operation of the form as a system and the system by which the operation is discovered, dissected, instrumentalized and applied. He terms this latter aspect the “generating system” (1968). A particular key to this strategy is that in the generating system the rules of both elements and interactions

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**Figure 1**

A: Bertalanffy’s simple feedback mechanism. B: Bertalanffy’s depiction of the three distinctions in defining the elements ‘a’ and ‘b’ of a system.

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A.

1: $a \circ \circ \circ \circ \circ b \circ \circ \circ \circ \circ$

2: $a \circ \circ \circ \circ \circ b \circ \circ \circ \circ \bullet$

3: $a \circ \circ \circ \circ \circ b$
are defined. Therefore the generating system is both a logic of discovering the rules and a method for enacting the rules to realize new possibilities within the range of phenomena possible with the system.

**FORCE SYSTEMS**

With this expression of systems, we can examine some of the key particularities which underlie the formation of force-defined surface structures, specifically tension-active structures. As an integrated phenomenon, tension-active structures operate on a distribution of tensile stresses within a thin textile membrane to arrange the geometry of a structurally stable surface. This inextricable relationship of form and performance considers the forces by which the geometry is initially formed, defined as pre-stress, and the structure's overall ability to withstand subsequent loading from wind forces, snow loading, etc. So complex is this relationship, in fact, that only recently proposed computational methods can approximate the influence of natural wind flows on a tensile membrane structure, better so than the typical method of scale model wind tunnel testing (Michalski et al. 2011). As wind load alters the geometry the tensile load distribution is changed thus giving a different response to continued wind loading and subsequent changes in geometry, and so on. These reciprocal affects between load and geometry emphasize the highly systematic nature of such pre-stressed structures. Nonetheless, while this exemplifies the need to understand the intense reciprocal dynamics of form and performance of tensile systems, such a level of consideration is beyond the bounds of the design generation system.

What serves as some of the fundamental principles for the generation of tension-active systems is a catalogue of basic geometries: saddle, cone or cylinder, and ridge-valley (Knippers et al. 2010). These geometries, as shown in Figure 2, assume a type of minimal surface which has an equalized distribution of tension force and a particular balance of double-curvature. The exact geometry relies upon these rules along with the definition of the boundary conditions, in their position and comparative difference in strength versus that of the overall surface.

What even these prototypical surfaces lack, though, is a mathematical constant which accepts the varied boundary definitions and can describe the particular geometric form. The surface state cannot be described with a singular function nor can the transition from one surface type to another be accomplished with a singular function. Ultimately, to study a more exhaustive design space than just the variation of the saddle, cone/cylinder, and ridge-valley types, production of the hybridization of these types is necessary. To establish a design space which intertwines these principles types, it is not the type that has to be established as the rules of the system. Such rules, as already stated, are not possible when viewing only the resulting geometry. This is not the simplest level of the system. Rather, it is the most fundamental terms of tension, double-curvature, and relative material properties that have to be implemented to discover a wider range of tension-equilibrium forms.

In defining the simplest principles of the design generation system, materiality is a necessary agent but not a primary input. In evaluating the
geometry, curvature serves to indicate the intensity of force at a particular location. Less curvature at a single moment within a surface indicates that more force is necessary to accomplish that degree of curvature. Materiality is an effector associated to the geometric description and the intensities of force that it describes. Where materiality does play a specific role is in the translation from computational to physical form. Because the system is pre-stressed and the geometry is doubly-curved, the translation from geometric form to panel description is not 1:1. The geometry must undergo “compensation” which calibrates the pre-stress and material characteristics to flat un-stressed textile panels. Figure 3 describes a scripted process, developed with this research, which simultaneously unrolls and shrinks the geometry. Considering force, geometry and material elasticity allows the possibility for higher degrees of double curvature to be solved within a single panel. Materiality rules the definition of the number of panels, the affect of the panel edges, and the degree of double curvature that can be accomplished.

When considering the hierarchical layers of this type of material and force-based system, we see that it can only be considered through integrated processes. Conditions of boundary, surface and force are inextricable while related in variable manners. This aspect exemplifies the need for a systems-based approach in understanding performance and executing methodology in generating form. From this, form is seen, not as layers of the static or “frozen” geometric entities to which other geometries adapt, but rather as the accumulation of dynamic integrated factors to which materially parameterized elements, in their position, orientation, and interconnection, have a reciprocal relationship. This eschews the parameterization of type, and looks for simpler terminologies by which the generating system operates to produce the phenomena of which define the functioning system. The striking question becomes how the processes are accumulated to exact this particular kind of form and performance phenomena, and how they function to provide the potential to develop new principles and opportunities.

**INFORMING SYSTEMS IN BEHAVIOR AND KNOWLEDGE**

Behavior-based and knowledge-based strategies have significant differences in how information is structured for the progression from abstraction to precision that is inherent in any design process. The primary difference between these two approaches is that one is based upon the determination and self-organization of fundamental properties by which global behavior (or form) emerges, while the other is a structure for the re-organization of mostly pre-specified information made applicable through interpretation (Mark et al. 2008). This is depicted in Figure 4 in how the state space for each approach might be defined. In a knowledge-based approach, the state space is fixed and knowable, though needing to be thoroughly searched. In the behavior-based
scenario, only the rules are knowable with the specific outcome to be realized by iteratively activating the rules. When we look at the whole of a design process, not only the execution of a particular set of procedures but the construction and alignment of those procedures, there is a logic which combines both types of information accumulation answering the question of how the generating system is specified.

Knowledge-based strategies implement precedents as design parameters. This happens through three modes: deduction, induction, and abduction, each having varying relationships to precedents, as shown in Figure 5.

Fundamentally, reliance upon cases limits the ability to produce results which are tailored to unique contextual conditions and integrated material behaviors. The only segue between case and application is through generalization. Where this approach can contribute, though, to a system-based methodology is in the application of abductive reasoning to the definition of prototypes. In this context, prototypes can be seen as both physical entities as well as schemata for procedures. With either case, they are defined as “knowledge organizing instances” (Coyne et al. 1990a). The production of prototypes serves to produce cases which test the degree of validity of the rules. Prototypes, as parameterized episodes, aid in establishing the backbone of the generating system through iterations which encapsulate aspects of the operating system.

The connection to a behavior-based approach can be simply stated as the bridge to which knowledge and specific performance is resolved. In John Gero’s framework of Function-Behavior-Structure, behavior serves as the transitional constants which generate the expected results given the structure of the process; structure being the catalogue of elements and relationships (2004). The behavior is the causal description of transitions defined by conditions such as physical laws, mathematical rules, structural constraints (referring to the computational structure), and states or transitions transferred from another behavior (Goel et al. 2009). The behavior-based methods, as transition functions, provide avenues for local rules to be integrated with external influences. Knowledge-based reasoning helps construct and validate the rules while behavior is the expression of specific transition-defining functions. Behavior serves to inform and specify symbolic or schematized knowledge, as an active model of local behavior and resolved global behaviors (or performance).

Figure 4
A: Design system, as compared to exploring a maze, is defined here as a problem-solving and search effort predicated on preset goals (Coyne et al. 1990b). B: Design system (b), as compared to billiards, navigates the possibilities of a design space through only local rules.

Figure 5
The three types of reasoning as stated by Coyne et al (1990a).
A behavior-based computational process for tension-active systems works on the basis of certain characterizations of material and variants related to its manipulation (fabrication) and topology (assembly). Comprehending the overall behavior of the system involves an initial step of design search, primarily accomplished through prototyping computational structure and physical artifacts. As the individual characterizations and variants do not contain the intelligence of the global behavior, the possibilities must first be searched, identifying particular capacities and performance, and embedded as knowledge in the design generation system. Design, it can be said, is then the quantification and qualification of the deciphered aspects of a particular discovered behavior or gestalt. Search becomes an operative design agenda from the initial identification of a solution space to subsequent steps of generative testing in continued specification and articulation of an individual form.

**COMPUTATIONAL GENERATIVE SYSTEM FOR TENSION-ACTIVE SYSTEMS**

This synthesized knowledge and behavior-based design strategy is exemplified through on-going research into the design and fabrication of complex and highly-articulated tension-active systems. This serves as a quite useful test case for such an approach and computational strategy in terms of integrated form (operating performance), and the structuring of computational mechanisms (frameworks and functions. The specific research shown here investigates the local definition of tensioned textile cells and their capacity as a sound buffering device. The global form, as shown in Figure 6, examines the complexities in distributing tension throughout a highly differentiated geometry.

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**Figure 6**
Physical prototype of Deep Surface tension-active membrane system. Michael Pelzer, Christine Rosemann, ICD University of Stuttgart - Sean Ahlquist, Prof. Achim Menges.

**Figure 7**
Prototyping studies to confirm the performance of the tension active system, primarily in relation to translation from particle-spring simulation to physical artifact and control of the cell “apertures”.
The principle behavior, captured within the computational process, is the relation of form to structural and acoustic performance realized through the interactions and parameters of force, material, and boundary conditions. The relation of form and structural performance is resolved in a strategy which integrates three specific behavior-based components: force simulation, topology, and translation (Ahlquist & Menges 2010). Translation has already previously been described as the point at which material specificity becomes invested in the process, a measured process integrating prototyping studies and behavior. Specific studies for this particular morphological strategy are shown in Figure 7. Force simulation and topology are interrelated through the use of a particle and spring method. A spring defines a force magnitude and vector following Hooke’s Law of Elasticity. While the stiffness of a spring functions in a linear fashion, algorithms are enacted to recognize the non-linear behavior of the selected textile material. A network of springs defines a surface and a diagram of force distribution.

In this project, the topology of springs follows that of a basic cylinder. The morphology, though, transitions to a form where one end of the cylinder is folded back on itself. This produces within each cell a center aperture, and across multiple cells a continuous closed surface. The continuous surface serves as a light and sound barrier, allowing for the apertures to be the primary control for diffusion of both atmospheric effects. The parameters of the springs within each cell are manipulated to control the aperture size, as shown in Figure 8. The transition functions translate the overall morphology via manipulation in the boundary conditions, the addition of internal stiffened springs acting as “cables” and also the local variation in force parameters in the individual cells. Most importantly, it is clear that the transition function does not rely upon geometric translation. Manipulation occurs in the altering of behaviors within the system to trigger change in the resulting global form, as shown in Figure 9.

CONCLUSION
The reasoning for a behavior-based approach for the formulation of tension-active systems is to provide the capacity for efficient computation of the intense levels of complexity inherent in the material system, and the possibility to discover increasingly advanced morphological descriptions. With a lightweight deep surface textile structure, as exemplified in the preceding prototype, it is possible to address form as a system of integrated systems, a gestalt, which negotiates

Figure 8
Determination of acoustic behavior in relation to aperture diameter and depth.

Figure 9
Generating system and feedback function for behavior-based spring model.
multiple atmospheric conditions. Such integrated form demands a clearly constructed framework for compiling and executing a design generating system. This encompasses both examination of architectural systems as active and dynamic agents within themselves and amongst their surroundings, and processes which dissect, instrumentalize, and discover potentials in dynamic and integrated performance. Design in not singularly or primarily about technique, but about relationship between and understanding of system performance and system generation. Such an approach and framework, or meta-process, wicks episodic knowledge, through prototyping, to understand the systematic potential of the resulting morphologies and calibrate the computational components. Enacted as a behavior-based generating system, process evolves form in specification and performance, while revisiting the effort of prototyping so as to allow for new principles to be uncovered, exacted, and reactivated within the evolving process. A framework which registers data of physical capacities as constraints and associative parameters, the local behavior, and actions, as mathematical transition functions which pertain to the magnitude of influence and reaction amongst the multitude of material elements and dynamic forces, realizes form as a material gestalt.

REFERENCES