ABSTRACT

The idea of an emergent or generative form based on repeating rules of growth borrowed from the field of developmental biology has provided fertile ground for inspiration in architectural theory and computational design. This work explores several biological and ecological analogues of form and developmental growth expressed through the computation of emergent pattern morphology and its application as surface embellishment in craft based material practice. The detail and complexity of the highly decorative material surfaces of early 20th century art and architecture are revisited; not just as visual complexity, but as highly rationalized systems for thermodynamic exchange or equilibrium. Through the intelligent aggregation of material through computational parametric modeling, the heat transfer characteristics of surfaces and material systems are creatively controlled in order to promote different thermodynamic properties. As the radiative and convective qualities of a given surface are changed, the resulting sensation and experiential qualities of a given material system are effectively altered as well. This is significant in terms of energy exchanged through material systems, but also in terms of more mundane everyday interactions with designed material surfaces in the built environment, which when replicated on the scale of local and global economies can prove significant to larger ecological systems. A series of physical prototypes where developed with different high-relief patterns and pattern densities. Positive prototype geometries were first produced using stereolithography for casting plaster molds for the production molding of finished ceramic pieces for thermal analysis using digital thermography. By studying the performance of these complex geometries as physical prototypes under controlled experimentation, high-relief surfaces and the resulting thermodynamic conditions can be understood not just by qualitative experience, but also as quantitatively measured performance metrics by innovative tools for analysis.
ANTHROPOGENIC ECOLOGIES

The built environment represents the physical manifestation and expression of design assessed primarily through normal human perception and its limited capacity for studying natural phenomena and experiencing change over time. Unfortunately, this has predominantly remained a prevailing force in the development of the built environment and its continued effect on larger ecological systems. Since human systems are typically resolved to meet the needs and respond to the comfort of their human occupants, with the aggregation of environments constructed according to what is typically seen, heard, or felt by their human designers and occupants, affects outside of that cone of perception have resulted in the accumulation of anthropogenic effects on much larger systems relative to the normal sphere of human influence, such as the hyperobjects (Morton 2013) [Note 1] of climate and ecological systems, which have come to define the Anthropocene Age. When studied in isolation, individual material constructions or assemblies may only have a small effect on their surroundings; however, when these systems are expanded and replicated continuously throughout local and global economies from cities to countries to continents, what is largely imperceptible can prove to be profoundly significant to the function of larger climatic systems. As a result, whole ecologies fully derived from constructed rather than natural environments are becoming common place alongside urban expansion, replacing natural ecologies stemming from dynamic pressures and forces of the environment interacting with natural biological systems.

A significant challenge is posed for contemporary designers for how the performance of material systems that aren’t immediately apparent through direct observation can be actively designed. As long as the performance or the relative success of a given design is primarily assessed by the sensations of the visible spectrum of light, the audible spectrum of sound, thermal comfort, and sense of smell of human agents; naturally, undesired affects to systems outside of human experience that must be observed through sensors of higher precision can be left unaccounted for, unless specifically resolved through augmented design. With the incorporation of thermal imaging, this study approaches such a condition through post-analysis. Nevertheless, emergent design responding to new criteria or larger ecological systems means moving away from an emphasis on human systems agency in design, and building new toolkits for predictive modeling and analysis outside of the traditional metrics of design success.

COMPUTATIONAL FRAMEWORK AND PRECEDENTS

A number of conventional precedents in computational design and ornamentalism in addition to natural analogs, such as coral or bacterial growth, were revisited as a basis for generating developmental surface patterns. The familiar L-systems of Aristid Lindenmayer (Prusinkiewicz and Lindenmayer 1990) [Note 2] for developmental growth were used initially as a reductive tool in order to develop simple conditional growth patterns and branching systems with geometric rules for development; for example, functions for the bifurcation of plant stems and control angles for new shoots representing the growth
of plants (Figure 1, 2). These types of studies were frequently used by designers seeking to develop more deterministic natural forms in architecture in order to limit the role of the designer as the main agent in the design process, preceding the introduction of more computationally heavy generative modeling now common place in contemporary architectural design. Here simple L-systems were revived as a convenient shorthand for developing organic textures and patterns of growth.

The necessity to integrate nature, natural form, and complexity into the built environment has been a reoccurring vein in architectural design theory since architects, such as Frank Furness and Louis Sullivan (Figure 3), looked to natural analogs and the work of naturalists, such as Sir D’Arcy Wentworth Thompson (1917) and Ernst Haeckel (1998) [Note 3], in order to introduce natural form and organic patterns to reduce the artificiality of architectural systems. Thompson’s translational studies between different species within the same phylogenetic tree are particularly relevant, in terms of contemporary design, when discussing deterministic form generation, translational geometries in parametric modeling, and topology. These computational design explorations reached an apex with the works of generative architects such as Greg Lynn experimenting with emerging tools for digital design in Animate Form (Lynn 1999) and Karl Chu’s studies based on the application genetic algorithms to the design process (Chu 2006) [Note 4].

The biological need for connections to nature—which cultivate not only benefits to human health and natural circadian rhythms but also to promote ecologies of beneficial organisms within living spaces—are yet to be fully understood in terms of designing healthier environments. Still less understood are the topological relationships, energy exchange characteristics, and the dynamic phenomenological conditions that emerge from articulate surface embellishments encoded through the controlled aggregation of material complexity; or how such augmented attributes reciprocally affect the larger ecological context. In line with this renewed interest in biological systems and natural analogs, this research in particular revisits natural geometries and developmental growth through the design of adaptive decorative embellishments and textures.
through the lens of thermal performance, tactile surfaces, and material properties rather than simple biomimicry or the development of organic geometries. Similarly, this study represents a continuation of a larger body of work exploring architectural ceramic structures and facades developed over many years, which was presented previously at ACADIA (Winn 2012).

Digital ceramic design has experienced an influx of new and renewed interest in recent years with many contemporary designers exploring projects in this area of study. Since the work described here represents a small part of a larger pedagogy, new emerging contemporary practices may recognize familiar sources in this field of research with roots extending back to the early work of Jason Vollen at the Cranbrook Academy of Art, as well as past work with the Emerging Material Technologies Research Group (EMT) at the University of Arizona (Vollen 2009) [Note 5], the work of Evan Douglis with the European Ceramic Work Centre (EKWC), and ongoing work with the Center for Architecture Science and Technology (CASE). This study in particular is an extension of the design methodology developed for the EcoCeramics High-performance Masonry System (HpMS) building envelope developed through CASE and the Nexus-NY New Energy Xcelerator Program. HpMS is a ceramic façade system designed in order to respond to variable climate conditions through the adjustment of surface properties and material complexity at the building envelope (Barlow 2014) [Note 6]. The explorations discussed in the following sections are a natural extension of this area of research, exploring the formal complexity of developmental semi-regular patterning and the resulting material systems as surface embellishments on smaller scale ceramic vessels. The thermodynamic characteristics of these object studies are then observed under controlled heat exchange conditions using thermal imaging. By studying the thermal exchange between these complex surfaces and their surroundings, the phenomenological and experiential qualities of these geometries can be understood not just qualitatively but also though quantitative metrics. Since the study is itself an adaptation and extension of a design methodology developed alongside previous architectural research, the resulting methodology for embellished geometries and developing transient thermodynamic effects are easily applied to many potential applications at multiple scales ranging from the more traditional decorative architectural elements to more novel applications in order to understand and control the performance of transient heat exchange through material systems; though these systems operate at different orders of magnitude and durations, the boundary conditions and heat transfer properties remain consistent as geometric relationships when transported to the larger architectural scale.

DEVELOPMENTAL GROWTH AND MODELS FOR SURFACE EMBELLISHMENT

The following material studies represents the interchange of ideas, material processes and computational design methodologies between ceramic material exploration and computational design in architectural ceramic research applied at a culinary scale natural to earthenware ceramics. This study explores material and morphology on a more
accessible ergonomic scale for small prototyping exploration, which has enjoyed a reciprocal life informing larger more architectural scale projects developed in past EMT and CASE projects propelling the work forward. In this study surface patterning is applied to small ceramic vessels. The base geometry was selected for use as a convenient geometry for handling and prototyping as new surface patterns are developed and applied as textures on the digital model, which can then be easily prototyped and observed under various heat transfer conditions typical to normal use containing various liquids at varying temperatures or when touched by hand. As a result, the ceramic vessel also allows for the study of unique conduction heat transfer conditions that may not pose significant with other applications. This provides a condition where conduction, convection, and radiation can all potentially come into play.

A series of compound surface textures were developed using pseudo-biological geometries in order to produce the pattern fields seen below (Figure 4). Much like the Malthusian ecological problem of the exponential growth of bacteria in a sealed glass jar, a contained 2D or 3D geometric area was used as the bounds for populating geometry (Malthus 1993). Compound textures were then produced using iterative growth modeling similar to the simple deterministic L-systems based on a series conditional statements expressed iteratively. In this case, a field condition is first generated in order to evenly distribute initial seed points for geometry that develop iteratively as the pattern grows through the propagation of branches or cells until all available resources are consumed, like the simple cellular automata games developed by John Horton Conway (Gardner 1970). In this case two distinct pattern languages are selected for each growth model. The separate patterns are then allowed overlap, creating areas of high relief in the resulting surface texture. The four growth models shown below combine closed or open cell patterns with branching systems, which were allowed to develop iteratively as an animated process. Four instances from each developmental sequence are shown in the diagram. By using a range of cellular versus branching patterns, unique pattern sets where developed resulting in a wide range of varying tactile conditions with potentially different performance properties. For example, cellular geometries trap pockets of air film that can prevent air movement across the vessel surface; while conversely, open branching systems provide similar surface area and relief, but allow the movement of the air film through channels over the surface. By controlling the pattern field condition on a given surface, heat transfer properties can be subsequently tuned or modified to meet design conditions. Surfaces that need to transfer energy faster are mapped with more open geometries, while surfaces that need to trap an air film and limit convective heat transfer are mapped with closed cellular geometries, and so on.

By controlling heat transfer and exchange through geometric and material properties, the perception of these surfaces are also altered as a result, due to a number of physical properties ranging from view factor (amount of radiative heat exchanged), contact temperature (surface relief height and conduction relative to the amount of surface area in direct contact), turbulent or laminar airflow across a given surface (speed of...
air movement or convective exchange), etc. All of these properties directly affect the phenomenological and tactile experience of these surfaces that compose the ceramic vessel, which could potentially be extended to applications in the built environment. As a result, the perception of each ceramic vessel is altered dramatically simply by mapping new textures, and altering the energy exchange on the surface (Figure 5). Similarly, these different textures modify convection and conduction through direct contact, thus altering the visual and physical perception of the material object and tactile experience of the object by the hand.

**PRODUCTION MOLDING OF STONEWARE CERAMIC PROTOTYPES**

Positive prototype geometries where developed and then 3D printed using stereolithography, in a plaster medium that was then sealed for casting. Some test pieces were developed and printed directly using an earthenware ceramic material; however, the expense and limitation of producing one piece at a time still presented an obstacle for the prototyping process, especially when the goal was producing multiple reproductions and testing multiple surface finishes. As the process for 3D ceramic printing becomes more common place, the technology will no doubt become effective for future material prototyping studies; however, cost and production quality of the 3D printed ceramic still proved prohibitive as a nascent technology in this case, especially considering the loss of control over production quality and design tolerances when outsourcing to a third party. As a result, 3D printed positives blanks produced in-house then cast in a plaster negative, proved a much more effective method for production quality and reproducing multiple prototypes through a craft based process.

Using plaster mold slip-casting as the production method proved to be an advantage, allowing for lighter pieces and less problems resulting from handling and finishing. Similarly, the slip-casting produced more stable and resilient material bodies in the greenware state. Plate-like clay particles in ceramic slip naturally orient themselves and build up tightly together to form a structural shell once dry, whereas the particles in a stereolithography process must be oriented in horizontal layers creating shear planes where flaws and fractures can occur in a less stable greenware. By developing plaster molds, multiple test pieces with different thicknesses, material compositions, or surface finishes were then easily reproduced. The plaster molds themselves were segmented into nine parts in order to compensate for the complicated surface geometry, so that the mold positive and the cast pieces could be removed (Figure 6). The depth of the surface relief almost proved too difficult for a nine piece mold; however, once a workable mold had been cast, the clay parts released without issue. These pieces were then cast using a white stoneware clay slip, then bisque fired to cone 04 in preparation for glazing and high fire finishing.

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*Figure 5*  
Diagram of 4 selected instances from growth models applied as surface textures to a base geometry. Points of high-relief are indicated in red while undisturbed geometry is shown in purple.

*Figure 6*  
Nine piece plaster mold (left), and multiple bisque fired pieces (right).
The fabricated ceramic vessels where then finally finished with cone 5 glazes. A number of different surface finishes from more resilient crystalline glazes to more amorphous glossy glazes prone to run or crawl were explored. The different surface finishes are distributed more or less evenly over the surface relief depending on how much movement occurs in the glaze during firing, resulting in variations in emissivity of the final pieces and varying degrees of modification to the original geometry of the digital model as an artifact of the material process. Similarly, variations from absorptive matte to reflective glossy surface finishes, produced different radiative conditions providing another mode of altering the properties of the test pieces for observation by thermal imaging. Below, a number of finished pieces are show with two basic surface relief patterns, one with a closed cellular pattern at an early stage in development, and another with a fully developed branching pattern (Figure 7). The finished prototypes were photographed on a mirrored surface in order to show reflected geometry revealing more of the pattern from below. Ultimately thru perserverance and engaging in the process directly—rather than outsourcing the fabrication through stereolithography—a level of understanding was reached through practice, tacit learning, and active engagement in the material process of ‘trial-and-error’ making as described by (Sennet 2008).

HEAT TRANSFER AND DIGITAL THERMOGRAPHY

The finished pieces where placed under controlled conditions for study using digital thermography to observe the transient distribution of heat over the surface of the material. The affect of the high-relief surface geometries on heat transfer is especially pronounced in direct contact with a the hand or a heat source in a cooler environment; high-relief is in direct contact for conduction, while low-relief is only subject to indirect convection (Figure 8). As a vessel is filled with a liquid higher than room temperature, the progression of heat through the material can be observed resulting in a level of thermal equilibrium in the thermal exchange of heat through the ceramic container. Due to the relationship of area expressed by Fourier’s Law in the equation for conductive heat transfer \( q \):

\[
q = \frac{k \cdot A \cdot \Delta T}{t}
\]

where, \( k \) = thermal conductivity, \( A \) = area, \( \Delta T \) = temperature difference across the material, \( t \) = material thickness

Similarly, because the thickness of the material is the reciprocal value to the area of heat transfer, the step change in temperature becomes particularly pronounced when viewed through thermal imaging. As a result, the thermal gradient separates into identifiable temperature regions. The unique conductive condition of the finished prototype can be clearly observed through digital thermography, and separate regions of surface texture can be identified by significant stepping in 3 to 4ºC temperature increments after reaching stable heat exchange. Additionally, the two distinct surface patterns developed in the
digital growth model are easily observed across the full time interval of the controlled study. As seen in thermal imagery the higher tactile pattern comes in direct contact with the heat source provided by the hand and quickly collects energy. The thermal properties of the surface relief was then captured at five second intervals, in order to determine the sequence of heat propagation from points of low-relief to high on the surface and through the material section (Figure 9).

**Figure 9**
Digital thermography showing 5 second intervals as heat transfers at different rates through higher and lower relief on the surface of the prototype.

**OBSERVATIONS**

The compound high-relief patterns developed over the course of this design project resulted in an efficient methodology for the development of significantly tactile and thermodynamically interesting physical textures for application to ceramic surfaces. Similarly, by animating the development of these pattern fields through iterative L-systems, a fine degree of control over the pattern density was achieved. Though more traditional manufacturing methodologies with lower expense and shorter individual production time where used, a greater control over quality of the finished object was maintained, suggesting that time tested methodologies for the reproduction of ceramic pieces still offer significant benefits to the lab scale prototyping and development process that newer rapid prototyping techniques may not yet be able to match for iterative material studies, and the production of multiple prototypes.

Separate regions of high-relief were noticed to exchange heat at faster rates and could be reliably identified by observable stepping in 3 to 4ºC temperature increments after reaching stable heat exchange. This is likely a result of the relative difference in the speed of conduction through the additional ceramic material of places of high-relief in contrast to reduced convective exchange in regions of low-relief. This means the exposed peaks began to quickly normalize to room temperature, while less exposed geometries began...
to normalize to the room at a much lower rate where temperatures were reliably different in correlation with material thickness of the surface relief, which could potentially be designed accordingly. In terms of the patterns themselves, differences were not readily observable and additional studies paired with computer modeling will need to be conducted in order to evaluate the effect of switching between the various texture patterns. Lastly, manipulating the controlling surface topology resulted in the modified thermodynamic conditions of a material object; in this sense, the study was also successful in opening up new areas of investigation by applying innovative tools for design and analysis for future research and material studies. Projected back to architectural facades, this presents some significant opportunities as well for new energy systems integration applications that might require reliable temperature differences across the building envelope to employ such a strategy for transient heat propagation, using similar heat transfer principles.

NOTES

1. Hyperobjects are massive objects in scope and distribution in time and space relative to humans (Morton 2013).
2. L-systems were popularized in Prusinkiewicz and Lindenmayer (1990).
4. Karl Chu explored some of the earliest applications of genetic algorithms to 3D modeling for the development of architectural form.
5. The past work with the Emerging Material Technologies Research Group (EMT) at the University of Arizona Best summarized in Vollen (2009).
6. As described by Barlow (2014) in the annual Nexus-NY program publication.
REFERENCES


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Kelly Winn is an Adjunct Professor at Rensselaer Polytechnic Institute and an architectural researcher with the Center for Architecture Science and Ecology. His PhD dissertation focused on the application of digital parametric design optimization and fabrication tools for the performance modification of local climatically adapted architectural ceramic facades. His work with a collaborative team of RPI researchers and local industrial ceramic and tile manufacturers won awards for technical design in at the 2nd Annual BrickStainable Design Competition. His continuing research encompasses the thermo-regulating Climate Camouflage façade system exhibited at the Innovate: Integrate exhibition at the Center for Architecture (AIA New York Chapter), and high-performance masonry system (HpMS) prototypes developed for the Nexus-NY New Energy Xcelerator program in collaboration with Tegula Tile. Before coming to RPI, he received his B.Envd from the University of Colorado and completed his M.Arch with the Emerging Material Technologies program at the University of Arizona.