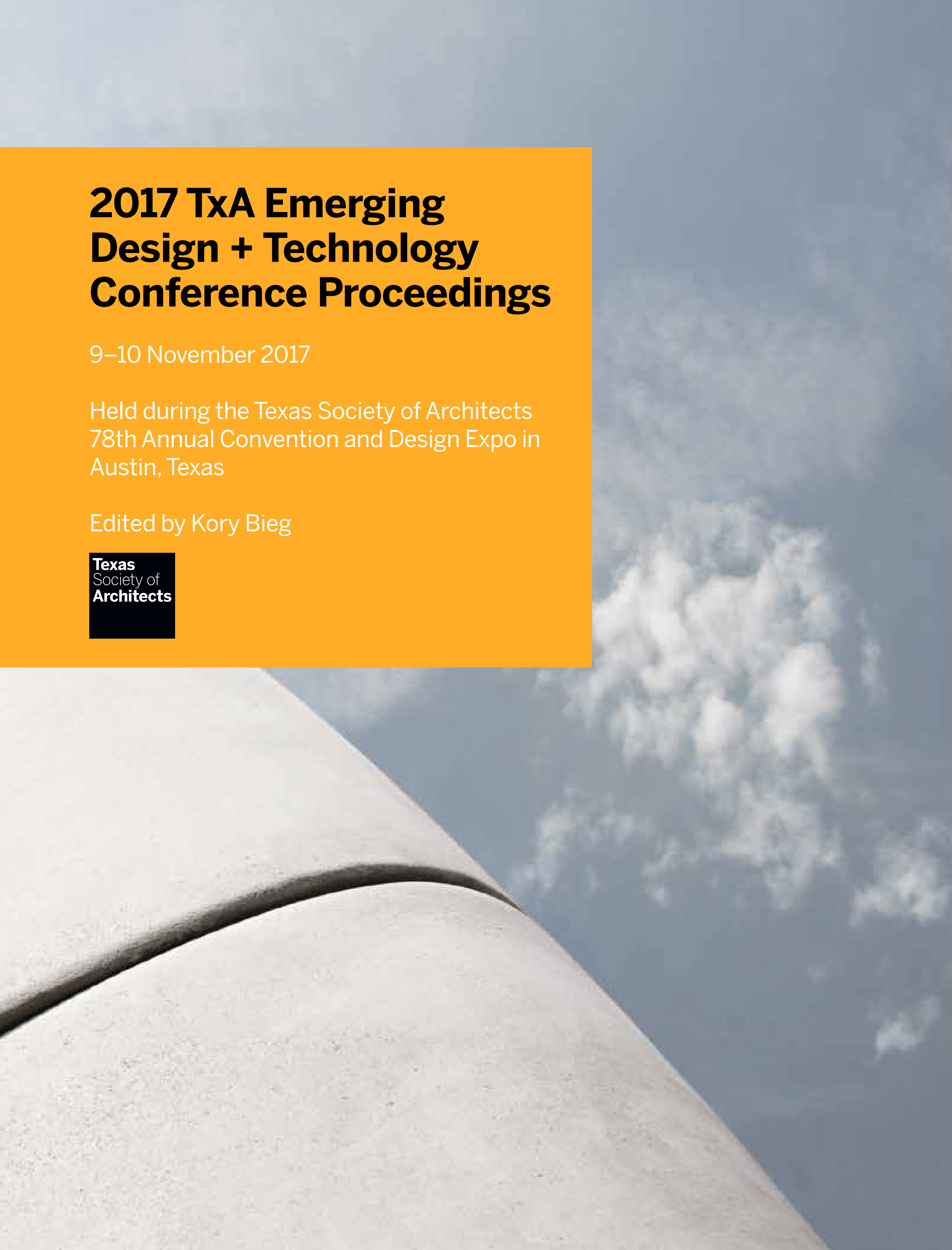

2017 TxA Emerging Design + Technology Conference Proceedings

9–10 November 2017

Held during the Texas Society of Architects 78th Annual Convention and Design Expo in Austin, Texas

Edited by Kory Bieg

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Introduction: The Multi Plication of Data

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Data is the currency of the information age. While we bear witness to this every day in the targeted ads we confront when we open our computers or turn on our smart phones, it is even more invasive and ubiquitous than it seems. It is constantly being produced, stored, duplicated, and exchanged. The challenge of this information surplus is how to process it into something meaningful.

Most of the data we store is not worth the computational power or energy required to classify and organize it systematically. Moreover, the continuous accumulation of data creates an ever-entangling, disconnected web that increases in complexity over time and further complicates any useful distillation. Complication, after all, is the multi-*pli*-cation of various, discrete complexities. And as Greg Lynn notes, "to become complicated is to be involved in multiple complex, intricate connections."[i] Such complexities challenge all forms of systematic organization—even processes that are rote for computers.

The traditional approach to data storage has always been one of classification. But for data to be more useful beyond simple tagging and recollection, one needs to understand its complexity—that is, the various attributes and peculiarities that are specific to and that might not be easily defined by a single category. Furthermore, data is rarely static, and as information changes over time, it further defies conventional cataloguing logics. The key to unlocking its usefulness is to sort data using new methods that allow previously disconnected information to co-mingle and form connections across categories. Such strategies provide constant feedback as data mutates and transforms. Who knows what will emerge from these new mixtures, and that is exactly the point.

In his book *Radical Technologies*, Adam Greenfield notes:

> *Most of the world's data—and virtually all that's germane to systems that operate in physical space and in real time—does not happen to reside in the neat tables or crisply cellular structure of any databases, and never will. So the new way of handling such situations is to look for emergent patterns in previously unstructured data, like a large body of text, a series of images, or indeed a real-time video feed…As they are iteratively resolved in ever higher fidelity, the patterns themselves begin to suggest the questions that might be asked of them.*[ii]

The papers from this year's TxA Emerging Design + Technology conference all tackle this theme in one way or another. The challenge facing contemporary architecture practices is not how to collect and organize data, but how to sift through large amounts of disparate things, bring new connections to the fore, and then to figure out what to do with them. This new frontier of information-based design unlocks hidden narratives and sheds light on the unrepresented. These new combinations can break boundaries, collapse hierarchies, and set up design possibilities that traditional classification techniques would never allow. As these papers prove, once data is free from its categorical shackles, these revelatory discoveries can inform new materiality, promote social agendas, and increase disciplinary overlaps. We can recover a generative and creative intelligence in data that has been buried up until now.

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i. Greg Lynn, "Architectural Curvilinearity: The Folded, the Pliant and the Supple," in *Architectural Design 63: Folding Architecture* (London: Academy Editions, 1993), 27.
ii. Adam Greenfield, *Radical Technologies: The Design of Everyday Life* (London: Verso, 2017), 211.

Informed Performance: Probabilities and Speculations in Architecture

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ABSTRACT
The pairing of speculation and physical testing informs the probability of material behavior in architectural surfaces and entities. This paper investigates the nature of an iterative design process that utilizes simulations and empirical testing to co-evolve a full-scale research prototype. The paper argues that simulation technologies have accelerated the ability to speculate the behavior of surfaces and entities while testing provides analysis, increasing the potential to evolve the design because the feedback loop provides information intimately tied to formal, spatial, organizational, or environmental aspects of a project. The acceleration allows the design to quickly iterate and empirically test the speculation in order to develop a family of options for the designer to compare, analyze, and then choose the iteration most suited to the broad range of issues involved in any project. The paper traces the design process for the research creation project "Klimasymmetry," which flickers back and forth between speculation and physical testing in order to investigate how the pairing of simulation technologies and prototyping informs the design process. Specifically, the project investigates the nature of the architectural surface's ability to generate a thermal environment, which requires methods to predict and test the behavior prior to fabricating a full-scale operating prototype. The thermal environment is generated by a custom heating and cooling radiant panel system in the prototype for empirical testing, which was used to compare to the digital simulations.

INTRODUCTION
The dialogue between digital simulations and empirical testing in architecture provides a critical link between speculation and material behavior, which suggests the degree of probability that the final built entity will act as predicted. This dialogue is enabled by the proliferation of information technologies into the design studio, which has resulted in two related impacts. The first is that the acceleration of generating iterations, when coupled with the ease of creating digital simulations for each iteration and quick prototyping of physical elements, provides a series of potentials to compare, cross-analyze, and make informed decisions about the evolution of the design proposal. The second impact is the increased ability to visualize complex data about a wide range of

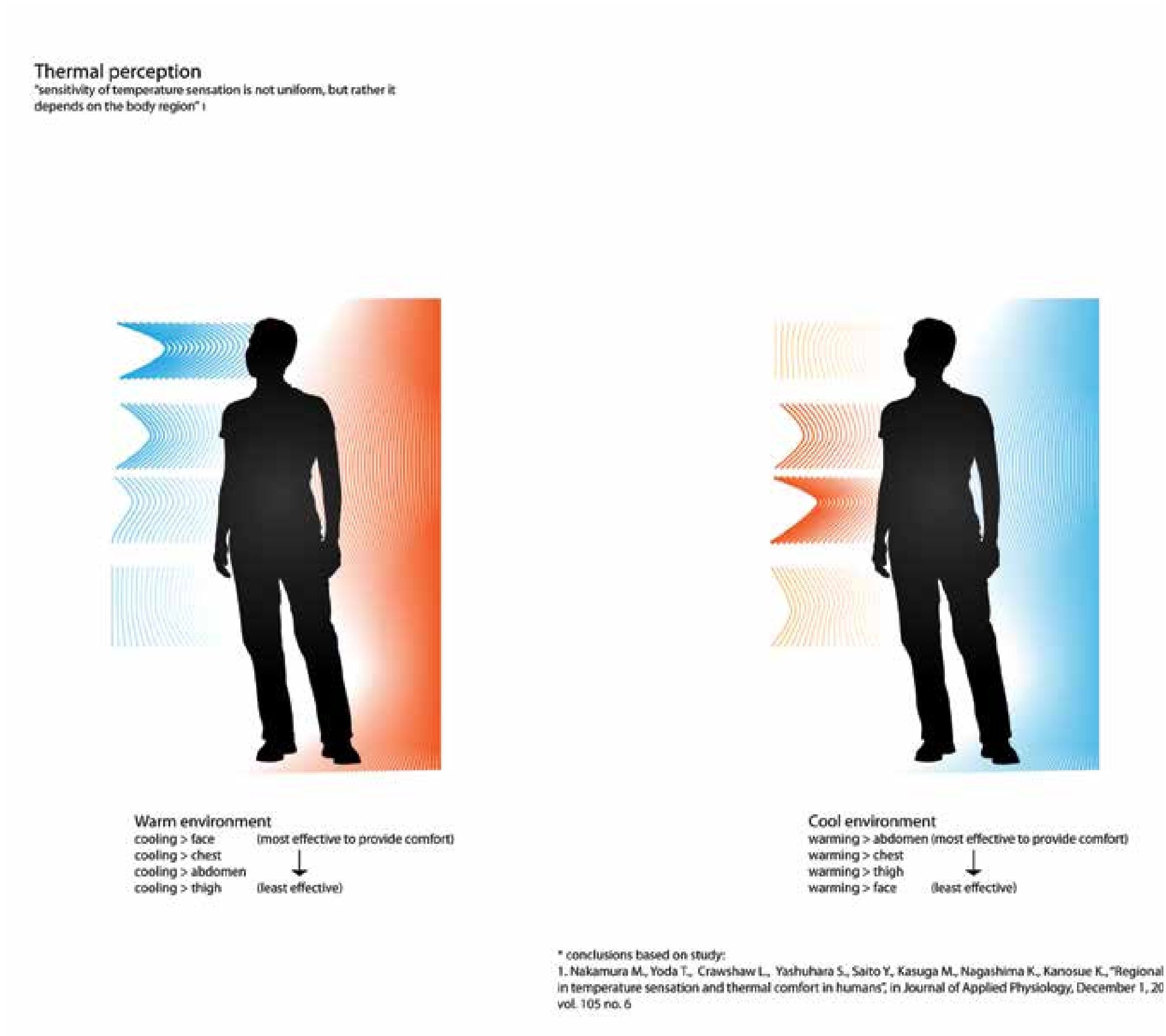
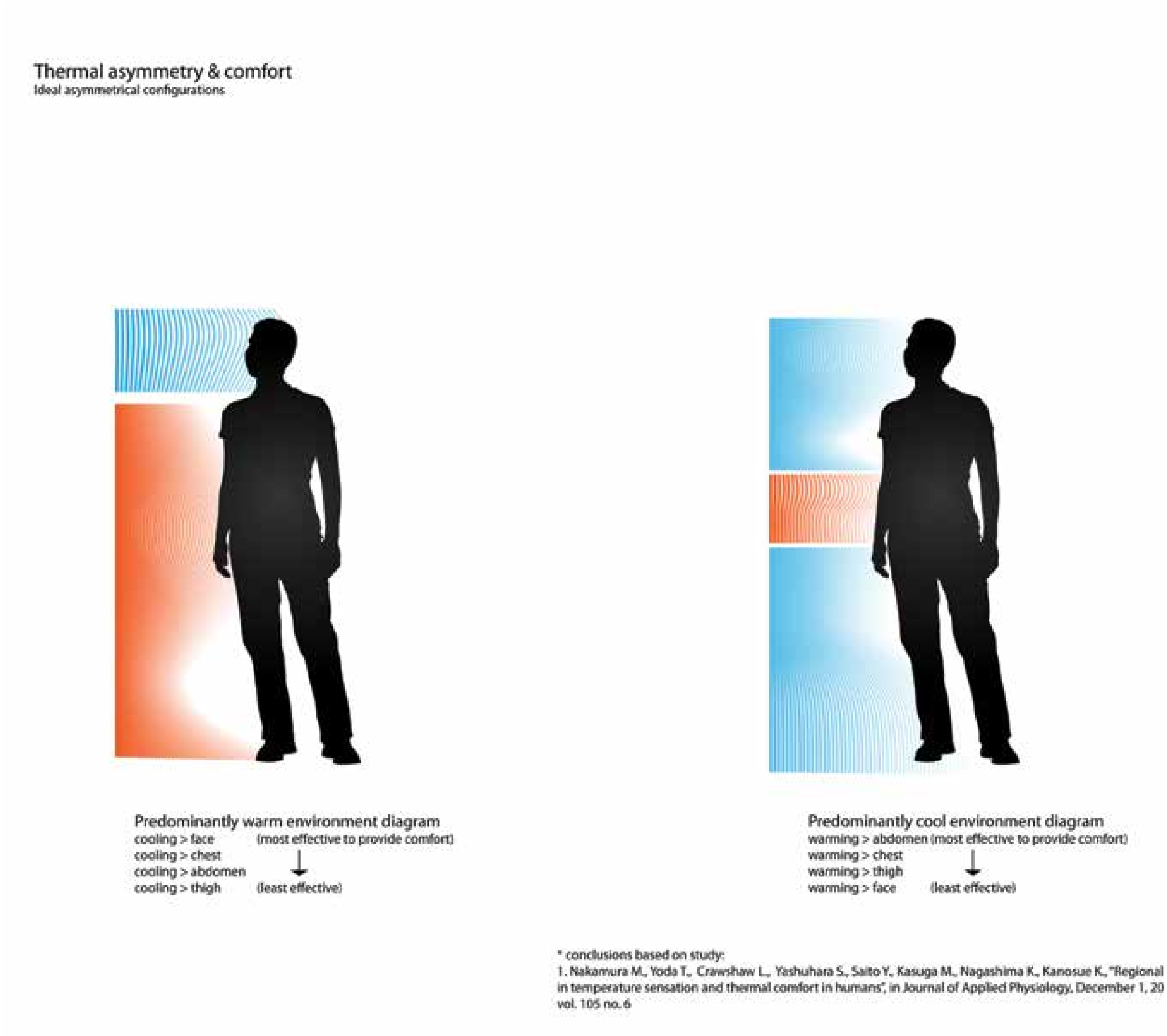


Figure 1: Physiological perception of thermal comfort in warm and cool environments.

phenomena associated with the technical performance of buildings. These two impacts are investigated in the research creation project Klimasymmetry, where the intimate relationship between speculation and empirical testing was investigated in order to discuss the reciprocal transfer of knowledge between behavior and form. The project addressed the speculative-testing relationship with two main goals. The first goal of the research was to closely link the formal speculation of designing the architectural surface with its behavior, which can be perceived via the physiological thermoreceptors of the people who occupy the space near the panel system. The second goal was to investigate the nature of visualizing non-visual phenomena through digital simulation technologies and physical thermal measurements.

The link between form and behavior was initiated through speculation based on thermal physiological research. Thermal perception is subjective, yet there are patterns of similar behavior in people based on age, gender, and the climate they inhabit. In particular, there are similar patterns in the way people perceive thermal comfort across different regions of the body. People do not perceive thermal comfort evenly across their skin; rather, it varies per zone relative to the immediate thermal context.[1] According to physiological research, the main zones of the body's thermoreceptors can be classified as the face, chest, abdomen, and thighs. The order of importance in which people are "more sensitive" to "less sensitive" according to thermal change varies relative to whether the surrounding context is warm or



cold. For example, in a cold context, thermal comfort is most effective when heat is applied to the abdomen, followed by the chest, then thigh, and finally the face. The hierarchy of body zones rearranges when the context switches from cold to warm. In a warm context, thermal comfort is achieved when cooling is applied to the face, followed by the chest, then abdomen, and last at the thigh (fig. 1).[2] The physiological study reveals that the link between the geometric location of where thermal conditions emanate can be linked to the physiological location of sensory receptors on a person's body.

The geometric location of thermal zones from the physiological study spatializes thermal conditions, providing distinct regions to design thermally active surfaces in relation to the people occupying the surrounding space. The guidelines for locating the thermal zones provided enough information to speculate on the surface geometry for the radiant heating and cooling panel system. The panel system was designed to be compact and approximately the scale of a human, and thus needed to generate its own thermal environment. The panels were divided into two thermal behaviors: warm and cool panels. One side of the object created a primarily cool environment by having a majority of surface area dedicated to cool panels, while the other side created a primarily warm environment with more surface area for warm panels. Radiant heat transfer is more effective as the surface area increases; thus, generating a distinctive thermal environment requires assigning a majority of the surface available to either radiate heat from warm

Figure 2: Geometric location of the cool radiant panel system in a warm environment and warm panel in a cool environment, according to the human body.

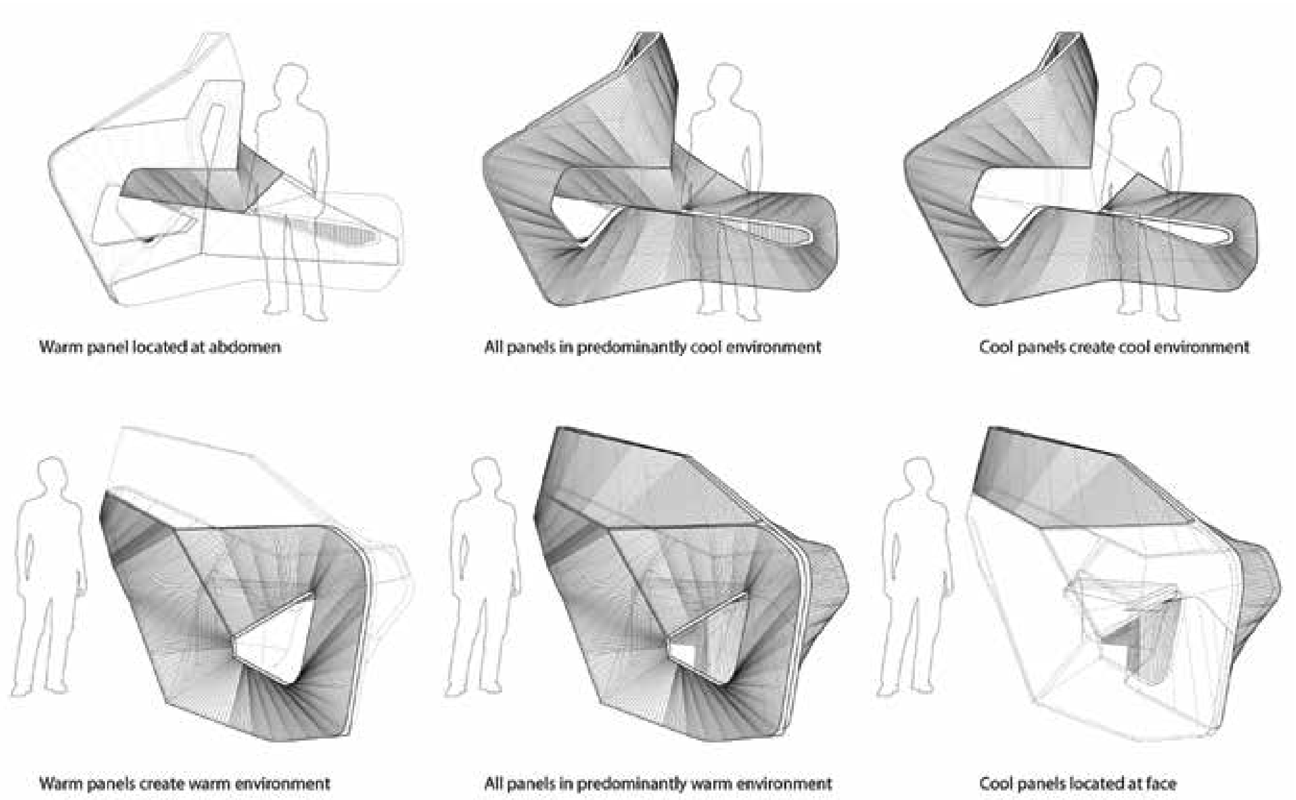


Figure 3: Large surface area creates a warm or cool thermal environment with strategic insertion of opposing thermal panel, according to the physiological analysis.

panels or absorb radiated heat from occupants with the cool panels. Maintaining a relationship to the physiology of the body's thermoreceptors, in a warm context cooling is most effective at the face, while in a primarily cool climate, heating is most effective at the abdomen (fig. 2). Therefore, informed speculation about the geometry of the panel surfaces locates a warm panel at the abdomen in a primarily cool environment, while a cool panel is located at the height of a person's face in a warm environment (fig. 3).

The second goal of the project was to examine the nature of visualizing non-visual phenomena through the generation of images. Thermal conditions are ever-present in our designed environments but usually so subtle that we rarely pay attention to them, unless they stray away from ASHRAE standardization.[3] Thermal conditions are usually only investigated in design for functional efficiency or standard levels of comfort but present a rich opportunity to be examined for their ability to inform spatial, organizational, and formal design potentiality.[4] The perception of thermal conditions is usually only noticed when there is an imbalance, and as such, it is usually seen as a problem to be corrected. Thermal conditions are dynamic and unstable, which challenges the Vitruvian notions of architectural elements providing stability. This unstable force that is ubiquitous in our environment is further distanced from traditional notions of an architectural material because it is non-visual. The predisposition in architecture toward surface, form, and texture favors light as an environmental variable that has legible tectonic behavior because the effects are visible and reinforce those traditional systems. The theoretician Michelle Addington argues that thermal conditions within the built environment are inherently spatial and thus as architectural as any other building component.[5] Therefore, how can thermal conditions be rendered to reveal their tectonic capacity?

The complexity of the fluctuating flows of thermodynamics requires a means to visualize the data to allow designers to recognize patterns of behavior. The need to synthesize complex phenomena through visualization is similar to the American scientific historian Peter Galison's description of the tension between data visualization and the mathematics of pure science in the way images are used in the sciences. On one hand, the scientific community is faced with the need for images because they create descriptions that words or numbers cannot provide, relying on our ability for pattern recognition for comprehension. On the other hand, there is the scientific community's rejection of images because they forego the abstraction of a logical and rigorous non-intuitive reasoning that is revealed in mathematics.[6]

In the case of understanding the behavior of building systems, simulation technologies provide the means

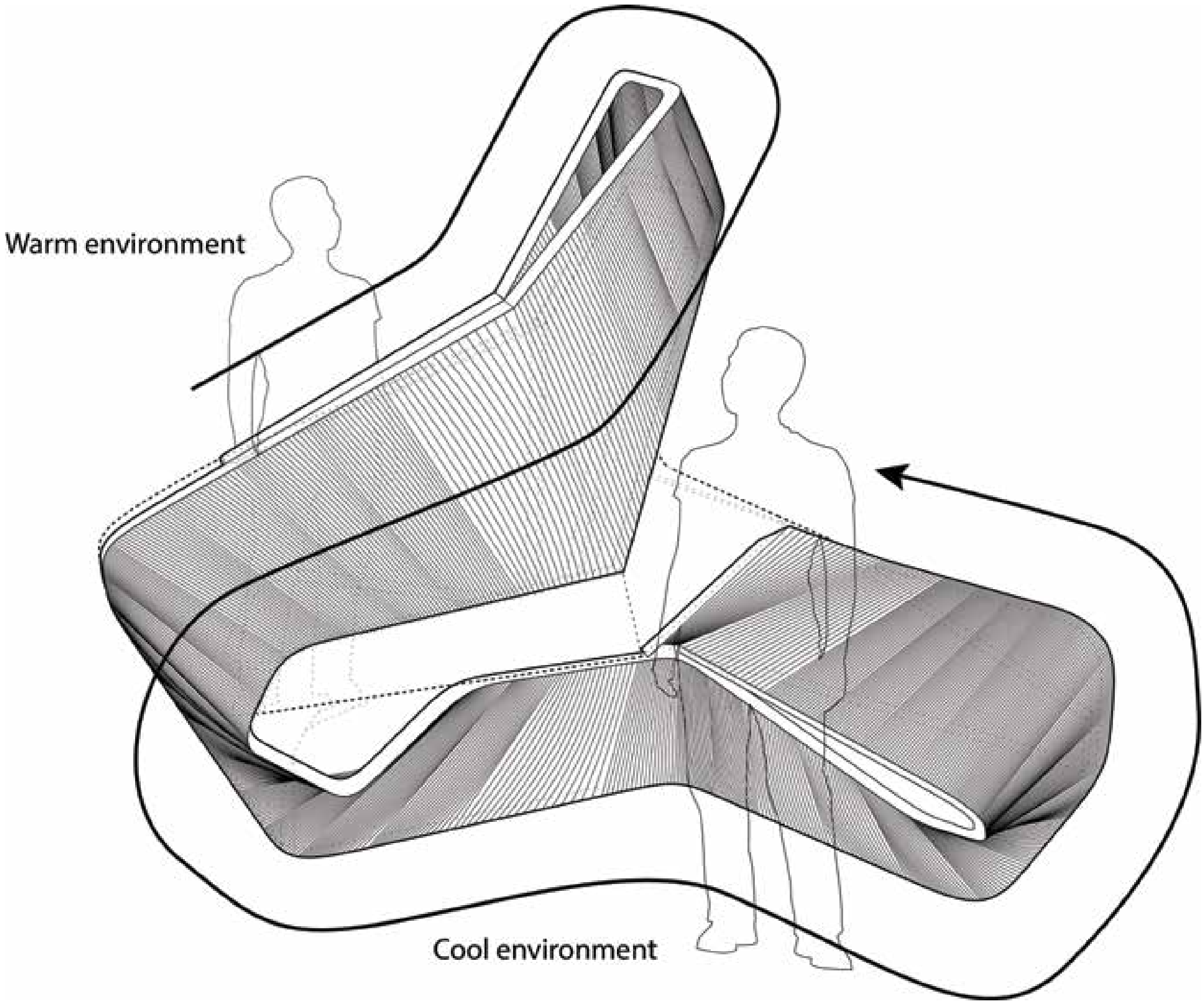


Figure 4: Continuity of thermal panel surface from one side of object to the other.

to visualize non-visible information. The generation of images to communicate these dynamic behaviors is crucial for architects that tend to prioritize visualization over mathematics or language. Computational fluid dynamics visualizes data from thermodynamic digital simulations, which generates images where pattern recognition is easily identifiable. It is the literalness of the images produced through simulations that reveals the probable behavior of the proposed surfaces. The generation of images through simulation is compared to the visualization of non-visual thermal information from physical prototypes via an infrared camera. Empirical testing provides the opportunity to understand the actual material behavior against the simulated prediction. Thus, the design process evolves through the comparison between the speculative simulation and testing of physical prototypes.

METHODOLOGY

The design process in the Klimasymmetry project can be defined as a back-and-forth between speculation, material experimentation, simulation, and empirical testing. This flickering movement through a series of iterations generates information that is brought forth to the next step. At the outset, there were several predetermined constraints, including that the general size of assembled panels would be similar to the scale of a person in order to provide potential positions of thermal surfaces from head to toe. The size equivalency to a person provides a range of variable geometries to be iterated while creating a compact object that generates two different primary environments. One side of the object created a primarily warm environment and the other a primarily cool one, in order to create the opposing thermal conditions to test for perceived thermal

Figure 5: Material prototypes with variable density of hydronic tubes.

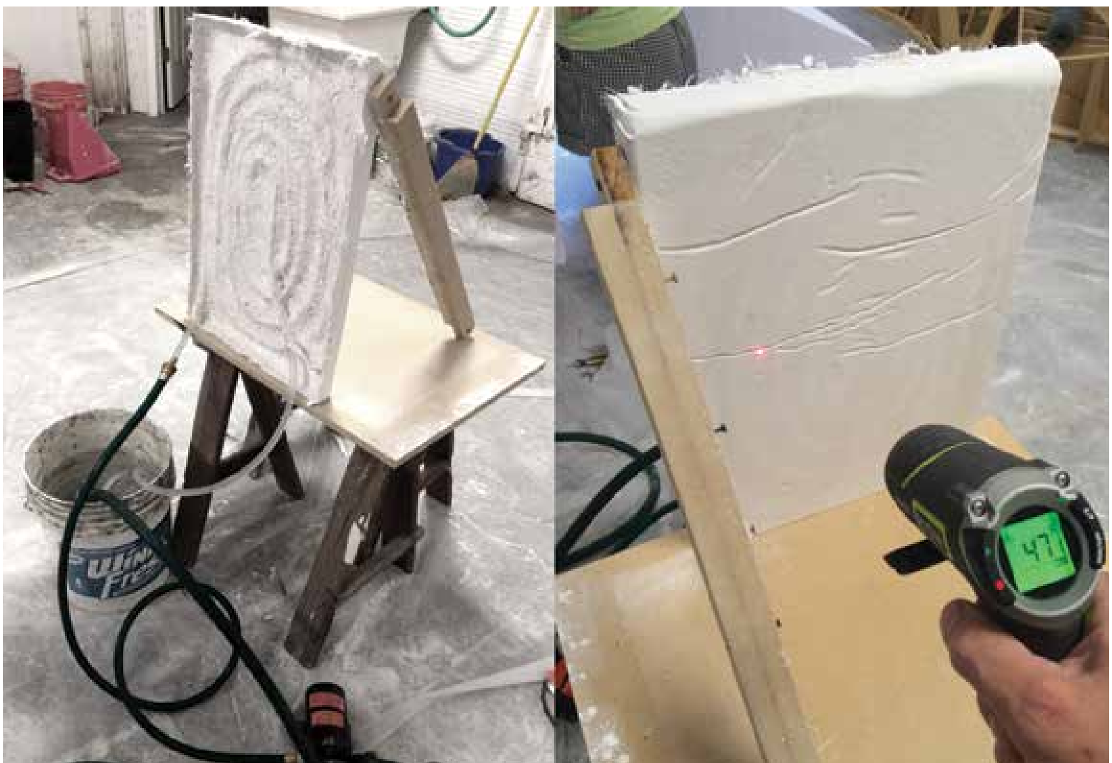


Figure 6: Infrared measurements running thermal tests of hot water circulating through the panel (measurement in Fahrenheit).

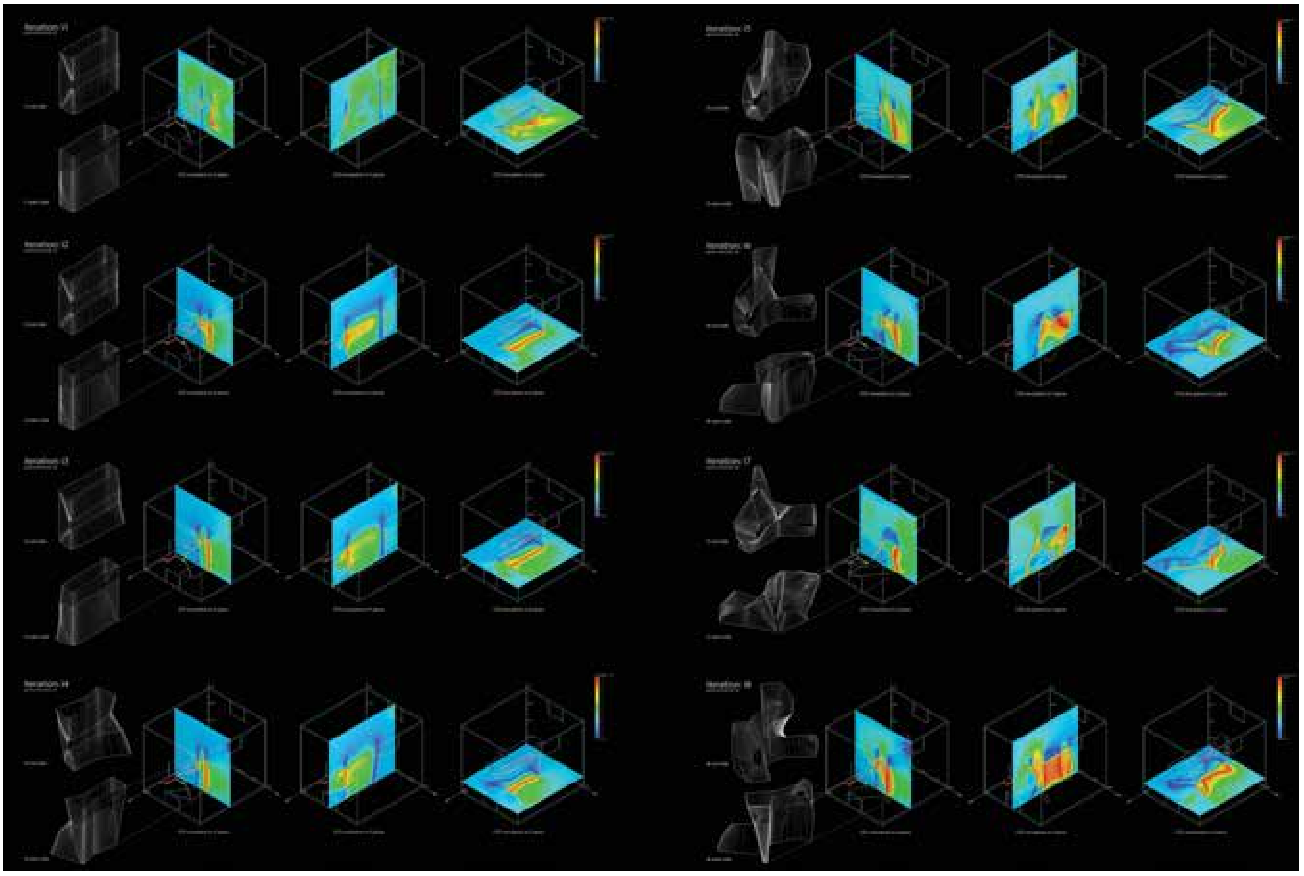


Figure 7: Design iterations and CFD simulations.

comfort. The method of providing heating and cooling was hydronic tubes embedded into the surface of the panel system, due to the efficacy of water at transferring heat. In order to form a continuous flow for the water in the tubes, the surfaces were linked serially. The implications of the continuity of flow between one panel and the next is the continuity between the panel geometry. The result is the appearance of one continuous ribbon surface for warm panels and a second for cool panels that wrap around the object (fig. 4). In order to create a warm environment, a majority of the surface area would need to be warm panels and the opposite true for the cool side. As the warm ribbon surface wraps around to the other side of the object to the primarily cool side, the surface area of warm panels needed to be drastically reduced so that the cool panels could have greater surface area to generate the cool environment. Thus, the same condition was determined for the cool panels: their surface area would decrease once the ribbon transitioned to the warm side. The asymmetrical distribution of the panel surfaces and thermal behaviors created a hierarchical thermal condition on either side of the object where the opposing thermal panel would provide thermal comfort. The specific geometry of the cool and warm ribbons, as well as the surface area for each, varies per design iteration.

In order to discover the thermal properties of the radiant panel, a series of material prototypes were developed (fig. 5). The material selected for the panels was gypsum, which was determined according to its ubiquity in the built environment as a way of proposing a radiant heating and cooling system that could be integrated into interior environments easily. The ability to form the panels to any geometry led to the use of Glass Fiber Reinforced Gypsum (GFRG), which can be easily sprayed into a form. Embedding a continuous hydronic tube into the GFRG thermally activates the panel. The spacing of the tube in the panel affects the efficacy of the gypsum to absorb heat; thus, a series of prototypes with variable density of hydronic tube testing was created to test and determine the thermal property for the panel system (fig. 6).

The operating temperatures of the empirical tests were input into the digital model in order to simulate a series of iterations that explore the implications of form on the surrounding thermal environment. The variations explored include different ways to wrap the panels from one side of the object to the other. This includes varying the surface area and thus adjusting its ability to radiate heat. The general rule of radiant surfaces is

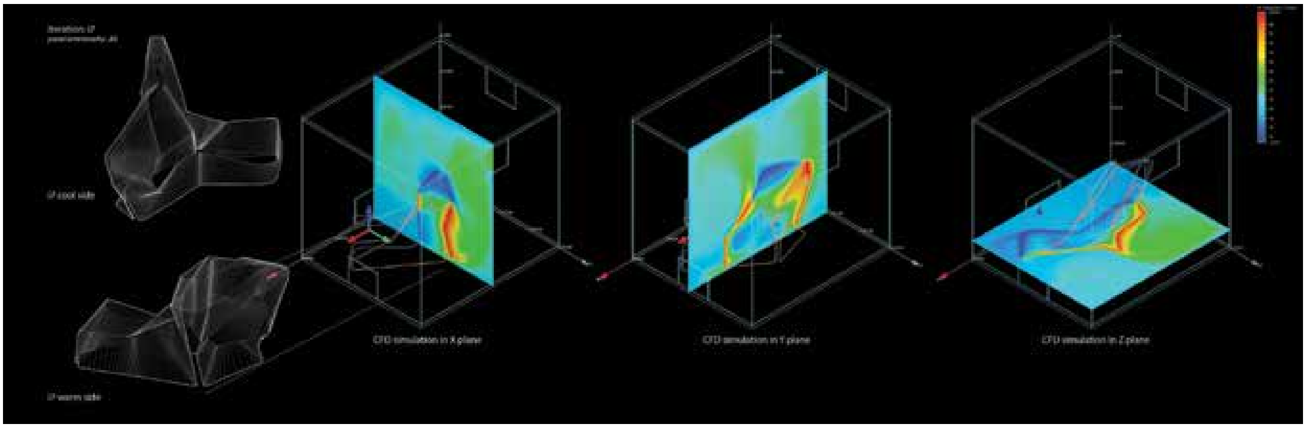


Figure 8: Enlarged view of the CFD simulation for the selected iteration.

Figure 9: GFRG spraying.

that the greater the surface area, the more effective it is at heat transfer. The first iteration started with a simple form replicating the general rules of geometric location according to the zones of perceived comfort from human physiological thermoreceptors. Subsequent iterations explored the effects of increasing the surface area of one temperature and decreasing the surface area of the other. In addition to surface area, topological conditions were introduced to inflect the panel to start to subtly bend around occupants. As each generation was modified, it was simulated using computational fluid dynamics. The simulation analyzed radiant heat transfer between the panels and the surrounding floor, wall, and ceiling enclosure, as well as convective air flow. The surrounding room enclosure was consistent in size and assumed to be concrete material with an emissivity of .63. The gypsum panels were assigned an emissivity of .85, where the heating panel was assumed to have a temperature of 105 degrees Fahrenheit while the cool panels had a temperature of 55 degrees. Due to the intensity of simulation time, a limited number of iterations were developed (fig. 7). The iterative design process was not attempting to resemble optimization, but rather searching the range of limits and providing a family of options to compare, filter, and discover patterns of behavior. Ultimately, iteration seven was selected as the one to advance into the prototype phase because the panel topology showed the creation of two distinct thermal environments that could balance the opposing thermal panel (fig. 8).

A single full-panel prototype was developed for empirical testing. The plasticity of gypsum when sprayed as GFRG allows it to form the topology of the digitally fabricated frame with tensile fabric surface. Since the final prototype object comprised of the panels is relatively small, the goal was to have them self-structured. Therefore, the glass fibers helped to stabilize the panel as the hydronic tubes were embedded within the GFRG panel.

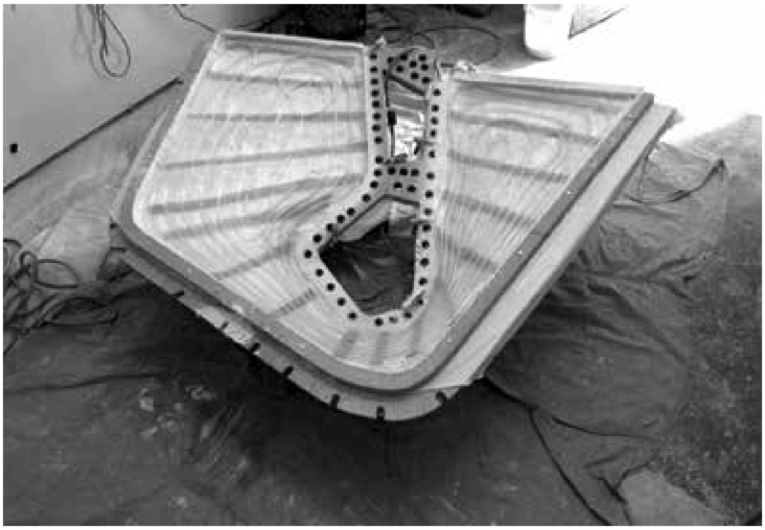


Figure 10: Hydronic tubing laid in.

Figure 11: Embedded hydronic tubing in GFRG.

Figure 12: Heating system.

The specific gypsum used in the panels is Hydrocal gypsum cement, which has a high yield strength, fast curing time, and, when combined with the glass fibers, good thickness-to-strength ratio. The fast curing time allows the panels to be quickly fabricated, laminating several layers together and embedding the hydronic tubes. The workability of the material prefers to be applied in a horizontal orientation and minimized vertical surfaces. The application of GFRG can be poured, but for an even distribution to create a consistent panel thickness, it was sprayed from a hopper gun with an air compressor. One-inch chopped glass fibers were distributed on the surface during the spraying process to ensure random orientation of the glass strands (fig. 9). Several layers of gypsum and glass fiber are laminated to achieve a minimal thickness of ½", but also thick enough to fully embed the ½" hydronic tubes (figs. 10 and 11).

The radiant panels were supplied with hot water from a small water heater and water pump designed for radiant heating and cooling systems. The pump continuously circulates the hot water through the warm panels (fig. 12). The cooling system operates in a similar way with the water pump circulating the cold water, except that the heat was removed in a small chilled water tank housed inside a refrigerator/freezer. The first panel was fabricated, connected to the heating and cooling system, and measured using an infrared camera (fig. 13). Following the single-panel test, the remaining panels were fabricated and assembled into the final prototype. The system was allowed to operate for one hour to ensure that the warm panels were no longer absorbing heat while the cool panels found a stable temperature. An infrared camera recorded thermal images around the prototype in operation.

RESULTS

The back-and-forth repetition of the iterative process between simulation and testing generated a collection of potentials that were analyzed together to reveal several patterns of behavior. The efficacy of the thermal context was related to how a person is able to perceive the opposite thermal condition at the physiologically most effective location. All iterations generally located the warm panel around abdomen or chest height in a cool environment while they also generally located the cool panel near head or chest height in the warm environment. The specific location, topology of the surface, and quantity of area varied per iteration. The series of iterations and the patterns of behavior in the simulations revealed that when the surface wraps around a space, it is more effective at creating either the warm or cool environment. Between the two environments, the simulations showed that the warm radiant panels had greater effect on the surrounding context than the cool panels.

The development of the final physical prototype allowed the ability to compare the speculation of the simulation of the selected iteration against the final built entity. The infrared thermal camera was used to record a series of images around the prototype. The camera used did not have the ability to set a standard range for the false color mapping, so the visualization varies per image. The camera was able to record the surface temperatures and localized surface conditions, but not the air temperature around the panels (figs. 14–16). Therefore, the infrared camera was not able to give the same level of feedback as the simulations predicted. The imaging was able to reveal that the physical prototype was more effective in heating than in cooling because the panels were able to maintain a high temperature (between 90 and 105 degrees Fahrenheit) in the heating panels compared to the cooling panels. This is related to

Figure 13: Single-panel prototype thermal test measured with infrared camera.

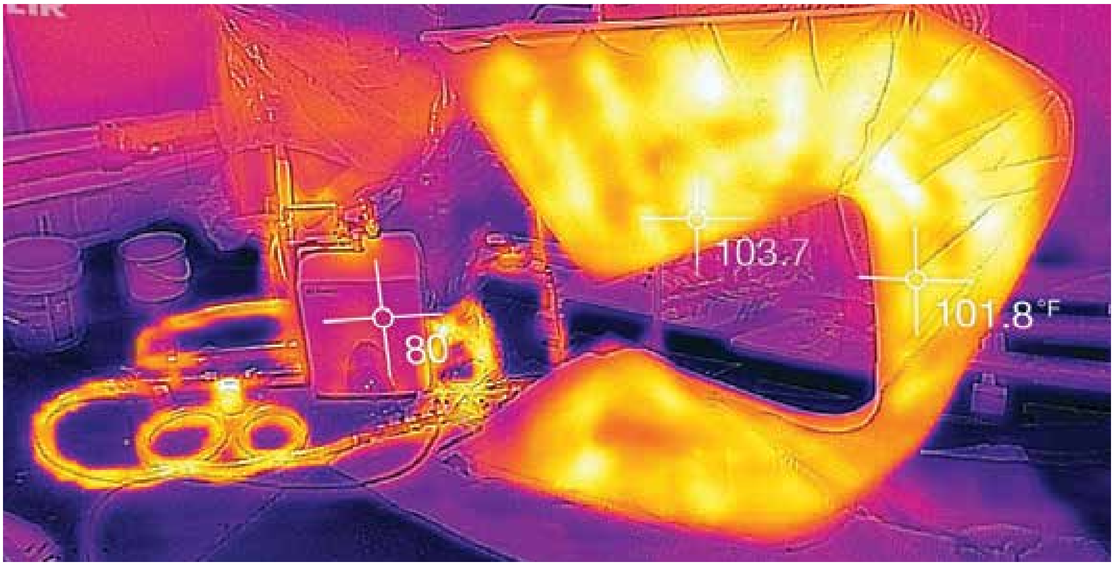


Figure 14: Cool side of the prototype (left) and infrared thermal imaging (below).

the cooling system, which was able to maintain a cold surface of 62 degrees Fahrenheit. This surface temperature was less than predicted in the simulations. A larger cooling system would be needed to maintain a cooler surface temperature.

DISCUSSION

The nature of thermal conditions is complex, and it is difficult to associate the invisibility of the phenomena with the design of the architectural surfaces that radiate heat or absorb it. Simulations and empirical testing helped to predict the potential impact the geometry and surface area had on the space surrounding the panels, providing a more informed speculation on the development of form and performance. The experiment avoided being overly deterministic by utilizing not an optimization algorithm, but rather a more informed process of co-evolving form and behavior. Focusing on the nature of an architectural surface made the behavior of a non-visible phenomena visible through the formal geometry as the initiator of the thermal environment. Synthesizing the entire investigation from design to prototype revealed that the speculative design decisions about the form seemed correct, but running the simulations and testing physical prototypes provided valuable feedback on the speculation. The knowledge was generated through a design process that flickered back and forth between speculation and testing to promote a deeply embedded relationship between form and performance.

With the rise of information technologies in the design studio, various notions of performance-oriented architecture have developed. The term "performance" can have a wide range of meanings, from visual expression to analysis, to modes of production and operation.[7] Upon investigating the nature of performance in the design process, it would be reductive to limit the term to either the making of form as image-based or deriving from utility as stated in the idiom "form follows function." With the influence of information technologies, the ability to fold in additional parameters such as technical utility into form generation begins to challenge the hierarchy of either function or form. Rather, the conception of the architectural entity is more nuanced and complex, synthesizing image and behavior. The theoreticians Eran Neuman and Yasha Grobman coined the term *Performalism* to incorporate both technical optimization and perceptual aspects of form as figure.[8] Rather than the dichotomy of form versus function, Performalism

Figure 15: Warm side of the prototype (right) and infrared thermal imaging (below).

seeks to consolidate the two within the process of generating the architectural object. Predicting technical utility in the design process relies on analysis, and, with the influence of information technologies, this often translates into the employment of simulations. Branko Kolarevic and Ali Malkawi discuss the interrelation between performance and design practices as "blurring the distinction between geometry and analysis, between appearance and performance." [9] This blurring has an impact not just on the how buildings operate, but on the way forms are conceived. The practitioner and theoretician Michael Meredith traces the development of a formalist approach to design and the influence of analysis and simulation on the profession. He describes how "in the last few years, formalism went from geometry-as-god to performance-as-god. If Eisenman would say, 'The logic of geometry made me do it,' today people would say, 'The sun angles made me do it.'" [10] As a critique, Martin Bechthold discusses how engineering has long been using performance-based analysis for optimization, while it is only within the last few decades that architects have been exploring performance in a very broad manner and often as a way to justify form.[11] Rather than seeking an alibi for form, performance collaborates with expressive aspects through a speculative and analytical design process that quickly evolves the architectural entity through *informed performance*.

CONCLUSION

The Klimasymmetry research project was a nascent investigation into understanding the nature of thermal surfaces that evolved from collaboration between formal expression and performative behavior. The iterative design process provided feedback between speculation and analysis that made it possible to visualize what are typically non-visual phenomena. The ability to predict and measure thermal conditions and rendering with spatial implications increases their potential to become architectural materials used in design with an importance similar to that of walls, windows, or floors. Thus, the inclusion of architecture's soft, dynamic environmental elements expands the possible mediums with which to design. While the feedback between simulation and empirical testing will increase efficiency and predictability, the opportunity to open new territory for conceptual exploration has greater potential to impact the architectural profession.

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Figure 16: Transition from cool side to warm side of the prototype (left) and infrared thermal imaging (bottom).

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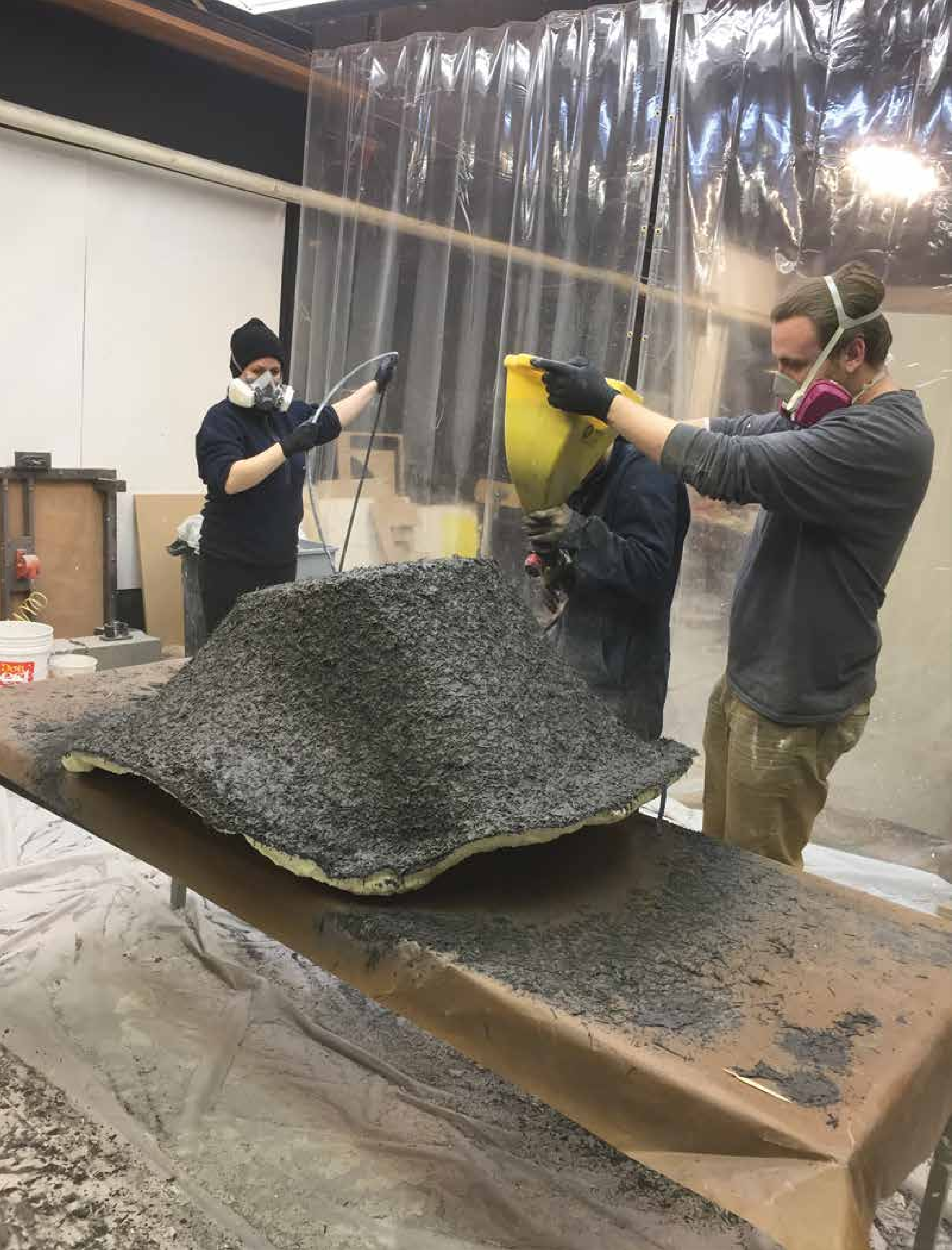

Thermoplastic Concrete Casting

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ABSTRACT

Thermoplastic Concrete Casting explores molding techniques for glass fiber reinforced concrete (GFRC) using non-woven thermoplastic textiles. Casting in concrete typically requires extensive formwork that takes time, material, and a significant amount of labor to produce. This project experiments with a novel way of creating formwork quickly for casting, while eliminating heavy, rigid molds and scaffoldings for support. Incorporating sartorial techniques borrowed from tailoring and patterning in clothing production, the textile is cut and felted together (a process of needle punching where fibers of the textile are entangled together), then heat-stiffened over a rigid frame, ready for GFRC casting.

Thermoplastic Concrete Casting attempts to integrate what otherwise are disparate areas of research — from computational design for developable surfaces using physics-based modeling software (Kangaroo plugin for Rhino/Grasshopper) to formal and performance testing of GFRC, to research and development of molding techniques with non-woven textiles. The prototypes produced are explored at two scales: first, at an object scale, with the reproduction of Eames' molded fiberglass armchair and Saarinen's Womb Chair, both in concrete, and second, at an architectural scale, with the installation of an 11' X 7' wall composed of five modules with an adjoining table surface. The full-scale wall not only tests the structural conditions related to joining discrete panels together without a framing system, but also the formal, spatial, and experiential effects through the design of exaggerated open-ended funnels as apertures through the wall. Beyond proof-of-concept, the project attempts to seamlessly integrate digital design and fabrication processes into textile concrete casting and to challenge typical casting techniques in service of novel design possibilities.

1 INTRODUCTION

Casting concrete is one of the most labor-intensive processes for building, often covering a large portion of the project's overall cost (Lab 2007). Beyond the time, material, and physical labor involved in building the formwork for casting, the formwork itself is already invested with intellectual labor by specialists ranging from structural engineers to concrete technologists that work with mixes, addressing specific applications and loading conditions. As such, the 'craft' of concrete casting is involved on all fronts. While prefabrication has made the use of concrete more cost effective and time efficient, developments in tools and techniques are reconfiguring the ways in which formwork is produced for shaping concrete. This project seeks to form concrete through non-traditional methods by exploring the use of thermoplastic textiles as formwork for casting glass fiber reinforced concrete (GFRC).

Thermoplastic (as opposed to thermoset) polymers undergo a reversible transformation from solid to liquid when heated. The non-woven thermoplastic textile used (trade name Fosshape) comes in two weights: 9 and 18 oz/yd. The textile, similar in texture and thickness to felt fabric, has typically been used for sculptural works or costume design. The material can easily be cut and sewn together like any fabric. But when heated with a steamer or heat gun, it shrinks and stiffens into a three-dimensional form. This unique characteristic of the material (heat-shrinkage) provides opportunities for both manual and digital investigations.

Employing techniques of tailoring and pattern making for clothing production, the project makes use of developable surfaces to transition between 2-D and 3-D to explore complex surface geometries. The cross-disciplinary link between the sartorial process of patterning and architectural modeling/formal investigation is the concept of developable surfaces whereby complex surface geometries could be rationalized to flatten into 2-D patterns. For clothing, patterning address how the 3-D shape of the body, especially a double curved form, could be fattened into patterns for textile cutting. The cut patterns, typically based on formal efficiency (least number of cuts for sewing), is then assembled with different types of seam structuring either based on performance or for aesthetic purposes. For architecture, developable surfaces enable complex geometric surfaces to be unfolded into a flat pattern that could be cut out of sheet material. The cut material could then be assembled, much like clothing production, into 3-D form with seam structuring considerations. *Thermoplastic Concrete Casting* takes advantage of these concepts and techniques for 2-D and 3-D translation in working with the thermoplastic textile. Computational tools are employed through physics-based modeling techniques that simultaneously allow for constraint-based design and analysis, especially in predicting the effects of the shrinkage of the textile as well as seam structuring. Working computationally and heuristically, the project developed through a series of prototypes, testing different techniques and processes for textile formwork making for casting with GFRC.

One of the proposed advantages of this approach is that complex geometries such as double-curved surfaces can be efficiently created, stiffened, and sprayed with GFRC (instead of relying on subtractive processes such as CNC milling or hotwire cutting to achieve complex geometries). The exploration includes not only the development of form-finding techniques in relation to patterning and seams, but also the addition of secondary stiffening material (such as polyurethane foam) to the surface to aid in prepping the mold surface. Felting techniques were employed to join discrete panels of

Figure 1: Overall view of installation with chairs and wall.

non-woven textiles together. Felting is a binding process whereby barbed needles punch through layers of non-woven material, entangling the fibers together. This process of binding does not require the addition of sewn threads or adhesives. The exploration of *Thermoplastic Concrete Casting* takes advantage of these concepts and techniques as molding processes, enabling the textile formwork to be:

- more lightweight and easier to handle;
- folded up for compact shipping (before the textile is heat treated);
- produced substantially faster than milling or other subtractive processes; and
- produced from significantly less material volume.

As such, this project is an experimental project about formwork making that also aims to further the integration of computational technology (of software and fabrication processes) in building practices that might challenge conventional ways of casting in concrete.

The outcome of this project was tested at two scales: one at object scale, which included a reproduction of the Eames molded fiberglass armchair and Saarinen's Womb Chair, and second, at architectural scale, with the installation of an 11' X 7' wall composed of five modules with an adjoining table surface. Working at the object scale initially enabled a familiarity to be developed in working with the textile. This knowledge was then developed further into a computationally based simulation of the material's characteristics to then design the larger-scale wall system. The following sections of this paper describe the techniques and processes, as well as the final documentation, of the project installed for an exhibition in March 2017 at the Liberty Research Annex Gallery, Ann Arbor (fig. 1).

2 BACKGROUND

The research and development of *Thermoplastic Concrete Casting* stems from three core areas that are interrelated: fabric formwork and the development of processes for casting concrete; complex geometries of developable surfaces; and non-woven textile manipulation (felting). This unique combination is possible given the alignment of contemporary digital technology available for architectural production and the availability of affordable materials for experimentation, in this case, of thermoplastic textiles and GFRC.

2.1 Textile in Architecture and for Concrete Casting

Textile in architecture is mostly relegated to interior surface applications. It lacks the structural capability that rigid materials offer for building. Soft in nature, textile has generally been explored for its material characteristics to absorb sound, filter light, and, spatially, to divide or articulate boundaries and thresholds (Semper 1989). Softness afforded by textile usually negotiates our body with the environment, be it as flooring treatment or as upholstery for furnishing. Textile's tactile properties dominate its functional role.

The most commonly used textile in the building construction industry is possibly Tyvek, which functions as a moisture barrier within the envelope of the building. This membrane is not rigid and must be fixed onto a stiff surface or frame. A more widely explored field where textile plays a crucial role in architectural production is its use for concrete casting as flexible formwork. This area of investigation for architectural designs has a long history, going as far back as late 19th century with fabric-formed concrete floor slabs, to more contemporary investigations by Mark West through his Center for Architectural Structures and Technology (C.A.S.T.) lab (Veenendaal 2017).

Fabric forming by West highlights the advantages of textile's flexibility, particularly its ability to drape, as a way of integrating structural intelligence (funicular forms) and material performance in concrete's capacity to be molded beyond the rectilinear flatness of typical mass-manufactured materials for building (West 2017). Fabric forming explored by West includes fluid pressurized formwork, as in concrete filling the fabric mold to achieve resultant forms vertically (columns or walls, for instance) and horizontally in open trough molds that are non-pressurized, casting onto textile surfaces. Building components produced include columns, precast panels, beams, and trusses. Beyond elemental components, concrete forming with fabric, for West, features the fluid nature of concrete as a material in its unique ability to mold into expressive, ornamental details. In most of these cases, the ornamentation is generated by the natural stretch and folds of the fabric, not by tailoring it into shape. The limitation of using flat textile was intentional for the sake of construction efficiency, to limit the extensive processing that was typical with conventional means for building.

More recent research on concrete thin-shell structures using flexible fabric forming have been done by the Block Research Group (BRG) at ETH Zurich in Switzerland (Veenendaal & Block, 2014). Their production employed the use of fabric and cable-net as formwork for a large span roof structure. Fabric, in this case, is cut and seamed to achieve anticlastic curvatures to optimize material and structural efficiency. Our exploration in tailoring is to account for either bunching or creasing for more extreme surface bends, or the potential for the textile to rip under stress based on deformation. Thermoplastic Concrete Casting differs in scale and focus primarily in the potential for more extreme design of: 1) anticlastic surfaces (especially in switching directionality) through computational means of working with tailoring processing for the fabric, and 2) pushing GFRC casting to achieve thinness and lightness for novel architectural forms to develop a building system of precast modules.

Figure 2: (clockwise from top left) Paper scaled model for seam and curvature analysis; GFRC tests for thickness, pigmentation, and form; felted seams of patterned non-woven textile; test mold using plywood stretcher showing textile and concrete layer; and early test of GFRC cast showing thinness and curvatures.

Figure 3: (clockwise from top left) Textile formwork for Eames molded fiberglass chair; foam-sprayed backing side of the Womb Chair; both molds prepared and sealed for GFRC casting.

Given these precedents, *Thermoplastic Concrete Casting* deviates from other flexible fabric formwork inquiry by asking: What happens when textile is made rigid, and how might architectural production take advantage of this novel circumstance? In addition, given the advancement of CNC tools and computational software to manage efficiency in streamlining workflow from design to output, could more non-conventional means of textile manipulation be integrated into textile casting for architecture? How might these combinations, of technological and material rethinking, guide and offer innovative ways to reimagine formal, constructive, and experiential designs?

2.2 Typical Molding Techniques for Complex Surfaces

Formworks for the molding of complex geometry are time-, material-, and labor-intensive. They are usually produced subtractively, either milled out of a solid material with a 3 or 5-axis router or hot-wire cut based on ruled surface geometries (or in combination). *Microtherm* by Matter Design and Cagliari Contemporary Arts Centre by Zaha Hadid Architects are good examples (Clifford and McGee 2016; Flöry and Pottmann 2010). *Microtherm* was cast from molds that were first hot-wire cut and then milled out of solid EPS foam, and the geometry of the facade of the Cagliari Contemporary Arts Centre was rationalized based on ruled geometries in order to consider how it could be built. A key advantage of using fabric formwork for complex geometric casting is to reduce the amount of material waste through subtractive processes for the mold's production as well as cut machining time.

Mold making for complex surfaces usually involves a geometric rationalization process. For this project, working with mostly anticlastic surfaces, the geometries are rationalized to be developable or flattened as patterns. The concepts of developable surfaces for manufacturing are shared by designers across a wide range of industries ranging from clothing production to shipbuilding (Clifford 2010). In clothing manufacturing, for instance, tailoring and patterning are fundamental, for giving garments form and more structure or stiffness at the seams, and for material efficiency in cutting from bolts of flat fabric. Such processes are similarly considered in architectural production, especially in shaping complex, non-linear surfaces of synclastic and anticlastic curvatures (Pottman 2007). Computational modeling and physics-based simulation for this project was necessary not only for geometric analysis, but also for incorporating parameters from material tests to inform design and direct CNC fabrication. A major focus of this project was to develop computational approaches for analysis, design, and fabrication as a comprehensive and seamless process.

2.3 Needle Felting for Non-Woven Textiles

Given that non-woven felt material comes in both synthetic (e.g. polyethylene or polypropylene) and natural (e.g. wool or bamboo) fibers of different densities, part of our testing was to understand the material properties and behavior of non-woven textile. Fosshape as an engineered thermoplastic textile has specific shrinkage behaviors. Our goal was to calibrate the shrinkage parameters unique to the material in order to generate a parametric script for design and fabrication.

One advantage of working with non-woven textile is that it does not have the directionality of warp and weft inherent in woven or knitted textiles. For non-woven

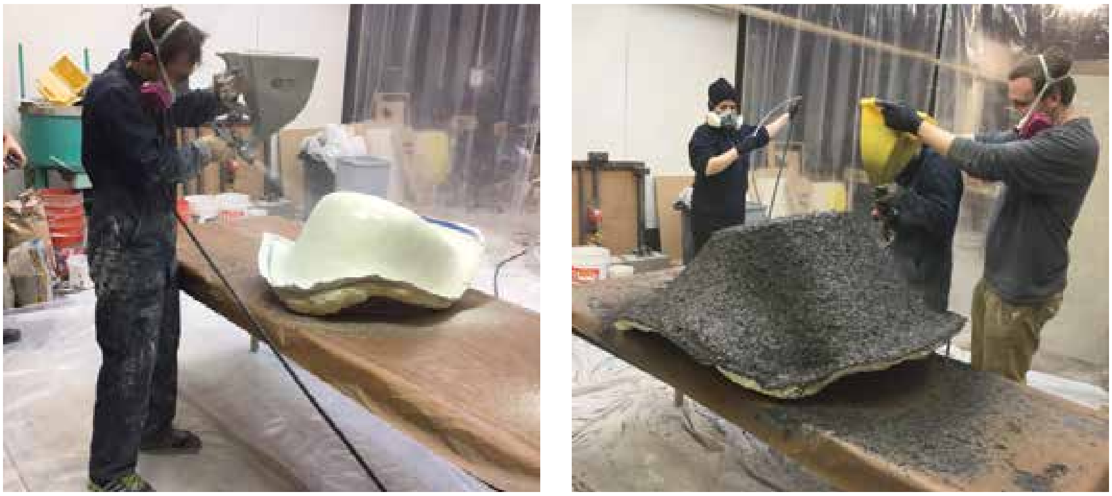


Figure 4: GFRC spraying process for both chairs.

materials, a process called felting was used to seam the patterns together. Felting involves punching with a barbed needle through layers of material and is mainly used for craft-based making. The advantage of felting is the actual meshing of fibers together to become a uniform whole, eliminating seams and producing an extremely strong connection without the use of binding agents such as adhesives or sewn threads. Typically, felting is done by hand in a repetitive motion with a single needle or a few needles bundled. Mechanical felting is achieved with a felter similar to the scale of a sewing machine. Given the size of our textile patterns, a mechanical felter was used to felt the 2D patterns together.

3 PROCESS, TESTING, AND FABRICATION

Our initial approach to the project was to develop models both digitally and physically to analyze complex curvatures. Using Kangaroo and explicit modeling in Rhino, we began with the development of a workflow that would enable analysis, design, and output for CNC fabrication of component parts. The modeling process was a way to analyze seam structure in relation to form for patterning. There were two branches of material testing that took place. The first was GFRC spraying processes, taking into account mix composition, thickness-to-strength ratio, pigmentation, and quality of final surface finish. The second was the felting processes for the non-woven textile. This includes not only needle felting to test seam strength but also deciphering shrink rate when the material is subjected to heat for stiffening. We found that the thermoplastic textile has a shrink rate of approximately 5–10%, depending on the extent of the heating process and the thickness of the material (as it is not absolutely uniform due to the textile's manufacturing process). A plywood stretcher was devised to hold the edges of the textile in place for the heat stiffening process. The non-woven textile is simply stapled to the edges of the stretcher before heating. After heating, the texture of the fabric was smoothed with a fairing compound, prepared, and sealed from moisture for concrete casting (fig. 2).

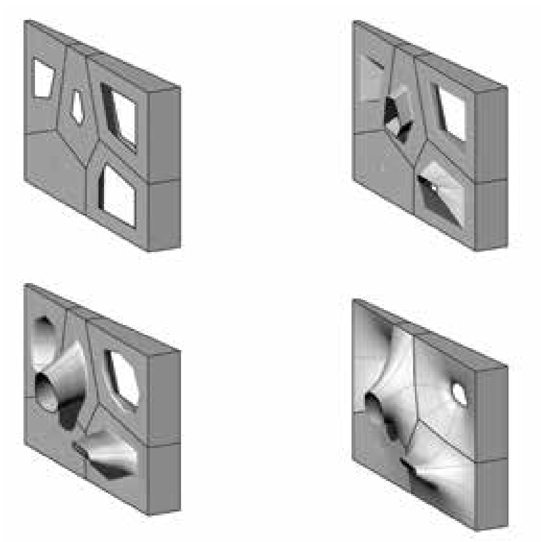
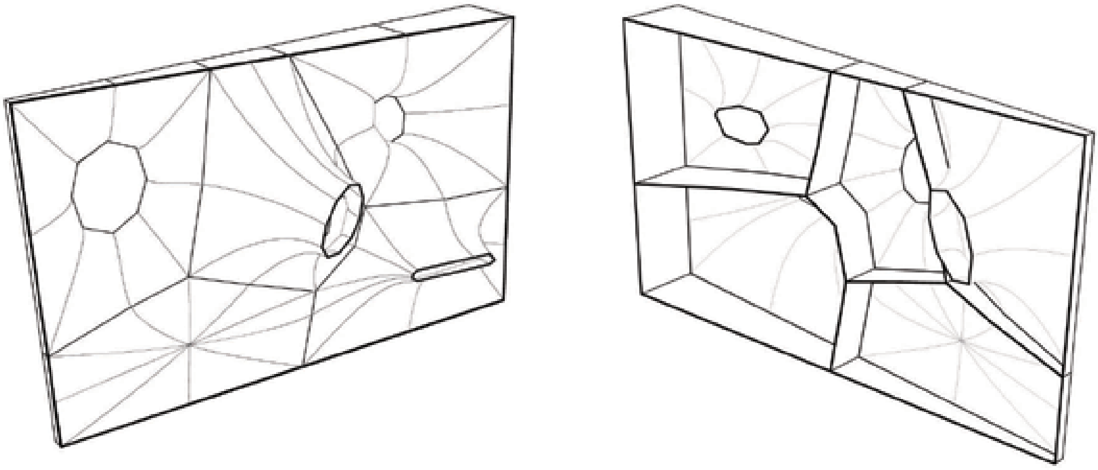


Figure 5: Progressive relaxation of mesh shown in different stages, from flat to double curve.

3.1 Concrete Chairs

At the object scale, using Eames' fiberglass molded chair and Saarinen's Womb Chair with complex curvatures, we developed the patterns by strategically locating the seams and unrolling the curve surfaces (by approximation). The patterns were then knife cut using the 4-axis CNC cutter. For the molded chair, the scale enabled the seamed textile to mold against the original chair. For the Womb Chair, since we did not have one available to mold against, we created a stretcher to wrap the textile on to heat stiffen. Once the textile for the chairs was stiffened, we found that, while it holds it shape, the mold would probably deform during the GFRC spraying process. The weight of the wet concrete would be enough to change the textile formwork's shape. To give the molds extra rigidity, we



Overall view of rationalized patterns for each panel, prior to unrolling

Rear view showing flange tapering from 18" to 2 1/2"

Figure 6: Variable-depth flanges are added to stabilize the wall and allow for the joining of discrete modules.

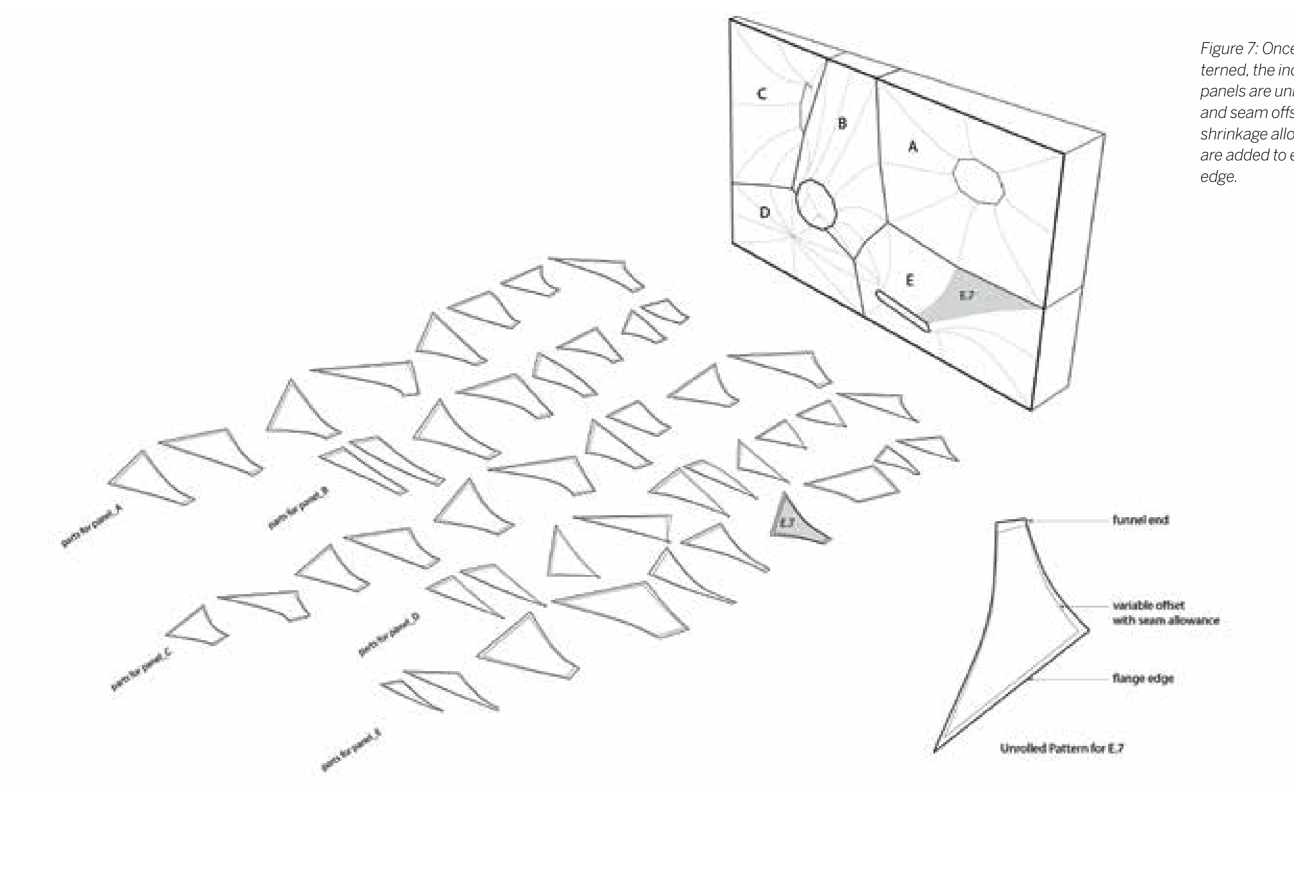


Figure 7: Once patterned, the individual panels are unrolled, and seam offsets and shrinkage allowances are added to each edge.

Figure 8: Each of the five individual molds consists of a plywood stretcher assembly, which is joined to the assembled textile surface. The material is heat-stiffened, backed with polyurethane spray foam, and then surfaced for casting.

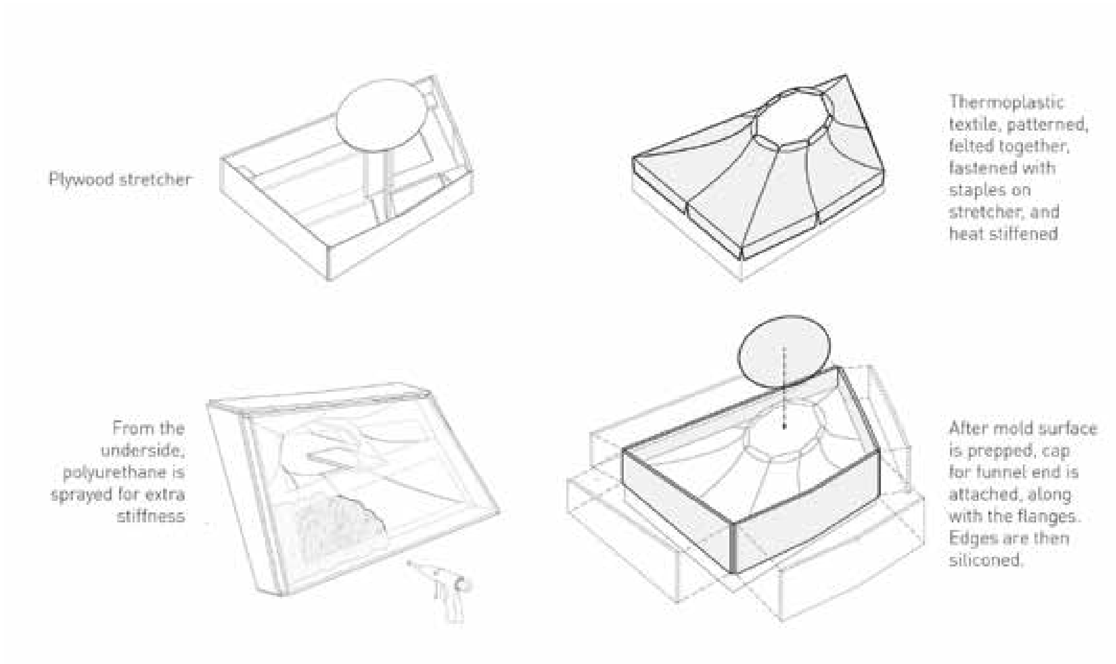


Figure 9: (clockwise from top left) Patterned non-woven thermoplastic textile; heat shrinking on stretcher; prepared mold with flanges attached—edges are silicone; underside of stretcher with thermoplastic stiffened on top.

sprayed polyurethane foam to the underside of the mold as a rigid substrate. While the heat generated during the curing process for the spray foam might further deform thermoplastic textiles such as those that are plastic sheets with a thickness of 4 or 6 ml, Fosshape, because it is a thicker felt material, could withstand the curing process with minimal global deformation. Small local deformations do occur, but the surface preparation process for casting smooths out the surface (figs. 3 and 4).

3.2 Concrete Wall with Funnel Apertures

Using physics-based modeling, the design of a 7' X 11' wall mesh was dynamically relaxed with real-time manipulation. The mesh is relaxed with differential warp/weft stiffness, combined with planarization constraints to force individual panels to remain developable (fig. 5).

The breakdown of the wall panels utilized a Voronoi diagram, each with a funnel center that is controlled with a varying protrusion depth and direction. The constraints are used to control orientation of funnels to produce site-specific views. The design of the wall accounts for balance with the modules' weight in compression, tapering from 18 in. from one side to 2 ½ in. at the other. This thickness is made possible by adding flanges (in plywood) to the sides of the stretcher after the thermoplastic has been heat-stiffened. The flanges for the GFRC modules also serve as coplanar surfaces to mechanically bolt the panels together (fig. 6).

Following a similar rationalization approach to working with developable surfaces through ruled geometry by Flöry and Pottmann (2010), our design and analysis of complex surfaces was derived through formal and construction logic. Each funnel was patterned using ruled surfaces to develop the geometry. While the rationalization of the curved surfaces is an approximation (one could infinitely segment to ever smaller panels for more accurate ruled surface development), the manual process of heat shrinking the textile against a stretcher enables the physical making to resemble the mesh design with reasonable accuracy. A script was written to automate the process for generating the unrolled patterns, including seam offsets and variable shrinkage allowances depending on directionality of the pattern's edge (funnel end versus flange edge) (fig. 7). The patterns were CNC cut, felted together, and pulled over a plywood stretcher. The stretchers for each module were CNC routed and assembled as a frame, enabling simultaneous fabrication with the textile surface.

Once the stretcher is assembled, the thermoplastic textile is stapled and stretched, heat-stiffened, then backed with polyurethane spray foam, ready for water-based fairing compound and sealant. Edges inside the mold are silicone sealed, and the entire surface is sprayed with a mold release agent (figs. 8 and 9) The GFRC spraying process includes a thin mist coat and a backer glass fiber reinforcement coat—where thickness of GFRC is built up by applying multiple layers of backer coat. This thickness ranges from 3/8" to 5/8", depending on whether it is a surface or an edge condition. Slightly thicker or rounded edges provide for extra structural stiffness for the GFRC panel. After the casts are demolded and fully cured, each of the panels weighs anywhere between 200 and 250 lbs. and can be lifted by two people for installation. During installation, the panels are clamped in place at the flanges, drilled to receive bolting hardware (fig. 10).

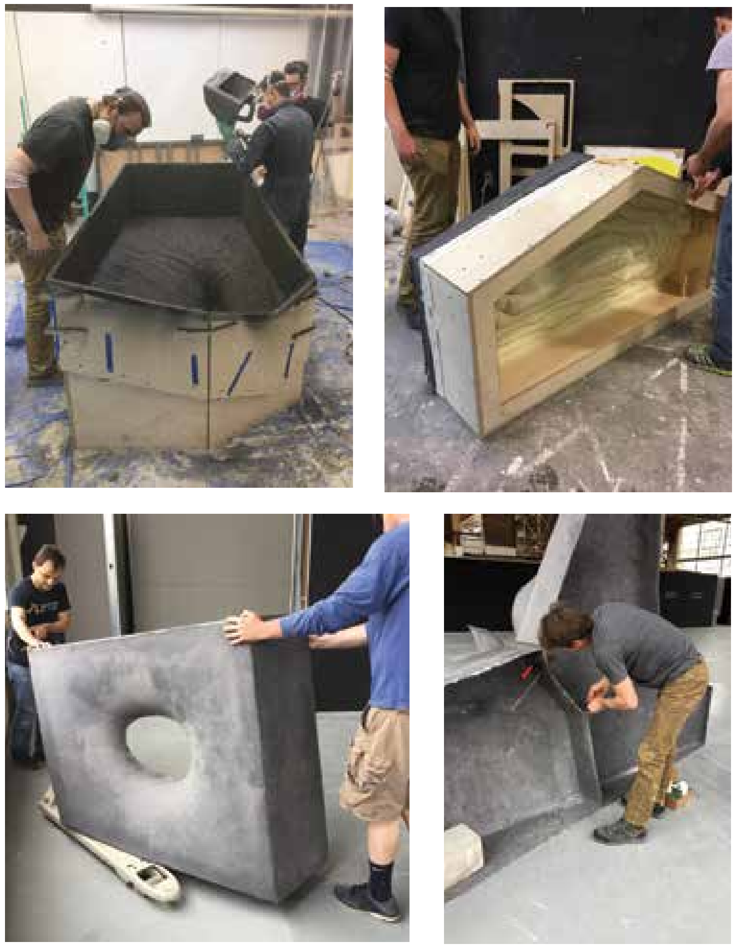


Figure 10: (clockwise from top left) Spraying process for panel; demolding process; bolting panels together; panel transport.

4 RESULTS

The intention for the funnel openings at eye level is to direct one's view through the wall. One of the funnel ends (at the base) is constrained to meet the end of a table, testing the variability of shaping curvatures with extreme sectional quality (figs. 11 and 12). With the directional switch of the funnels, the continuity of the mesh surface from one panel to the next highlights the fidelity of the initial mesh design in relation to the built construct as the curvature smoothly matches adjacent panels (fig. 13). When a viewer walks from the smooth (front) side to the back, the thinness of the GFRC casts is revealed.

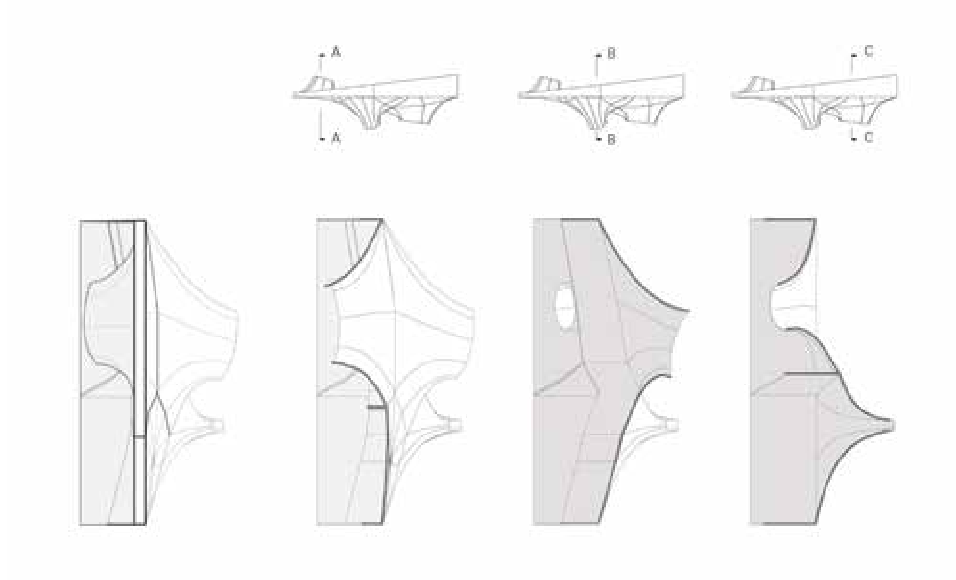


Figure 11: (left to right) Side elevation from 2 ½" side, with section A, B, and C through center of funnels.

Figure 12: Plan view showing the final subdivision of individual mesh faces. A balance is struck between accuracy of the unrolled geometry (higher-resolution meshes) and responsiveness of the parametric model.

While the panels were able to hold their own weight without extra support, given enough resources and time, it would be beneficial to analyze the wall system as a whole so that future designs and adjustments could be based off of quantitative data. This includes ratios of overall wall depth to height, panel size to GFRC thickness, and funnel opening size and protrusion depth in relation to surface stiffness.

To further reduce labor involved in the formwork preparation, the surfaces of the non-woven textile could be sprayed with multiple layers of polyester coating with light sanding in between. The spray coating process would eliminate manual surfacing with fairing compound and heavy sanding in between layers, as well as the final layers of polyurethane coating necessary for water sealing.

5 CONCLUSION

Thermoplastic Concrete Casting aims to challenge typical processes for formwork making for complex geometries, offering an integrated process for computational design, fabrication, and construction. While other fabric molding processes have invariably been explored especially for material and structural performance, this exploration tests more extreme designs that are often difficult to achieve given their complex geometries. The project comingles sartorial techniques with architectural processes to address construction challenges—one that is not limited by the orthogonal flatness of normative building material and techniques. Through a discursive process of full-scale prototyping and computational design, the project links digital technology with heuristic knowledge of building. The latter includes certain types of skilled crafting, such as heating techniques for the Fosshape, as well as GFRC mixing and spraying. In being able to control the entire process from ideation to construction, tolerances are controlled, offering more precision in what otherwise could be a loose process for concrete construction. Ultimately, *Thermoplastic Concrete Casting* attempted to challenge conventional casting techniques for forming complex curved surfaces with less time, material, and labor.

Figure 13: View of cast panels composed.

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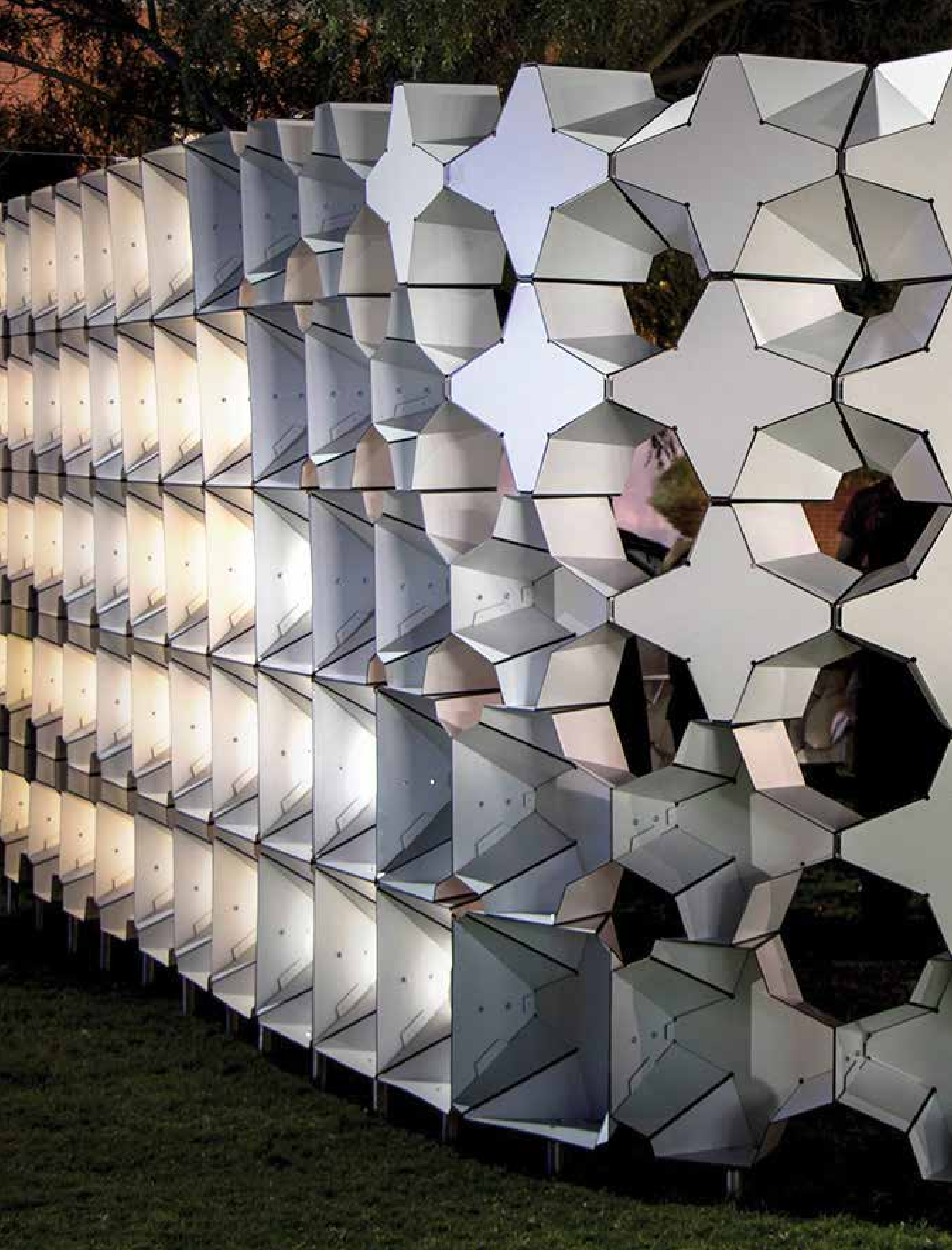

Selfie Wall: A Public Space for Private Data

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A NEW PUBLIC

In the last few decades, instantiations of social connections have become untethered from physical space; their existence is now transferred to the 'substitute reality'[1] of the digital realm. As we become more digitally connected in the simulated[2] world of the Internet, the notion of a traditional public space deteriorates, locating the designer's work within increasingly complex spatial entanglements.

As new publics form around various types of shared connections, the idea of public space, park, and infrastructure becomes layered and extends its reach beyond physical space. This shift necessitates updated modes of publicness, where behavioral protocols reconfigure public and private relationships. The public life of an online celebrity, for instance, relies on specifically scripted behaviors, which do not directly translate to physical environments conceived before the Internet era. However, as various behaviors increasingly visit both realms, public space must be re-calibrated to host and proliferate new hybrid protocols. If the physical realm is to update its spatial logics in order to more directly connect to the simulated environment, a new kind of park must be imagined—one that embraces multiple intersecting cultures, bridging the worlds of the instant digital celebrity, the follower, the maker, the consumer, the avatar, the bot—in other words, the newly-minted everyday citizen. Paradoxically, through this layering, much like in its past iterations, the public park becomes an outlet for individuals seeking self-expression on multiple realms. In its most basic form, the selfie is the activity of this expression and is able to generate protocols linking the physical and the simulated milieus.

While perceived as a seemingly recent phenomenon, the 'selfie' is the latest development in a long history of self-portraiture. Selfies have evolved with dramatic changes in technologies, but, in some form, they have been with us for over a century, since the birth of photography. Andy Warhol, Colin Powell, and Ai Weiwei have experimented with various forms of selfies. Their flexibility and ease of use continue to build upon the long trajectory of photography, acting as a record of self, a chance to capture time with a group, or a desire to express one's self alone, and they are generally triggered by feeling good in a specific location. With the advent of social media, their popularity is growing as they instantly

Figure 1: Each unit is comprised of a folder perimeter sheet and a flat, cross-shaped member. When riveted together, the units become self-supporting structural components.

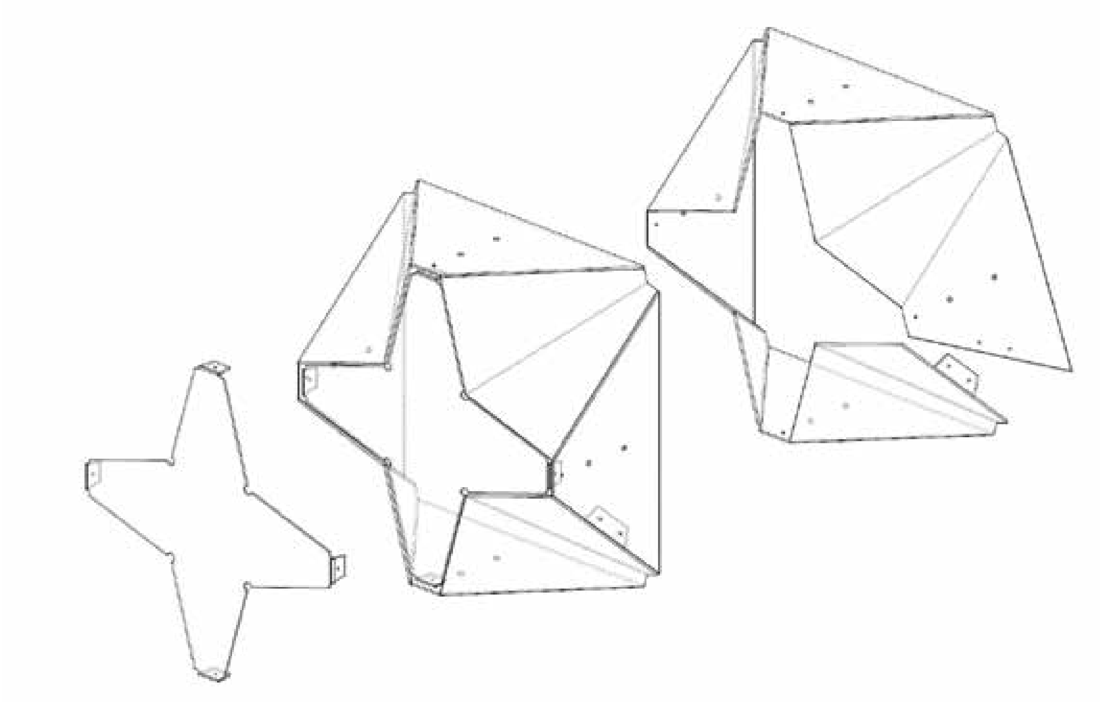
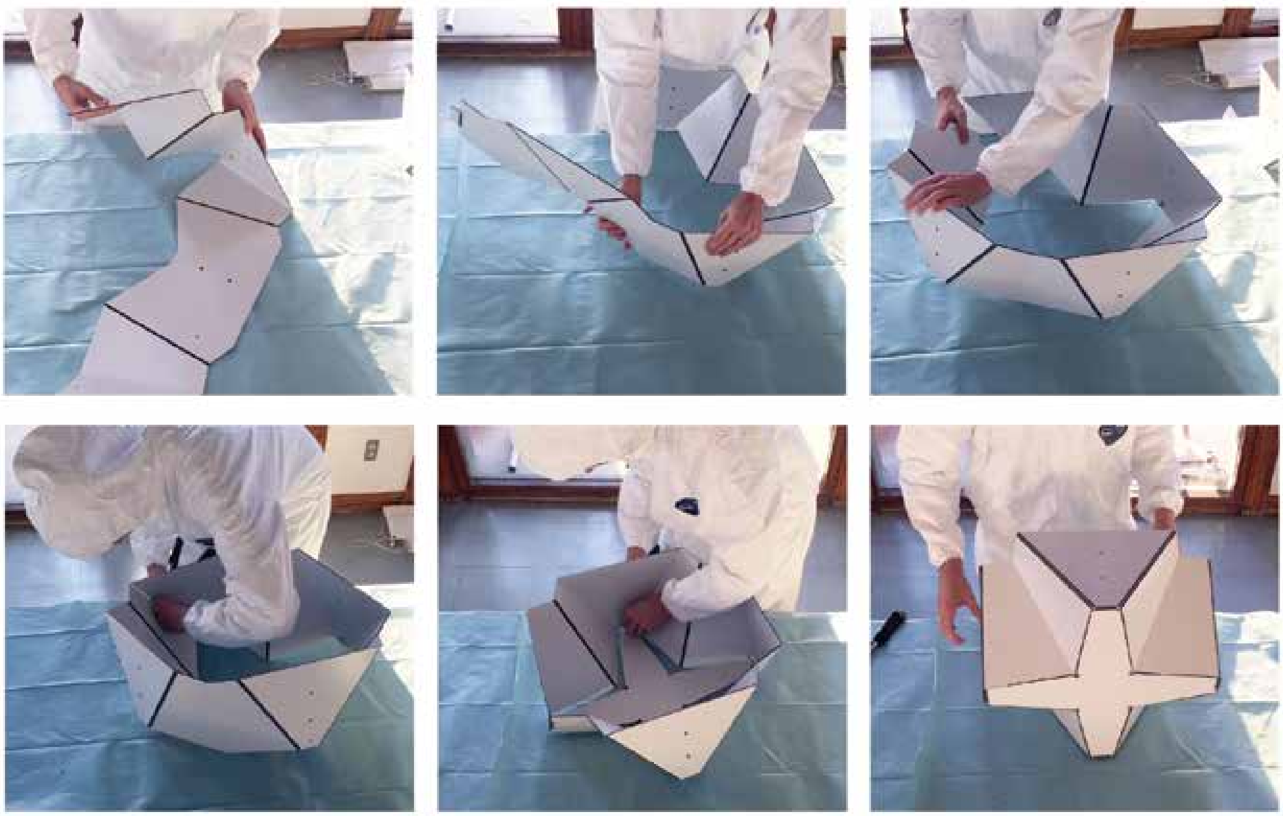
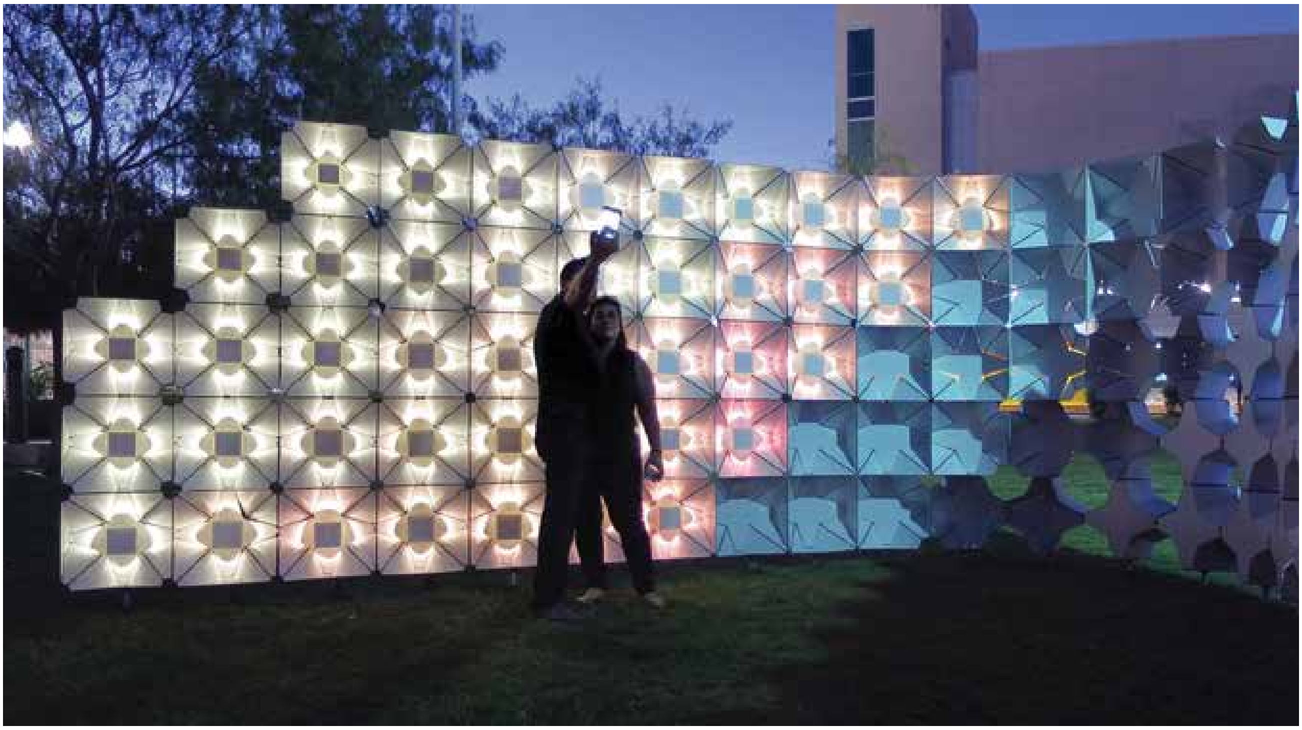


Figure 2: Each unit takes 3–5 minutes to assemble with simple tools.





deploy to larger audiences and even invade daily language globally, becoming Oxford Dictionary's 'word of the year' in 2013. Selfies are a nascent and growing art form, able to spawn Internet memes and infect various cultures with shared behavioral patterns globally. Over the last few years, they have gained notoriety primarily for the self-promotional and distorted culture of individual celebrity they can perpetuate.

SELFIE DANGER

However, beyond its apparently harmless self-expression, the selfie's ability to record one's personal mood, facial characteristics, location, and activity imbues it with deeper concerns about issues of privacy, surveillance, and intrusion. The unprotected excessive sharing of self-photography online has expanded the reach of surveillance by government entities, law enforcement, marketing corporations, and criminal organizations, which are able to operate beyond clear legal boundaries and stand to benefit from using the data. Despite their generally happy mood, selfies are powerful vectors for data transmission; the pixels are capable of revealing untold stories about their subjects and the environments they are captured within. Data scrapers and security bots use facial recognition software to map an individual's location at any given time, their mood, and their social habits. As personal data becomes available to the highest bidder, new protection protocols are necessary. Researchers in Germany have detailed a list of thirty-eight information types that could be gleaned from selfies via visual inspection alone, including fingerprints, tattoos, and other physical characteristics, that could lead to identity theft. The environment captured in the photograph is equally data-rich. Locational 'cues' like street signs and landmarks help identify the coordinates and movement of the selfie taker, and, by analyzing a series of photos of a single user over time, one can elaborate spatial patterns and abnormalities, which can predict behavior. Savvy thieves[3] may identify personal documents or valuables inadvertently exposed in the background of an image, which could further expose other vulnerable addresses related to the user, off-site, as well as the signaling of sensitive information.[4] While spatial information like 'landmarks' and 'locations visited' rank as lower security concerns than more private identifiers like 'medical history' or 'political opinions' across most age groups, they rank as higher concerns than more visually obvious and easily gleaned 'public' features of an individual like 'clothing' or 'hair color.'

The selfie, then, clearly problematizes issues of identities in space, and the expectations of spatial privacy within this radically public, but perhaps inadvertent, form of spatial documentation. Noting that users tend to violate their own standards of privacy when posting photos themselves,[5] researchers are developing an app that could identify sensitive information before it is posted. As the secondary uses for the selfie emerge, they layer spatial data with private biometrics and behavioral prediction in order to construct a full digital imprint of any given individual. As such, their large-scale collection

Figure 3: The interior of the wall is equipped with an LED array ranging from warm white to warm pink tones, expanding the range of flattering selfie moments.

Figure 4: During the day, in the absence of artificial lighting, the bright aluminum material diffuses light, creating a brightly filtered physical space.

has become another type of Big Data and a vector for biopolitical manipulation. Apps like the Chinese app Meitu was under fire in early 2017 for covertly tracking its users' locations and behaviors, and for sharing unique identifiers with advertisers which could then target specific users.[6] Photo-mining startups are mining publicly shared selfies from public sites like Flickr in order to identify trends and consumer attitudes.[7] Moreover, facial recognition software analysis can pinpoint users' identity with increasing precision, distinguishing even identical twins by the microtopographies of the skin it can recreate. Companies are exploring analyzing selfies for signs of premature aging or illness in order to relay them as inputs for actuarial calculations which determine life and health insurance rates.[8]

SELFIE SPACE

By linking biometric indices with spatial metrics, selfies can restructure our relationship to the built environment. Programs can scan bulk photos of large populations to generalize the mood of a city or site, or to measure the success of an event. The location of the photo can recast the photo-taker as suspect, or even criminal, as in a number of cases of selfies taken illegally at polling places, or photos taken on private land without permission.[9] As architectural and urban forms are caught in the selfie's gaze and re-transmitted, other complications emerge. The EU sought to ban the use of selfies in front of recognizable landmarks, citing concerns over copyright violations of the work of artists or architects, and potential damage to the sites.[10] In contrast, the Selfie Park was built in order to test issues of entanglement of physical public space and its digital proxies by encouraging selfie-taking behavior and fostering a public discussion of the data this behavior transmits.

The project posits that a physical device that coerces selfie-taking activity in public can engender a public space that fosters open debate and supports layered relationships between the physical and the digital. The device is designed to act as the physical equivalent of an Instagram filter, in the form of an architectural wall, and to create ideal conditions for self-photography. The Selfie Wall creates a range of lighting conditions day and night, offering a dynamic and interactive space for self-photography. The project is both a public art installation and the beginning of a public awareness campaign highlighting the dangers of online sharing. It creates a space of custom lighting that can both entice self-photography and confuse facial recognition software. The variable lighting array allows selfie-takers to choose the amount of data they broadcast by taking either recognizable or undetectable photographs. In this sense, the Selfie Wall is able to create a public space for private data. The user is free to choose between a clear photograph when facing the wall, and a darkened, color-filtered one when using the wall as a background, as facial recognition software is proven to be less effective in conditions of low contrast or low light. The physical environment of the wall is augmented with an online platform, which collects the hashtagged selfies and projects them real-time on a digital screen on site. A team of volunteers explains the process of metadata collection to selfie-takers in hopes of rendering them aware of the ease and speed of surveillance collection.

SELFIE FABRICATION

The Selfie Wall was conceived and constructed as an exercise in testing permutations between digital imagery and physical material organization. The wall is built from 162 custom-fabricated units, CNC-milled from composite aluminum panel and folded to frame various apertures for bouncing, scattering, and collecting light. The geometry of the modules transforms from a structural cross-shape to an open 'umbrella,'

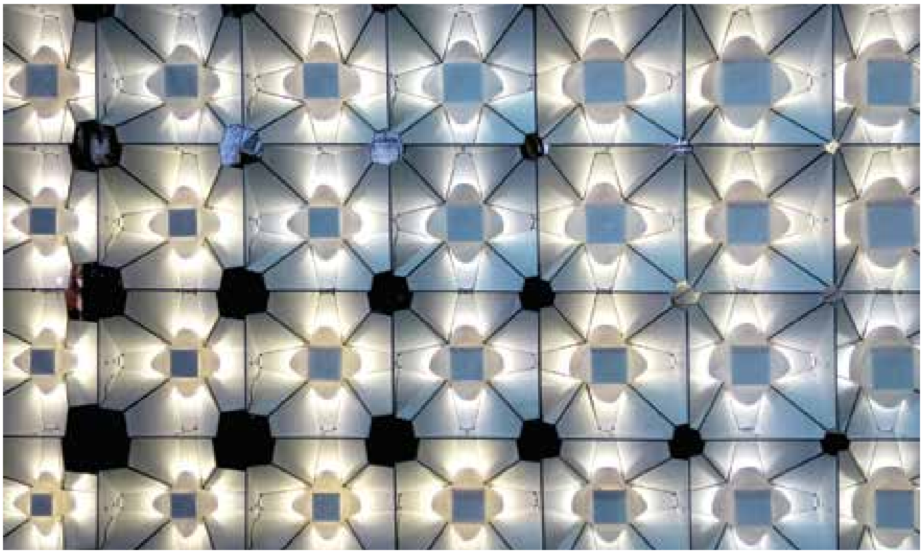


Figure 5: The exterior of the wall is equipped with an LED array ranging from cool white to blue tones, confusing facial recognition software.

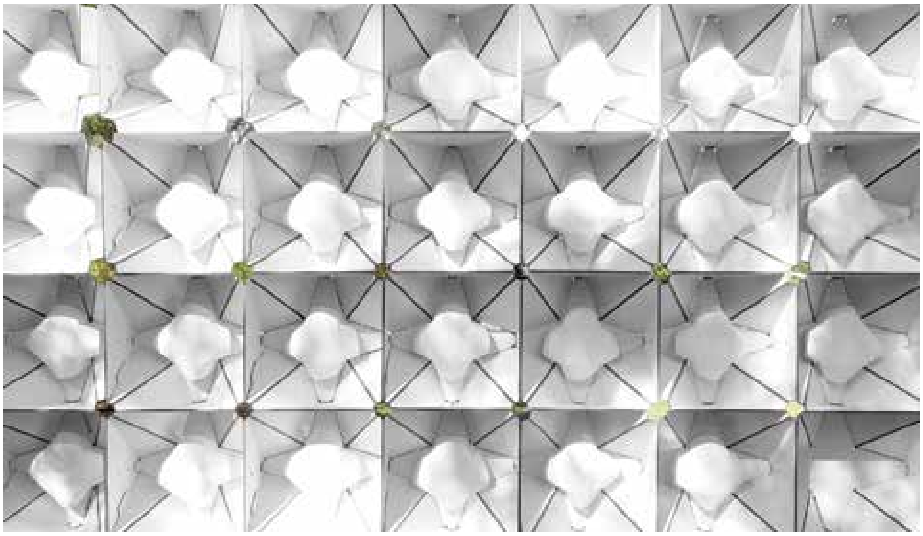


Figure 6: The artificial light is diffused and distributed to the edges by soft foam sheets that block direct light, much like professional photography.

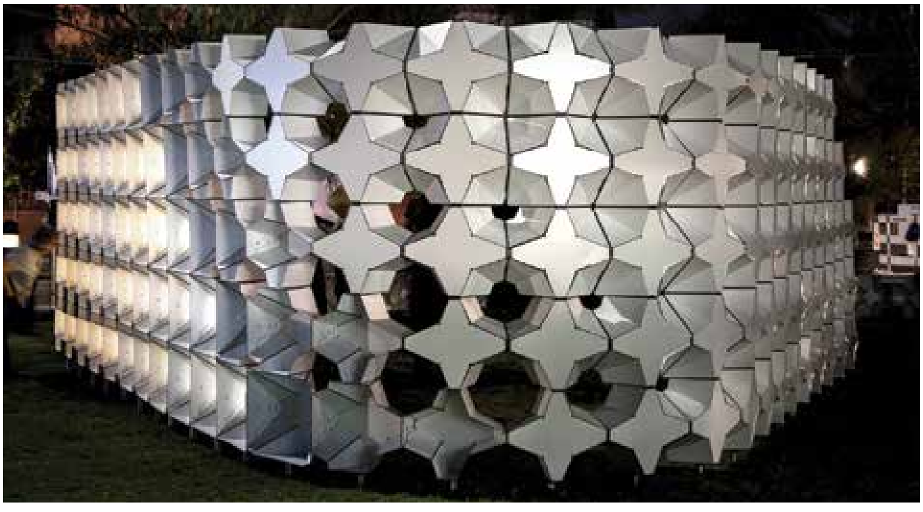


Figure 7: Openings of varying degrees invite a game of voyeurism with the otherwise private behavior of self-photography.

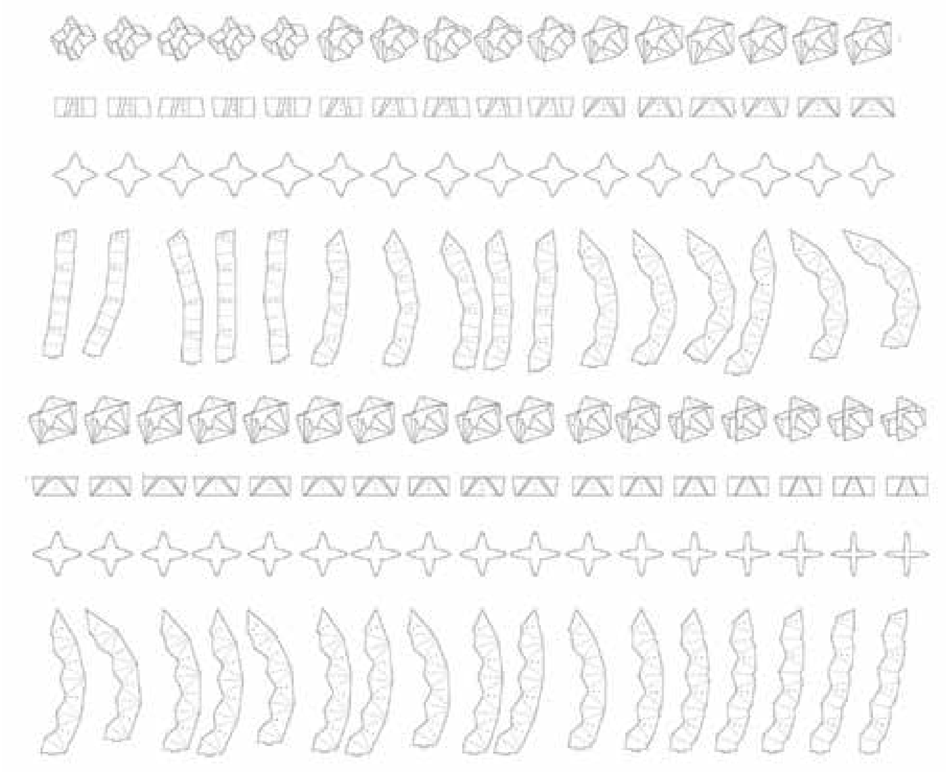


Figure 8: The wall is constructed of 162 differently shaped units—a variation afforded by CNC flip milling and a precise calculation of dimensional gains and losses during the folding process.

providing consistent structural rigidity while offering a range of lighting options. The mass-customized variations evoke, replicate, and evolve lighting devices used across a variety of industries, simultaneously signaling 'barn doors,' on-stage lighting, photo umbrellas used in portrait photography and film, and vanity fixtures. A grid of LED lights is inset to provide zones of varying color temperatures at night, from warm pinks and whites that flatter most skin tones on the inner surface of the wall, to cool whites that provide a more accurate color rendering on the outer surface. The public is encouraged to explore the dynamic matrix on site, finding the lighting condition and background most suitable for their self-portrait. The geometry of the modules is designed to be flip-milled on a CNC router, 'scored,' and folded bi-directionally to aggregate into a precise, mass-customized form. Constrained by restrictions of the site, the wall uses lightweight and readily available sheet material to create a rigid self-supporting structural assembly. Each of the units is composed of two pieces, a vertical 'cross' shape, and a 'loop,' which folds at various angles to shape a 3-dimensional, tapering form around the cross. The two-piece units can be assembled in less than five minutes, using rivets to join them through pre-cut holes. As a cross is fit into the loop, the flexible material becomes rigid and self-supporting. The full assembly can be quickly deployed on site, using bolted connections through another series of pre-cut holes. In this way, the project leverages unskilled labor by making the construction procedure 'foolproof.'

Each unit creates a 'cell' in the overall assembly, roughly sixteen inches square and eight inches deep. Stacking from the ground to seven feet tall, the modules provide different alignments for users of all heights. The plan of the wall is bent at sixty degrees, creating a partial interior enclosure and sense of compressed scale within the larger park, and allowing the narrow linear structure to resist overturning. The siting uses existing trees as an additional enclosure and privacy screen. The patterning of the modules is based on two opposing and shifting stacking patterns, starting at each side and joining in the middle near the bend, creating a narrow but diverse range of lighting options. Where the patterns join, the openings are at their largest, creating an open corner that allows the public on the outside of the wall a voyeuristic peek into the more private photography sessions within. The assembly was refined through prototyping both typical and atypical modules, which showed that the scoring and folding technique distorted the loops and as they bent around the cross. We compensated for the material realities of this distortion by adjusting the cut files and not the digital model, in order to predict the precise results.

We continue to work on the project to find new sites and iterations. We are working to beta-test the effect of the modules and the full array with the types of facial recognition software deployed by border and transportation security agents.

ENDNOTES

1. Greg Lynn, *Animate Form* (New York: Princeton Architectural Press, 1999), 10.

2. 'Simulated' here is to be understood as the world of the digital realm. It agrees with Greg Lynn's correction of the use of the term 'virtual,' which posits that it should describe a condition which can actually become physical/possible, not a digital condition which may never become physically possible.

3. See Geoff Manaugh, *A Burglar's Guide to the City* (New York: FSG Originals, 2016).

4. Kevin Murnane, "Your Selfies Can Hurt You, But There Is A Privacy Adviser That Can Help," *Forbes*, April 10, 2017, https://www.forbes.com/sites/kevinmurnane/2017/04/10/your-selfies-can-hurt-you-but-theres-a-privacy-adviser-that-can-help/#4cb3fc4a589a.

5. Tribhuvanesh Orekondy, Bernt Schiele, and Mario Fritz, "Towards a Visual Privacy Advisor: Understanding and Predicting Privacy Risks in Images," arXiv, August 7, 2017, https://arxiv.org/pdf/1703.10660.pdf

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7. Robert Mann, "How Marketers Are Mining Your Selfies for Data," *Adweek*, October 10, 2014, http://www.adweek.com/digital/how-marketers-are-mining-your-selfies-data-160696/.

8. NerdWallet, "Could Selfies Affect Life-Insurance Rates?" *Orlando Sentinel*, April 20, 2017, http://www.orlandosentinel.com/business/technology/os-ap-selfie-life-insurance-20170420-story.html.

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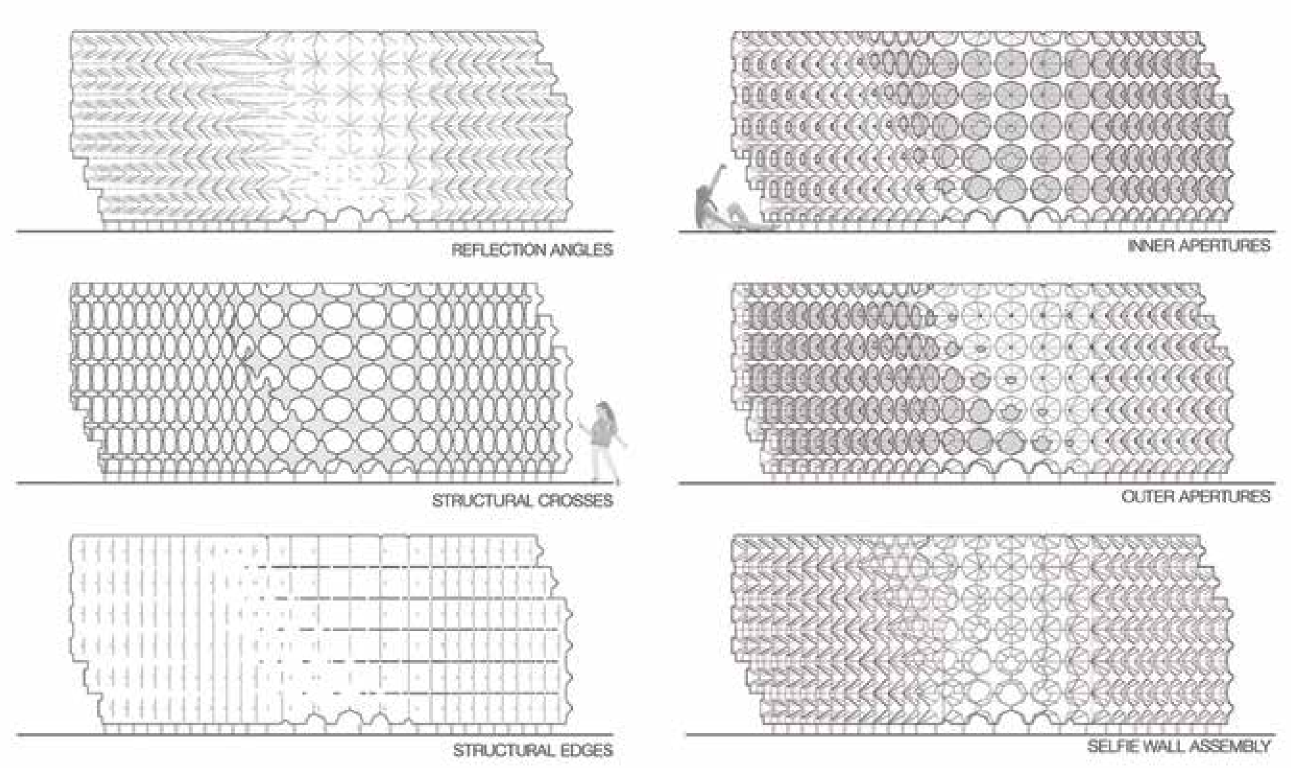
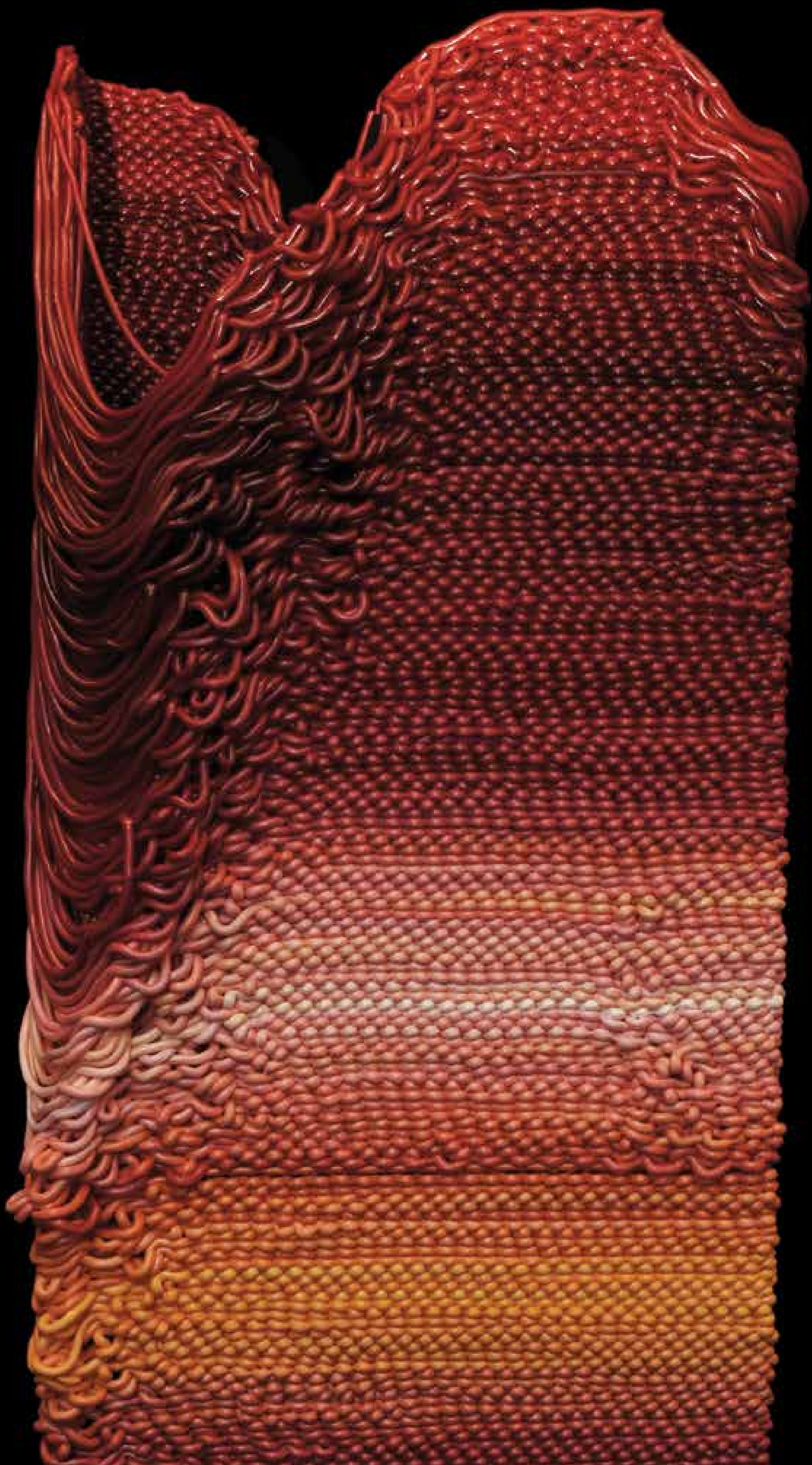
10. Erika Owen, "The EU Wants to Ban Your Eiffel Tower Selfies," *Travel & Leisure*, June 29, 2015, http://www.travelandleisure.com/articles/eu-ban-landmark-selfies.

Figure 9





Plato's Columns: Platonic Geometries vs. Vague Gestures in Robotic Construction

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ABSTRACT

Platonem ferunt didicisse Pythagorea omnia.
—Cicero

This paper examines the inherent possibilities for architectural production in automated deposition modeling techniques, primarily explored through the use of industrial robots in combination with plastic deposition heads. These robots, in combination with various polymers, toolpaths and colorations, served as a design ecology for the exploration of emergent behaviors in robotic construction. The relationship between geometry (Euclidian, topological, fractal), mechanical properties of material (plasticity, elasticity, viscosity, resilience), optical properties (color, absorbance, transmittance, scattering), and the gestural qualities of robotic toolpaths constitute the palette adopted for the presented project. The project combines the rigor of a platonic body (fig. 2) with the emergent properties of vague gestures. The introduction of moments of uncertainty in the process produces glitches that are embraced as an opportunity to find novel aesthetic conditions. The profound entanglement with the post-digital realm is discussed as the discursive plane of thinking applied to the project.

INTRODUCTION: AN EXCURSION INTO POST-DIGITAL THINKING

When discussing the emergent properties of automated processes, it is essential to touch on the topic of post-human and post-digital conditions. Post-human does not entail a condition after the dominance of the human species or without humans, but rather emphasizes an alternative perspective on design that shifts the focus away from an anthropocentric position of observation and control. Post-human design practices decentralize the role of human judgement and embrace the notion that creative agencies can be conferred to nonhuman entities such as objects, tools, materials, other species (organic or machinic), and environmental forces. Externalized knowledge begins to take identity and instrumentality, and participates in the process of generating novel design ecologies and alternative design agencies for architecture at large (Velikov et al. 2016).

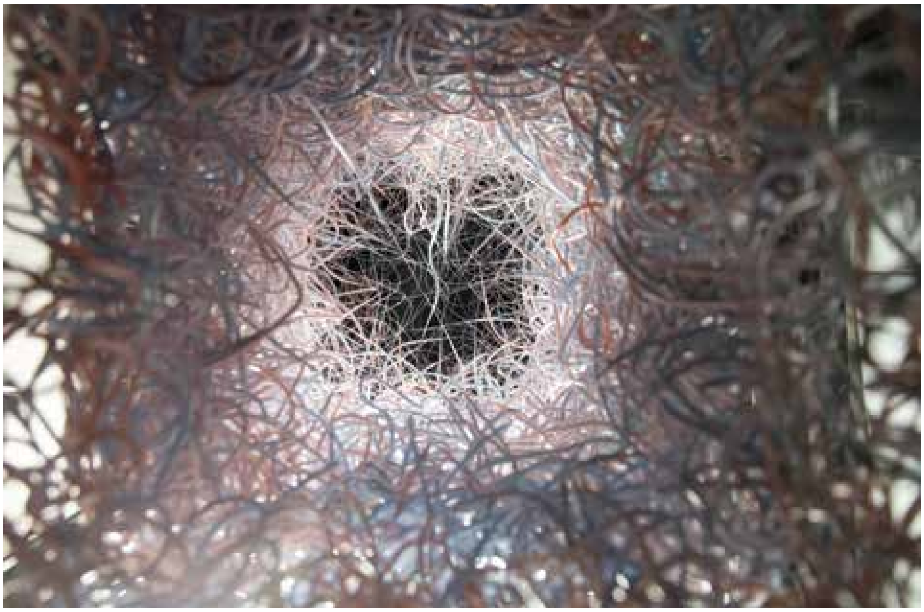


Figure 1: Hirsute Column, interior view.

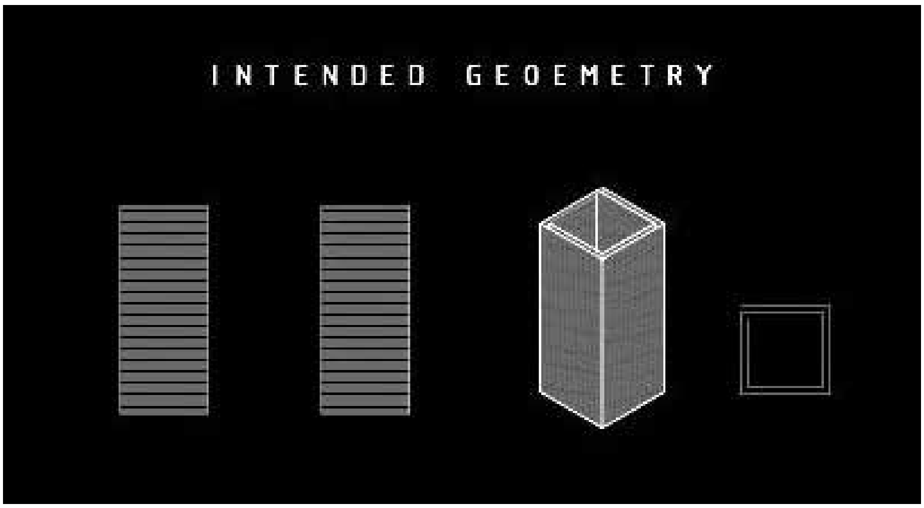


Figure 2: Extruded square as initial definition.

The term "post-digital" emerged in digital arts discourse around the year 2000 and was coined by the musician Kim Cascone, specifically in regards to using glitches in digital technology as a source of inspiration. Cascone, an electronic music composer by trade, used the term for the first time in his article "The Aesthetics of Failure: 'Post-digital' Tendencies in Contemporary Computer Music." In this article, Cascone observes that as digital technologies have become part of the mainstream world and are deeply entangled in everything from commerce to "Hollywood cranking out digital fluff by the gigabyte" (Cascone 2000), the initial fascination with digital tools per se has evaporated. This has created a space for novel developments that do not utilize technological terms to describe the work, but rather interrogate the errors and mishaps (fig. 3) in the process as potential sources of inspiration (del Campo and Manninger 2014).

In this light, the term inherently approaches the explosive evolution of digital technologies in the arts and how it mutates the relationship to the human condition. It explores the notion in creative disciplines where computational tools have become standard practice, and the emergence of novel insights do not rely on the tool as a mode of explanation. This is a tendency that can also be observed in the architectural discipline, where the notion of explaining a project (of any kind) by highlighting the applied toolset is observed with an increased amount of suspicion—a suspicion that, in the best case, produces novel lenses of observation for architectural problems. On closer examination of the paradigm of consensus, there is a selection to be made: Either there is intrinsic

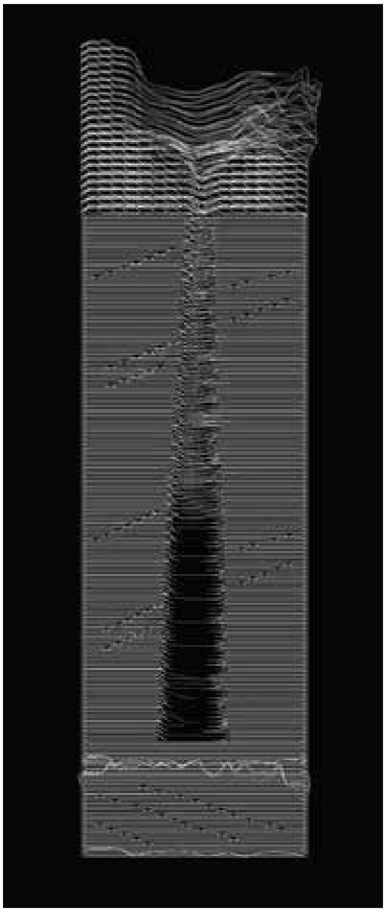


Figure 3: Mapping of the deposition result post facto.

Figure 4: Image sequence displaying the fabrication process.

meaning in a post-digital society, or it is swallowed into a contextualized paradigm of consensus that includes art and architecture as a totality. It is probably best summarized in Roy Ascott's (2003) averment that the discernment separating the digital from the post-digital is part of the economy of reality. In this sense, it does not represent a disruptive moment of cultural change, but rather demonstrates a continuous slow transition from one state to the other, or in Heideggerian terms, from Ereignis to Sein (Heidegger 2003).

In terms of architectural discourse, the ballistic trajectories of conversation can be put in perspective by Mario Carpo's (2012) book *The Digital Turn in Architecture,* which serves as an excellent marker to define the time frame of the digital and post-digital lineages in architecture. Carpo's book defines the period of the digital turn as occurring from 1992 to 2012. The time after 2012 marks a shift in the architectural conversation with the emergence of alternative theoretical constructions, such as object-oriented ontologies, speculative realism, and an elevated interest in aspects of phenomenology. These tendencies most certainly frame a paradigmatic shift in architectural discourse from the computational, seamless, and continuous narratives of Deleuzian thinking to a critical interrogation of the toolsets developed in the process. As to the definition of the term "paradigm," Giorgio Agamben (2002) might be helpful here with his description of a paradigm as something that we think with, rather than a condition, thing, or object that we think about. To this end, the post-digital can be described as a paradigm, comparable, for example, to post-humanism, which does not describe a universe after the digital, but rather characterizes the contemporary attempt to examine the consequences of the digital age. In other words, the emanations of the human enhancement achieved with computational tools—the ramifications of the globe-spanning prosthetics that are achieved by the application of software—all of which present themselves as exquisite specimens for speculative interrogation and theoretical inquiry.

CELEBRATING THE GLITCH

In the project *Plato's Columns*, the notion of the glitch is celebrated within the framework of a rigid robotic setup. On one side, the G-code of the toolpath that fluctuates within the precise figuration of a rigorous geometry; on the other, the programmatic sequence of varying speeds, and the immediate response of material

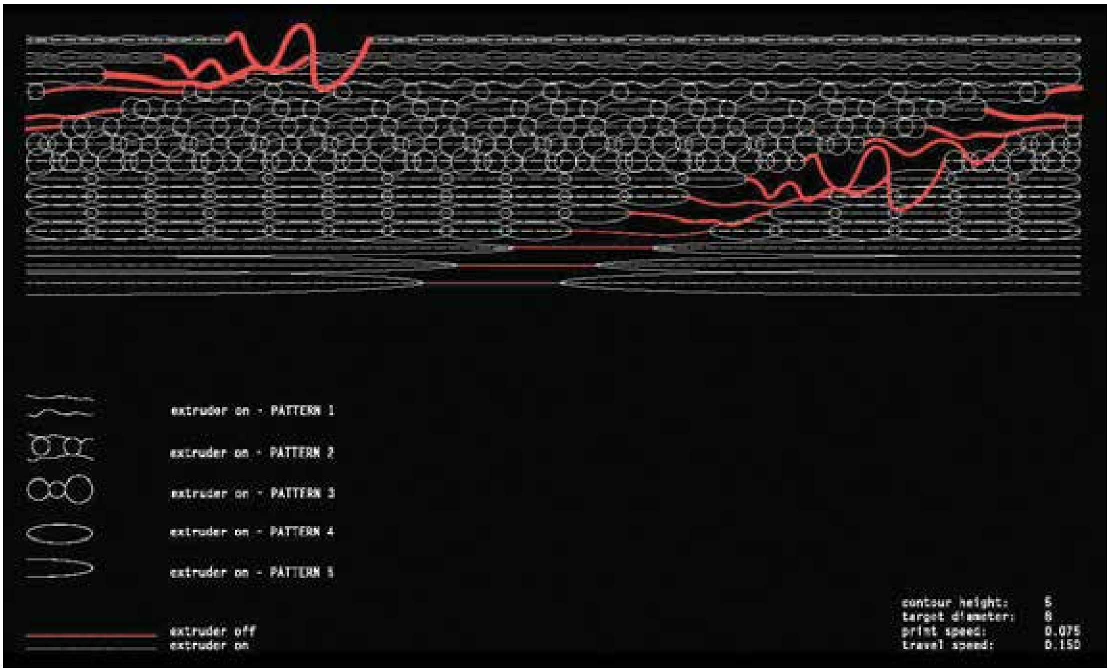
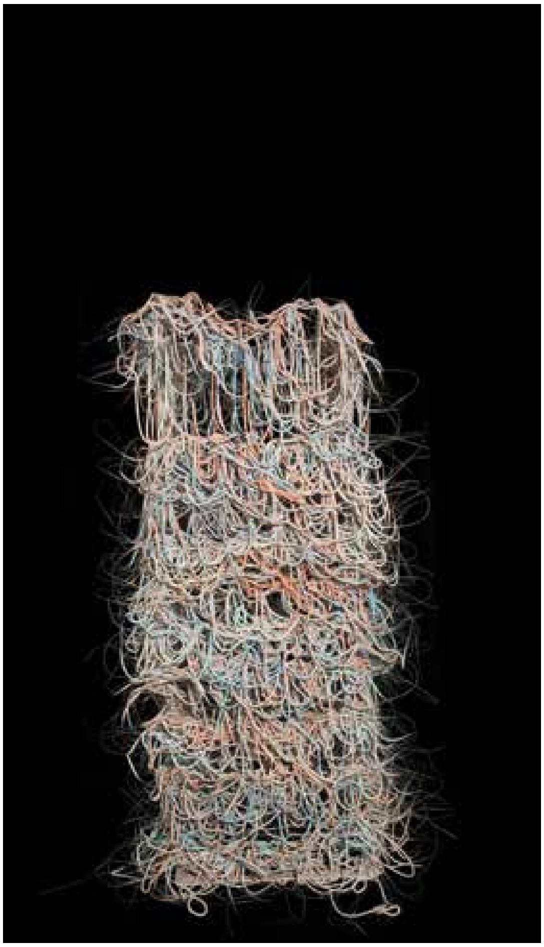
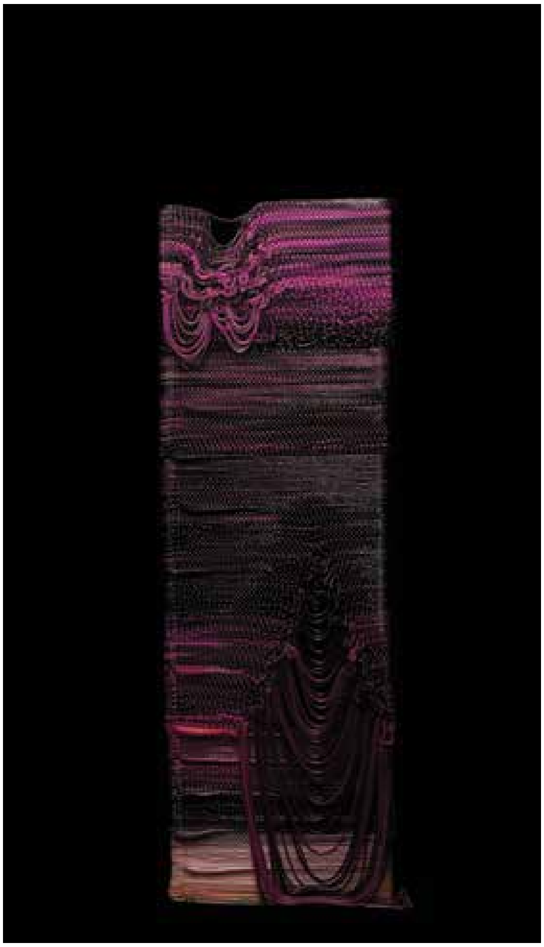


Figure 5: Analysis of the deposition result post facto to refine the G-code.





Figures 6: Designing the G-code resulted in varying articulation qualities.

properties. The combination of the inherent precision of the robotic setup and the vague deposition created by the infusion of varying speeds, as well as fluctuations in the material's response to the laws of thermodynamics and gravitational forces, results in glitches in the morphogenetic process (figs. 4 and 5). The initial figuration in the form of an extruded square is intentionally chosen to demonstrate how a distinct and precise form can achieve intricacy through variations in the material's response, as well as by mixing colorations in the pellet chamber of the deposition head. One of the more telling moments at the very beginning of this research was when students suddenly stopped the deposition process every time an error started to emerge. It was difficult for them to grasp that this was precisely what the studio was looking for: not the prevailing tendency for the perfect replication of a computational model, but rather a dialogue between computational information and physical properties, which results in forms informed as much as by binary code as by environmental forces.

The moment students got the task to just keep going, interesting things started to happen. First and foremost, a self-healing quality of the deposition process emerged. Errors that presented themselves as holes in the platonic figure started to incrementally close again. This behavior allowed for the introduction of an alternative method for creating apertures in platonic geometries. These were neither violently inserted into the body nor elegantly inserted in accordance with the underlying geometry in a topological fashion. Instead, they emerged through a procedural approach to material deposition akin to the emergence of holes in leaves of plants, which occur due to the lack of nutrients in specific areas. Students were then encouraged to develop strategies that involved designing deposition paths that implemented variation in the deposition speed. A regular deposition speed will always result in an identical deposition thickness for the utilized polymers. A variation in speed yields results that range from bulbous, pearly chains to ultrathin, fibrous sections of paths. In an analogy to painterly techniques, the interplay of both can be read as a crossbreed between impasto, thick and expressive strokes, and the finesse of delicate glaze painting. In contrast to the intuitive expressive gestures found in Jackson Pollock's oeuvre, this approach relies on the rigorous toolpath of an extruded square. These impressions are enhanced

through the bold use of color. The use of colored polymer pellets, mixed inside the container of the deposition head, created bold colorations that gradually transitioned from one color to another. The palette was intentionally chosen to resemble Baroque color schemes.

Probably one of the more interesting results was the Hirsute Column (fig. 6, first image). This column has a very interesting toolpath in that it is not of a continuous nature but starts and stops in a random crosshatch fashion, vaguely following the original platonic form. In a computational model, this random set of lines does not produce a result that can be perceived as a possible project. It only starts to make sense once the column starts to emerge in the fabrication process.

The setup consists of a robotic arm in combination with a plastic deposition head, as depicted in Figure 7. The material for the explorations is various synthetic granulates with color additives. The deposition head was outfitted with a pellet feeder that allows for the creation of continuous color changes, since it avoids discrete feeding of the deposition head, as with uniform filaments. The basic architectural archetype of the column served as a testing ground for the combination of a rigorous geometric body with the gestural qualities of sensible robotic toolpaths. The basic prismatic shape of an extruded square (fig. 2) forms the origin for all the conducted tests and was chosen to facilitate the comparison between the models. The range of results, from tight rhythmic patterns to fluffy hirsute clouds, demonstrates the panorama of possible design options with this technique (fig. 6).

The common motif in all models is the application of alternating sequences as the forming method. This pulsation is achieved through a rhythmic variation of speed of deposition. These fluctuations in the deposition speed proved to be a successful method for achieving a variety of effects, from the introduction of apertures in the prismatic proto body by applying higher speeds to the introduction of curls and pearls on the surface by reducing the speed. In combination with the saturated coloration of the material, the process results in richly informed surfaces that make the process of modelling matter highly readable:

> *In the age of Big Data and 3D printing, decoration is no longer an addition; ornament is no longer a supplemental expense; hence the very same terms of decoration and ornament, predicated as they are on the traditional Western notion of ornament as supplement and superfluity, do not apply, and perhaps we should simply discard these terms, together with the meanings they still convey.* (Carpo 2012)

One of the main issues raised by this research is the necessity of creating a novel method of architectural notation that does not rely on the manifestation of a unique, specified condition—as is the case with traditional recording methods of architecture, such as plan and section—but rather utilizes a system that only defines a few key design specifics and leaves the rest to the emergent properties of the chosen fabrication methods and material qualities.

CONCLUSION

In borrowing from the post-digital discourse in music, an alternative method of thinking about architectural production for our contemporary age also calls for alternative methods of describing the current work. To this end, the post-digital can be described as a paradigm, comparable, for example, to post-humanism, which does not describe a universe after the digital, but rather characterizes the contemporary attempt to examine the consequences of the digital age. In other words, the emanations of the human enhancement achieved with computational tools—the ramifications of the globe-spanning prosthetics that are achieved by the application of software—all of which present themselves as exquisite specimens for speculative interrogation and theoretical inquiry. The project Plato's Columns combines the rigor of a body with the emergent properties of vague gestures. The introduction of moments of uncertainty in the process produces glitches that are embraced as an opportunity to find novel aesthetic conditions.

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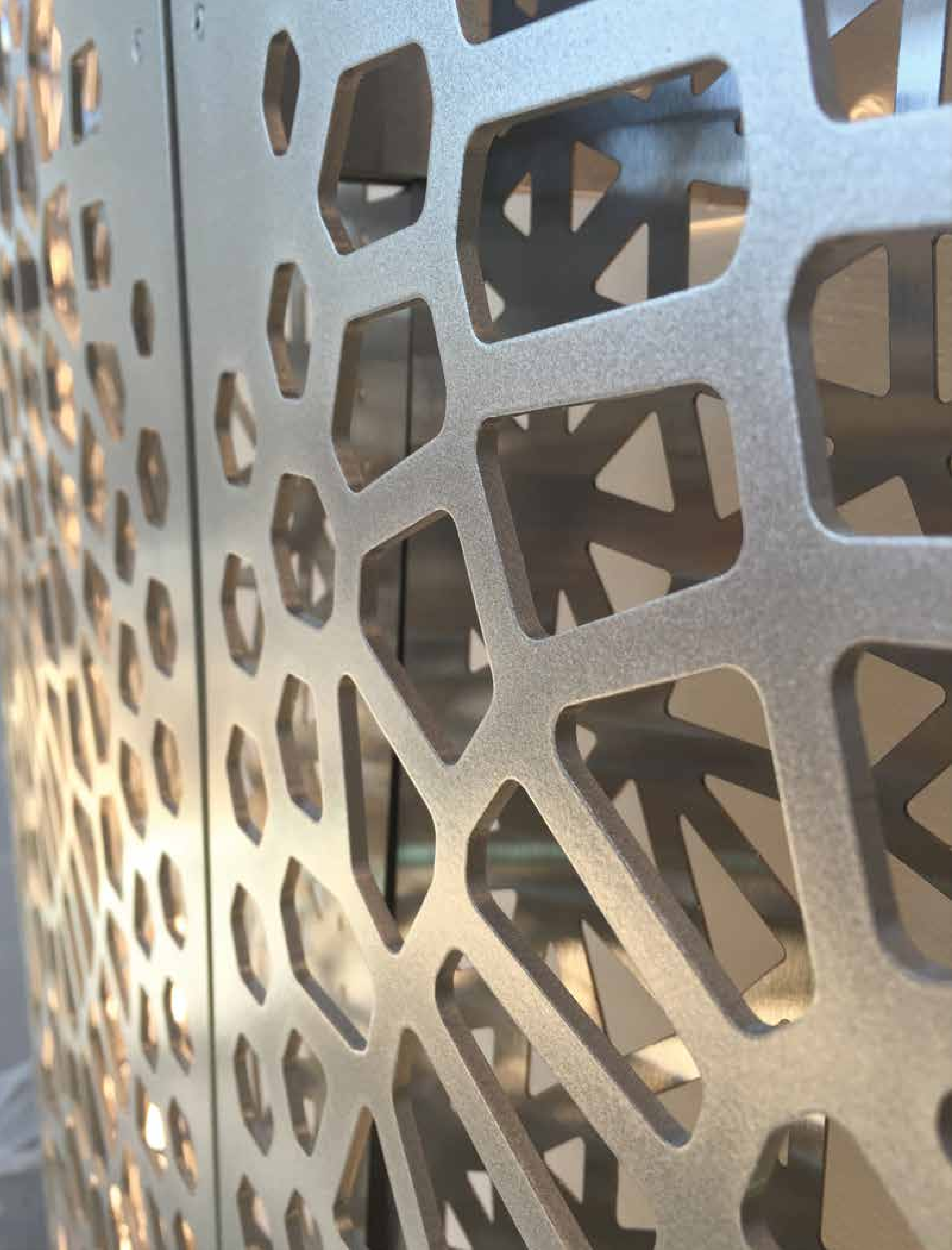
IMAGE CREDITS

Figure 7: The robotic setup, consisting of a six-axis industrial robot and an extrusion head.



Data Moiré: Optical Patterns as Data-Driven Design Narratives

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Anna M. Chaney
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ABSTRACT
Big Data (data sets so complex or expansive where conventional data processing is insufficient) has continually had a big impact. It is affecting the worlds of commerce, media, and design, amongst many others, and more recently it is becoming an industry in itself. This paper documents the research and design process of *Data Moiré*, a large-scale feature wall designed and installed for the IBM Watson Experience Center in San Francisco, California. The project merges the territories of "data spatialization" and "data narrative" by using the cognitive computing capabilities of IBM Watson to inform a data-driven generative design processes. The result is a digitally-fabricated physical installation that illustrates monthly spending cycles by mapping the growing influence of mobile devices on all digital sales from 2013–2015. The data is materialized as a CNC-milled, double-layered aluminum, back-lit screen wall, producing a moi*ré*-like effect through abstract visual interference patterns generated by the overlaying of two mappings of the same data set.

The resultant project is simultaneously an abstract representation of Big Data that offers a uniquely spatial marketing narrative, as well as a dynamic architectural feature with a visual experience that is amplified through the movement of visitors through the Experience Center. The paper reviews initial research and data mining, digital mapping and visualization studies, and the development of tectonic including spatial logics which have proved effective both representationally and atmospherically.

1 INTRODUCTION

Big Data (data sets so complex or expansive that conventional data processing is insufficient) has continually had a big impact. It is affecting the worlds of commerce, media, and design, amongst many others, and more recently, it is becoming an industry in itself. IBM Analytics has emerged as the leading commercial technology platform for uncovering insights into large quantities of highly curated unstructured data.

Similarly, recent conversations in architectural discourse have theorized on the emergence of data-driven design as a paradigm shift, one that leverages computation in using the expansiveness of Big Data to conceive of an architecture that is understood as the registration of "reality as it appears at any chosen scale, without having

Figure 1: Entrance to the Immersion Room at the IBM Watson Experience Center.

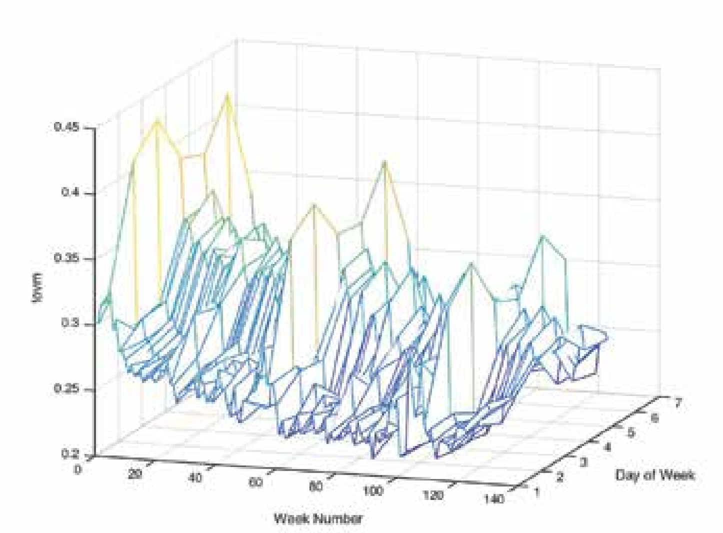


Figure 2: Surface of tovm values.

to convert it into simplified and scalable mathematical notations or laws" (Carpo 2014). The term "data spatialization" has emerged to describe novel architectural materializations that utilize computational design processes to generate novel architectural expressions and spatial opportunities informed by Big Data (Marcus 2015).

In parallel, the media world has witnessed the emergence of a new form of storytelling as "Data Narrative," whereby the crafting of stories happens through the collection and analysis of new or existing sets of Big Data. These data stories utilize data visualizations embedded with narrative components to produce a form of narrative visualization that tells a story through the analysis of data (Segel and Heer 2010).

Data Moiré is a large-scale, data-driven feature wall that merges the territories of data spatialization and data narrative. It uses the cognitive computing capabilities of IBM Watson to inform a data-driven generative design process to articulate a vast quantity of data as a spatial experience and marketing narrative for the IBM Watson Experience Center in San Francisco, California. The result is a digitally fabricated physical installation that illustrates monthly spending cycles by mapping the growing influence of mobile devices on all digital sales from 2013–2015. The data is materialized as a CNC-milled, double layered aluminum back-lit screen wall that produces a moiré-like effect through abstract visual interference patterns produced by the overlaying of two mappings of the same data set. This screen wall is used as the cladding for the Watson Immersion Room (fig. 1).

The result is a dynamic architectural feature that provides identity and enhances the visual and spatial experience of visitors to the Watson Experience Center, while simultaneously providing a uniquely spatial marketing narrative that highlights Watson's ability to analyze large quantities of unstructured data.

2 PRECEDENTS

Several important precedents were referenced and studied to inform the research, design, and development of the project. Many examples were studied and explored in the field of data visualization, and in particular, the precedent of highest importance was the "Centennial Chromograph," by Adam Marcus/Variable Projects. This large-scale installation not only extends the trajectory of data visualization toward data spatialization by physically representing statistical data spanning 100 years in the institutional history of the University of Minnesota School of Architecture, but it also focuses on the abstraction of the data as a means of producing atmospheric effects. Additionally, the work of British Op artist Bridget Riley was further referenced, specifically her studies of variable, non-repetitive two-dimensional patterns that give the illusion of three-dimensional depth and movement.

3 DESIGNING DATA

In an effort to showcase the capabilities of their cognitive computing services, IBM is launching a series of showrooms known as Watson Experience Centers (WEC), with each center focused on a particular commercial market. Current centers exist in New York City and Cambridge, with our project located in the San Francisco WEC and focusing on the retail and commerce industries. The focal point of each WEC is the Immersion Room, an immersive media space where clients of IBM can experience Watson technologies as a visually stunning complete environment. Each WEC Immersion Room is a small circular room floating within an open floor plan. We were commissioned to design the custom exterior cladding for the San Francisco Immersion Room. The brief provided by IBM was simple: to design a custom wall, with a maximum depth of six inches, that would provide a unique identity for the center.

In response to the brief, we proposed a collaborative design approach that challenged IBM to utilize Watson's cognitive computing capabilities to provide us with relevant data analysis to drive our generative design processes. The intent was to consider the feature wall as a physical representation abstracted from a chronological set of Big Data that on its own provided an iconic identity for the center. However, when the wall is experienced as part of a guided tour and explained by a docent, the skin could be utilized as the physical manifestation of narrative visualization, thus providing a powerful analytical, creative, and narrative tool in revealing new ways of comprehending, navigating, and experiencing information (Schneider 2015). To achieve this task, IBM chose a data set that would express the changing face of e-commerce, and the growing influence of mobile devices on all digital sales.

3.1 Collecting Data

IBM Digital Analytics Benchmark delivers aggregated and anonymous competitive website data. The data is collected by measuring every single interaction on every single participating site, capturing comprehensive behavioral data. For our project, we wanted to express the growing power of mobile devices in digital purchases, and we chose the following data series from the Benchmark data:

- a = Daily average order value in USD
- b = Daily mobile sessions as a percent of sales
- c = Daily total number of orders

The data for each of these series was sampled for 123 weeks, from Wednesday, August 21, 2013, through Tuesday, December 29, 2015.

3.2 Translating Data

Data translation was a three-step process:

1. Collate the three daily series into one metric that expressed the strength of mobile devices on digital sales.
2. Transform the data into a two-dimensional pattern.
3. Interpolate the series to the dimensions of the skin.

The data that needed to be combined are of very different scales, and can be combined using the simple transformation:

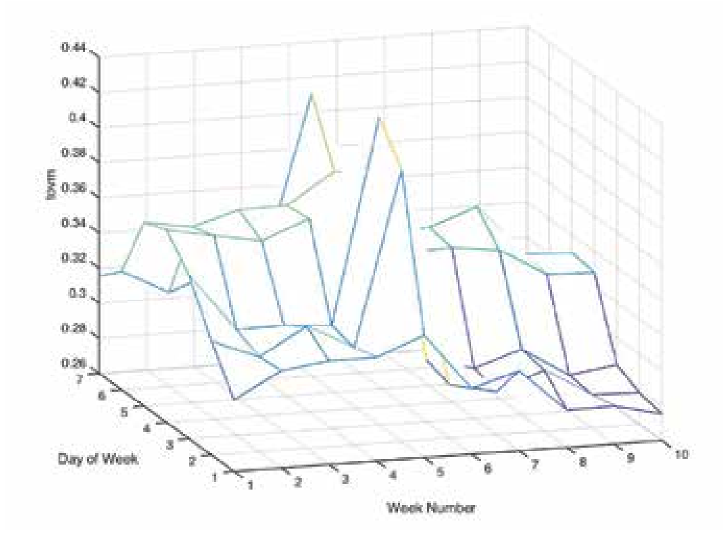
*a*c* = daily total order value (*tov*)

*tov*b* = daily total order value on mobile (*tovm*)

To find trends in the *tovm* data series, we organize the data set into a 7 x 123 matrix, where the rows are days of the week, and the columns are weeks, like so:

DAY OF WEEK DAILY ALIGNMENT FOR TOTAL ORDER VALUE ON MOBILE DEVICES

Tuesday:	29 Dec 2015	...	3 Sept 2013	27 Aug 2013
Monday:	28 Dec 2015		2 Sept 2013	26 Aug 2013
Sunday:	27 Dec 2015		1 Sept 2013	25 Aug 2013
Saturday:	26 Dec 2015		31 Aug 2013	24 Aug 2013
Friday:	25 Dec 2015		30 Aug 2013	23 Aug 2013
Thursday:	24 Dec 2015		29 Aug 2013	22 Aug 2013
Wednesday:	23 Dec 2015		28 Aug 2013	21 Aug 2013



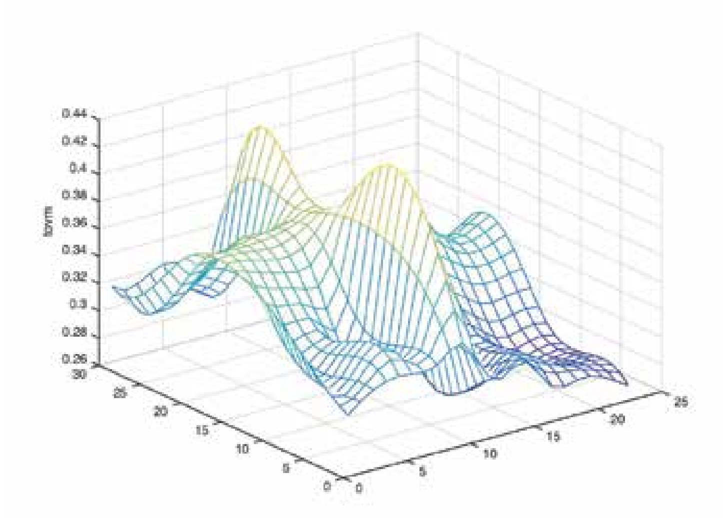


Figure 3: Last 10 weeks of data before cubic spline interpolation (top) and after (bottom).

Using the guide from this table, we then create a surface using the position in the matrix as the (x,y) coordinate, and the tovm value at that day as the z coordinate (fig. 2).

Now, there are several interesting patterns that have started to appear in the data. We see three specific weeks that stand out from the rest of the data set as lateral peaks. These are the weeks containing Thanksgiving, Black Friday, and Cyber Monday. The other pattern visible is a stronger mobile usage for digital commerce on the weekends, as opposed to the weekdays, which reads as a longitudinal intensity across the length of the pattern.

At this point the raw data pattern has two problems:

1. The skin has an aspect ratio of 30 x 280, while the data set has an aspect ratio of 123 x 7.
2. The legibility of the data set is hard to interpret with the hard peaks and jagged edges.

To solve these problems, we resample the surface on the finer using cubic spline interpolation to find the new data points. This solves both size and clarity issues for

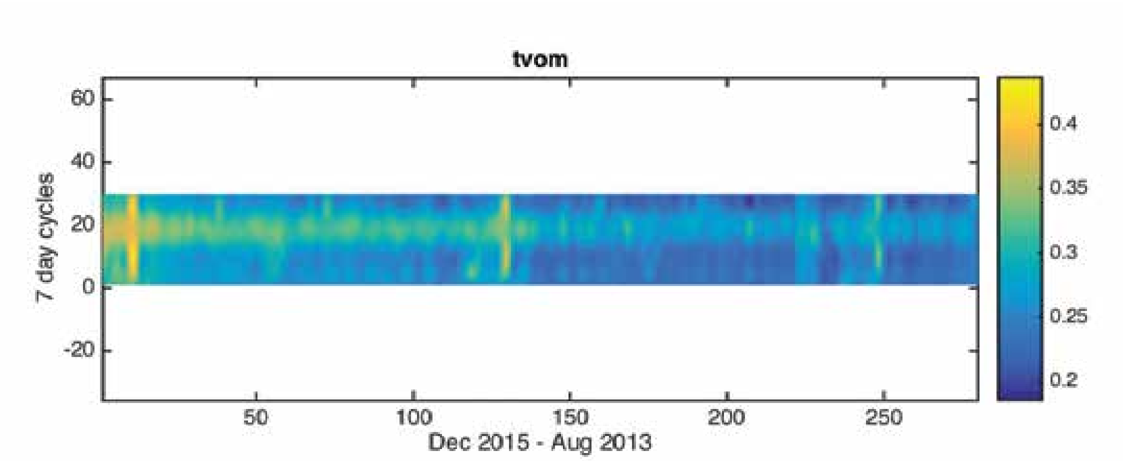


Figure 4: The final data set used to inspire the skin design.

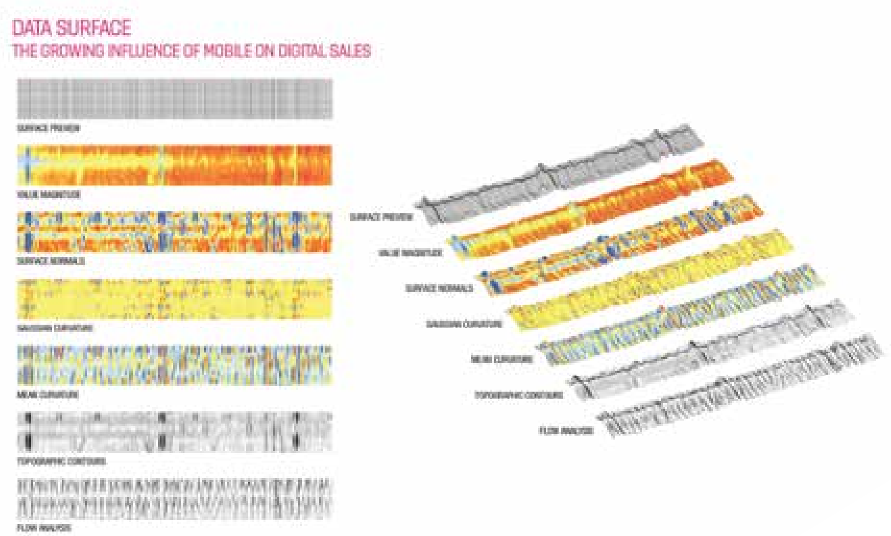


Figure 5: Processing raw given data into producing the patterned networks.

the pattern (fig. 3). Now, the data set for the whole skin can be seen in Figure 4, looking down on the surface and visualizing the z-height as a heat map.

4 DESIGNING FROM DATA

This raw quantitative data was provided to the design team as a three-dimensional data surface produced in the multi-paradigm numerical computing environment MATLAB to illustrate the distribution of digital sales as a chronological continuum of peaks and valleys. The next challenge was to materialize the varying intensities of this three-dimensional data within a six-inch depth. In order to achieve this, it was decided to translate the three-dimensional data surface through the Grasshopper parametric modeling platform as a two-dimensional geometric pattern that could be CNC-milled or laser-cut out of flat sheet metal material to be assembled as a back-lit feature wall. This strategy would allow the three-dimensional data to be compacted to fit within the constraints of the six-inch wall cavity we were provided.

In addition to the physical constraints of depth, we were interested in the ability of geometric patterns to do two things:

1. Adapt their autonomous internal logics to heterogeneous external forces without losing either their organizational or aesthetic identity (Andersen and Salomon 2006).
2. Provide the illusion of depth and motion through variable patterning organizations that produce vivid dynamic illusions that trigger involuntary eye movements (Zanker 2004).

With the previously described design characteristics in mind, a series of design objectives were established as patterning criteria:

1. The materialization should be a two-dimensional pattern that had the legibility of the three-dimensional data surface.
2. The pattern should abstractly express, rather than be a literal representation of, the varying intensities (peaks and valleys) of the data surface.

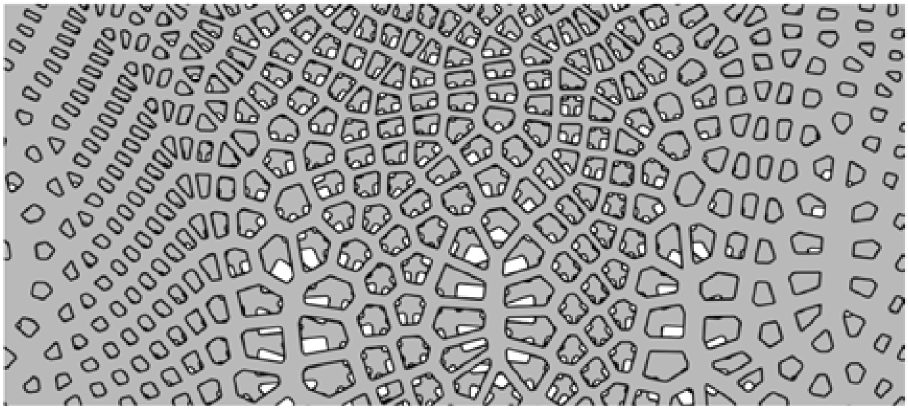


Figure 6: Voronoi network overlaid upon the Delaunay.

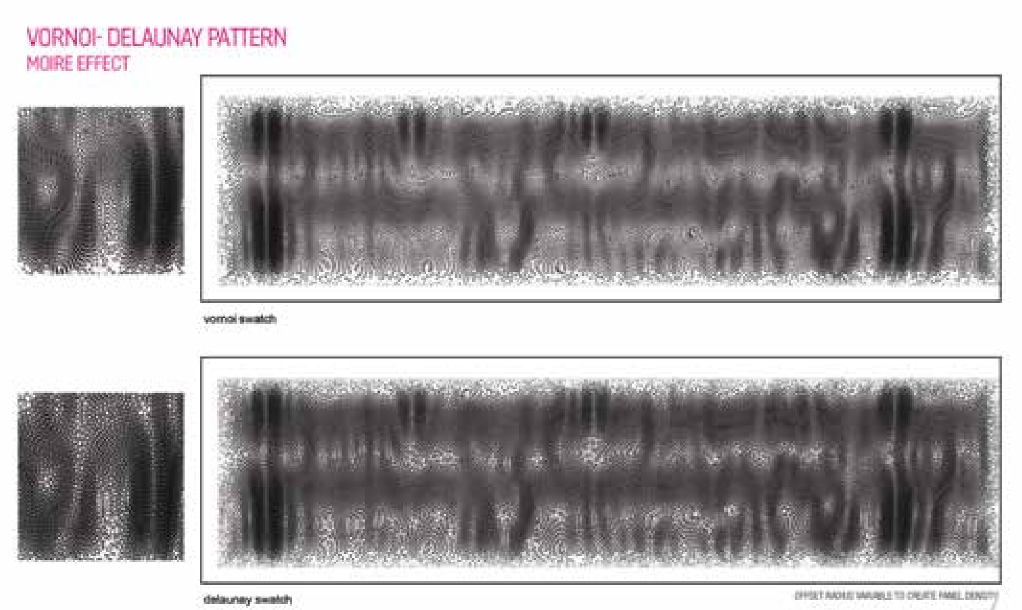


Figure 7: Voronoi and Delaunay pattern shown independently.

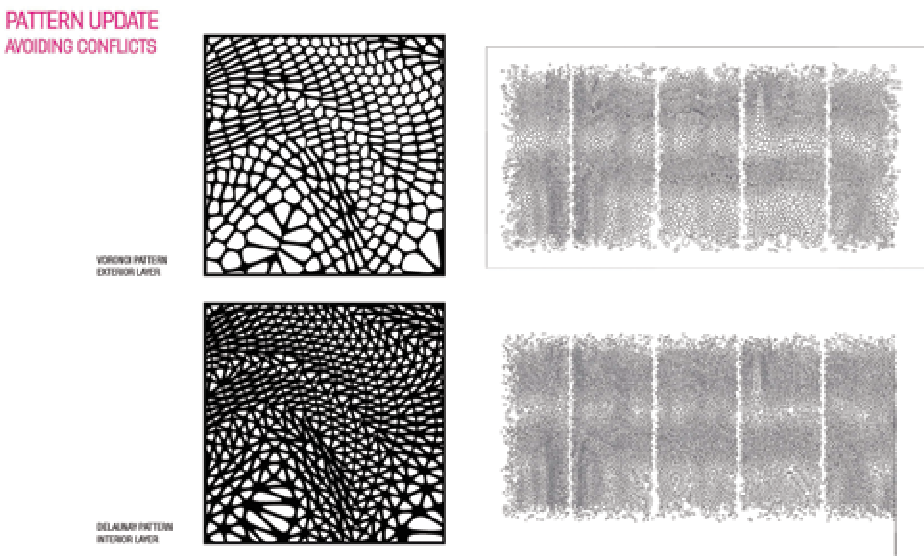


Figure 8: Network inherently avoids misalignments and conflicts.

AXON - VIEW 2 | 3
SCALE = NTS

AXON - VIEW 1 | 2
SCALE = NTS

3. The pattern should provide a dynamic visual experience that would both encourage visitors to walk around the Immersion Room and appear to be different from each and every vantage point.
4. The pattern should be integrated with all structural requirements.

Based off of the established design criteria, a number of explorations were produced to test various patterning techniques and materialization options for the conversion of the three-dimensional data surface (fig. 5). Following these explorations, a design pattern was selected for further development.

4.1 Patterns From Data

In the tradition of architectural representation, a three-dimensional surface is best described as a two-dimensional topographical map. In our instance, by sampling the topographic contours of our data surface as a series of evenly distributed points along the length of each curve, that topographical map is translated twice: once as a Voronoi diagram that defines a series of polygonal cells around each point, and once as a Delaunay diagram that defines each point as a node within a network of connections (fig.6).

This translation abstracts the original data surface into two opposing diagrams of solid (the presence of material) and void (the absence of material), each of which is organized to express the varying intensities of amplitude and curvature that are embedded within the original surface, while maintaining a two-dimensional materiality. While the Voronoi diagram creates an arrangement of cellular voids divided by the perpendicular midpoints of their adjacent cells, the Delaunay

Figure 9: Assembled panels in place, cladding the WEC Immersion Room.

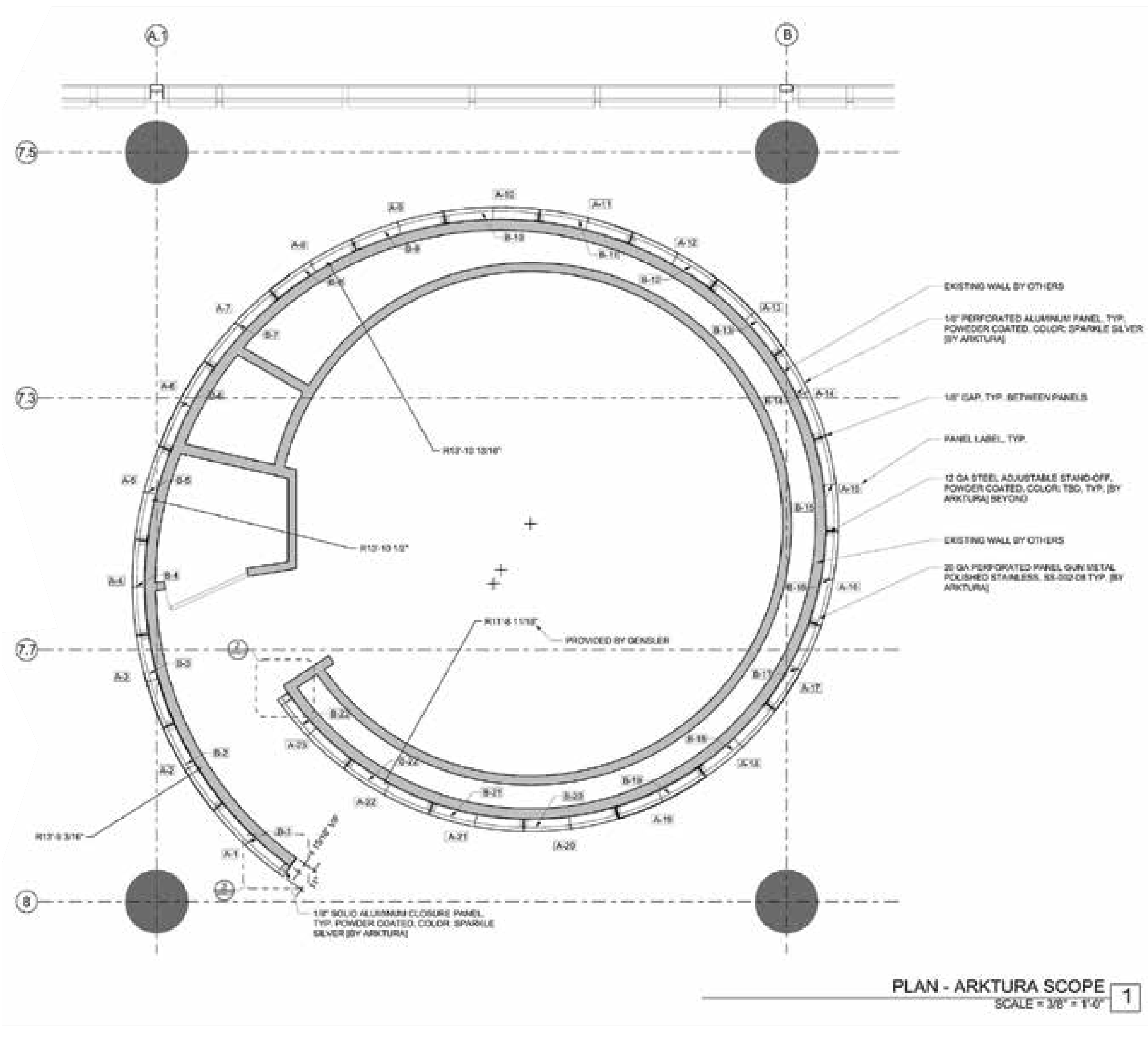


Figure 10: Detail views of CNC-milled and powder-coated exterior skin vs. laser-cut and PVD-coated inner skin.

takes those same points and creates a network of lines connected by them. When overlaid one on top of the other (figs. 7 and 8), the two patterns work collectively to produce a third emergent pattern—one which produces a dynamic visual effect akin to that of a moiré pattern. This visual effect capitalizes on the ability of the moiré to produce an illusion of motion and depth that dynamically engages a viewer and encourages visual interactions through the skin that are exponentially amplified by the viewer's position in space and the variable readings enabled by the alignments, misalignments, and interference patterns produced through the spacing of the two overlaid patterns (Wade 2016).

4.2 Build-a-bility vs. Legibility

The further development of the project required multiple rounds of refinement to the pattern to balance a number of fabrication and assembly criteria (build-a-bility of the installation) against a series of design criteria (legibility of the data within the pattern). Whereas the organization, density, and porosity of the pattern had to be adjusted to contend with the integration of anchor points to the substructure, structural integrity of the individual panels, and visibility of light sources, it was critical not to lose the legibility of the varying intensities within the pattern. In particular, it was key that the dates of Thanksgiving, Black Friday, and Cyber Monday were identifiable as the absolute peaks of intensity within the pattern.

Adjustments were made to the pattern to subtly shift the organization of the pattern to contend with structural anchor points, reduce the density of perforations to maintain structural integrity, and incorporate a created gradient fall-off condition at the outer edges to conceal the visibility of light sources.

4.3 Fabrication & Finish

The entire assembly is digitally fabricated. The outer layer is CNC-milled out of 1/8-inch cold-rolled aluminum sheet with a silver sparkle powder coat. The inner layer is laser-cut out of 20-gauge steel with a gun-metal PVD coating (fig. 9).

The thicker sheet material on the outer layer enables the sheet to be cold-rolled to an accurate radius to ensure visual continuity between the individual panels, but requires a more expensive process of CNC milling. The thinner sheet material on the inner surface allows a more economical laser cutting process and the ability to bend the sheets to fit on site (while not being concerned about visual continuity since the inner layer is covered), thus further reducing costs. The powder-coated finish on the outer layer enables a durable and easy-to-maintain surface condition, while the PVD-coated finish of the inner layer provides for a highly reflective surface condition that is shielded from fingerprints by the outer layer (fig. 10).

5 BIG DATA, DESIGN SPATIALIZATION, & DESIGN NARRATIVE

While the project is driven by data, the legibility of that data is abstract rather than literal. Instead of a statistical or analytical reading of the data, the project provides a spatial and atmospheric reading that enhances the experience of visitors to the center and encourages them to engage spatially (fig. 11). It is only through the guided tour of a docent that the legibility of this data is conceded through a verbal narrative. That oral explanation activates the skin to act as more than a narrative visualization—it becomes a narrative spatialization that not only illustrates the findings of the data that produced it (the chronological metrics of e-commerce affected by mobile sales), but also highlights the technology that produced it (the cognitive computing of IBM).

Figure 11: Photographs of the completed installation.

6 CONCLUSION

The data visualisation focuses on beauty, seen as a kind of aesthetic engagement with big data, a form of knowledge encounter that turns on the complexity and aura of an unimaginable object.
—McCosker and Wilken (2014)

Data Moiré capitalizes on two computational paradigms: the capacity of cognitive computing and machine learning to analyze and provide insights into massive amounts of unstructured data, and the ability of generative design processes to drive geometries that are informed by data. However, it is not the analysis nor the geometries themselves that are the impactful products of this project, but rather the capacity of the analysis and the geometry combined that are able to communicate.

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Quarra Cairn: Incremental Stability Through Shifting and Removal of Mass

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ABSTRACT

Recent advances in integrating physical logic into computation strategies have brought the master-makers mentality back to the forefront of the digital era, and yet, a persistent problem continues. These ongoing efforts to develop reciprocal structures with gravitational forces tend to generate forms that are unable to construct without massive false-work. This paper exercises the potential to intelligently remove material from the interior of a column drum in order to produce a leaning column that could contribute to this age-old problem. The paper describes the computation and fabrication logic. It then demonstrates a full-scale prototype (fig. 1) and some of the discoveries that emerged as a result of the computation process.

INTRODUCTION

Though it is commonly assumed Antoni Gaudí employed a "hanging chain" method to design La Sagrada Família, the famous image of the sandbag-laden, inverted chain model is actually of Colònia Güell, a partially realized project (Burry 2007; Huerta 2013). While Gaudí developed this method prior to the construction of La Sagrada Família, it was not implemented because of a fatal flaw of this strategy. The hanging chain model prioritizes an optimized load path to the ground. The flaw in this noble structure is that in order to become structurally stable, the building needs to exist in its entirety, making it impossible to build without a massively wasteful system of centering and falsework. A clear distinction is manifest in the two projects. While Colònia Güell's columns buttress the forces at angles, La Sagrada Família reverts to the more typical vertical column. As it turns out, it is quite difficult to support a leaning column while the mass above is still being constructed. The intelligence

Figure 1: Full-scale prototype on site at Quarra Stone Company, Madison, Wisconsin, 2015.

of funicular geometry is brilliant in its complete state, but the problem of incremental stability throughout the construction process presents a significant challenge.

While Gaudí pioneered this reciprocity between form and force, other researchers, such as Frei Otto, have continued this line of inquiry (Rasch and Otto 1996). A paper translated this methodology into digital procedures, and The Block Research Group is currently continuing the fight to bend thrust through matter (Kilian and Ochsendorf 2005). A recent work titled "The Armadillo Vault" demonstrates the most recent advances they are making in creating computational techniques which integrate form and force. This work also exemplifies the same issue that Gaudí faced with stability throughout the assembly process. This vault is constructed on a custom falsework consisting of standard scaffolding towers that support four marine-grade plywood waffle structures (Block et al. 2016). The need for falsework in such a project is a minor conceit; however, the necessity for falsework can derive complications at scale, when doubling the geometry, or if attempting to span something that cannot bear weight. Recent research has investigated methods for casting metal details to incrementally support voussoirs in space throughout the assembly process to contribute to these efforts (Ariza et al. 2016).

Is it possible to remove material from the interior of a column drum in order to ensure stability? Asymmetrical stability by means of mass distribution and interior hollowing has also been explored in spinning objects (Bächer et al. 2013). As a case study, a column is designed in a manner that it cannot stand—similar to Gaudí's leaning column problem—without the aid of external support, or in this case, the removal of material. This paper describes the computation and fabrication of a non-idealized column that maintains an equilibrium state during assembly.

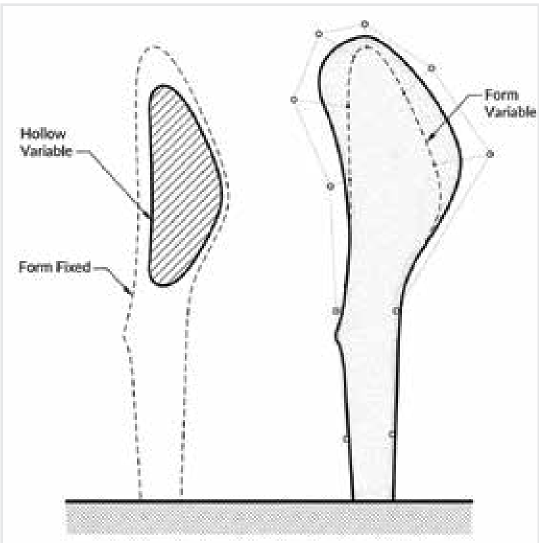

Figure 2: Comparison of computation methods: Mass Carving vs. Shape Deformation.

Definition of Terms

An object is in balance if its center of gravity is above its base of support. The average position of an object's weight distribution is called the center of gravity (COG). For simple, solid objects, such as a sphere or a cube, the COG is located at the geometric center. If an object does not have a uniform weight distribution, then the COG will be closer to where most of the weight is located. The average position of an object's mass or matter distribution is called the center of mass (COM). The point where the line of gravity touches the ground is called the center of pressure. An object is balanced if the center of pressure is inside the base support. When there is more than one area of contact, the base of support is the area

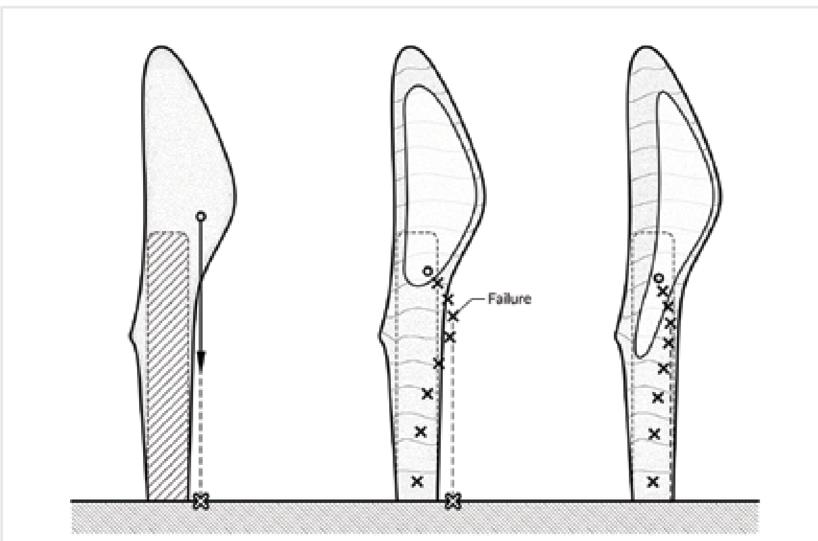

Figure 3: Center of mass and stability throughout assembly. Left is solid; middle is hollowed but only solved for final stability; right shows solving for incremental assembly stability.

inside the perimeter. The line of gravity is an imaginary vertical line that extends upward and downward from the COG. Falsework is framing structure necessary to temporarily support an assembly during the construction process.

COMPUTATION

The intent of this research is to stabilize a stone structure by shifting its COM. For this purpose, a non-stable volume was generated (fig. 2). The input geometry is derived from a polygonal control point rig to produce a calculus-based curvature continuous surface with T-Splines in Rhinoceros.

In Figure 3, in the column on the left, the COG is not above the base support, generating a misalignment between the line of gravity and the base support; the two forces cannot align, and instead, this creates a torque that rotates the object, tipping it over. For the two columns on the right, the COG is above the base of support, so the upward support force from the base is aligned with the downward force of gravity. The line of gravity helps you determine balance; if it passes through the base of support, then the object is in balance. If the line of gravity touches the ground at a point outside the base of support, then the object will tip over.

Stability Optimization

To achieve a stable design, there are an infinite number of deformations that could satisfy the goal of static equilibrium; however, due to fabrication constraints, not all solutions are able to be carved. Additionally, some of the solutions go below the minimum desired wall thickness, rendering a non-structural piece. This computation establishes a range that ensures these other criteria are met while the COG location is being optimized.

Shape Deformation

Given the nature of a polygonal control point rig, a series of control points were specifically selected to remain as fixed constraints, allowing the designer to determine which parts of the volume could deform. As a starting point, the lower portion of the geometry was fixed, and only the top portion of the volume was parameterized to allow for deformation. This approach discretizes the surface into multiple control curves that can be redrawn within a particular range. Consequently, each curve is described by a series of control points that can be moved in the x & y axis, recalculating and comparing the stability for every iteration. Two parameters were established to govern the deformation: First, a range zone was established to allow the point to move in the x & y axis, and second, the surface area was monitored to allow for minimal variation from the original geometry. While it is clearly possible to morph the exterior surface of the geometry to achieve stability, as stated previously in the introduction, there are appropriate scenarios in which to have leaning columns, and for that reason, this paper assumes the Mass Carving strategy.

Mass Carving

The carving approach intends to balance the input geometry by removing interior volume from the object while preserving its external geometry. The goal of this method is to optimize the distribution of material where it is needed to ensure the stability of the object. To achieve static equilibrium, the COG must be within the base of the object when projected along the gravity line to intersect with the base—in this case, a horizontal planar face. An evolutionary solver is used to optimize the interior cavity by redistributing the mass across the overall volume. As previously described during the Shape Deformation method, the geometry was subdivided into point-controlled curves, allowing for better control of the resultant geometry, and limited by a minimum thickness of two inches between the interior and exterior surfaces. This constraint owes to the material integrity of the selected stone, Indiana limestone. The volume described by the curves was then subtracted to generate an interior cavity, redistributing the mass to achieve balance.

Incremental Stability

One of the challenges of fabricating with stone is the substantial weight of the material. Greek builders held tremendous ingenuity with regard to proportioning and discretizing column geometries; the Acropolis is great example of these techniques. While most of the ongoing research in discrete structures evaluates performance once the assembly process is completed, this research contributes to the effort of computing the static stability of structures during construction by calculating the incremental stability at each step of the stacking process. In a paper titled "Make It Stand," static equilibrium is computed via an interactive solver that carves and deforms as a formfinding-driven calculation for 3D-printed objects (Prévost et al. 2013). This research explores solutions to equilibrium at each stage of construction by computing and modifying the COG of individual components.

After satisfying the global stability using the Mass Carving strategy, the next step of the process is to calculate the stability after each of the drums are set in place; for this, we needed to take into account the COG of each individual piece and the ones below. In this example, the global geometry is composed of 17 drums; therefore, all 17 local centers of gravity produced during the erection of the structure need to rest within the overall global base support of the geometry. The incremental stability is resolved by feeding the 17 volumes to the fitness criterion while solving for a global line of gravity so that each drum can be carved individually but associated to the rest with the common goal of shifting the global center of pressure

Figure 4: Cutting Indiana limestone from slabs to blanks.

Figure 5: Finish milling of exterior surface utilizing a seven-axis toolpath.

deeper into the center of the base. As a result, the drums near the top preference a denser mass opposite the side of the cantilever, almost aligning all the centers of gravity in a vertical array; non-external deformations are used to achieve the desirable stable solution.

Evolutionary Solver

Evolutionary algorithms, derived from biological evolution, are a series of mathematical operations that approximate solutions to a specific fitness criterion by self-informed mutations. The fitness criterion uses the volume Grasshopper component to calculate the COG for the input geometry, and each iteration redefines different x & y values for each curve control point. All the curves then define an interior geometry that is subtracted from the initial geometry, generating a different calculation for the COG. Each of these iterations learns from the previous, narrowing down the solutions. For the purpose of this research, the optimizer evaluates the stability of the global geometry by measuring the distance between the center of gravity of the column and the centroid of the base on a horizontal plane. The closer the COG is to the centroid of the base, the more stable the global geometry is.

Once the global geometry in reference to the COG was established, a series of other parametric Grasshopper scripts were employed to slice the whole column into individual drums and to define the amplitude of the matching drum faces. These parameters were established in reference to the fabrication requirements discussed later, and to contend with rotational equilibrium, ensuring a specific, unique fit for each matching drum face. The key geometry for each male/female drum face was derived as a parametric offset of the surface perimeter to further address rotational instability.

Calculating Wind Load Stability

Although computation allows us to calculate the COG relative to the geometry, there are other physical factors that influence the stability of an object. A site-specific installation, like this one, can encounter other environmental factors, such as wind, rain, snow, and earthquakes. Given the characteristics of the site, Madison, Wisconsin, the lateral wind load presents the most significant challenge. Autodesk Flow Design virtual wind tunnel served to simulate the point load reaction applied by the wind. Based on the local wind rose datasheet, there is a maximum reported average speed of 11.4 mph from a northwest direction, with a maximum speed of 47 mph. This calculation uses a factor of error of 1.5, for a wind speed of 70.5 mph. Given the surface area of the volume projection onto a northwest vector, a maximum wind load of 60 pounds has been applied to the surface at a 12.4-inch height. Because of an approximate total weight of 6 tons, the wind load does not present a significant threat to the stability of the structure.

FABRICATION

A seamless digital workflow from file to production allowed rapid prototyping and proofing of the computation concepts. A KUKA KR 500 robot with a high-speed spindle and electroplated diamond-tipped cutting tools were used for wet machining the limestone. The milling process uses water as a coolant for the tooling and ensures the minimization of airborne dust particulates as the material is pulverized during the machining process. Quarried stone was cut into slabs initially, then stock blanks using a large circular saw (fig. 4). The bulk of material removal was done with a standard three-axis milling procedure, while the most critical operations synchronized the six-axis robot with the external rotary axis (fig. 5). The sequence of operations was determined by a key indexed flip milling process, which utilizes the previously produced part as a fixture for sequential parts (fig. 6).

Figure 6: Key Index Strategy – roughing operation of stacked drum.

Figure 7: Key joint detail of drums showing the male/female match to ensure rotational equilibrium and stability.

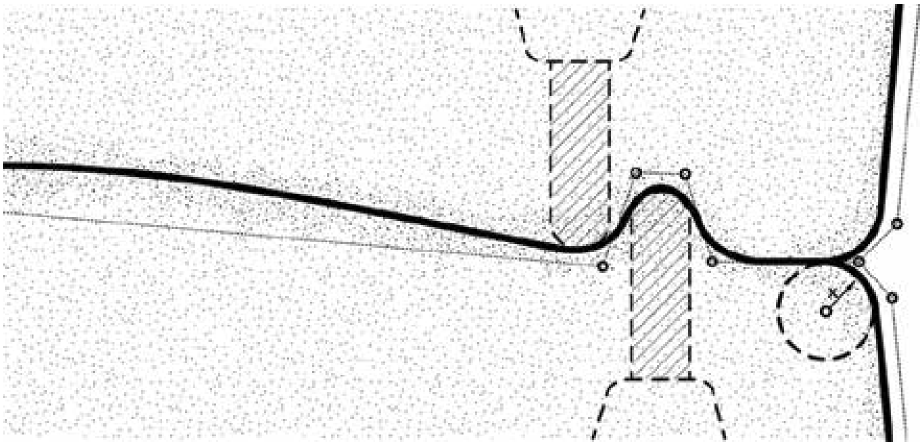

Figure 8: Male surface key detail (top) of drum. The key is a parametric offset of the drum face geometry.

Figure 9: Filleted drum seam as seen from the column exterior.

Mass Carving

Prototypes were made with Indiana limestone due to its homogeneity of grain and texture, and its ease of milling. Material removal by kerf cutting with a radial saw blade is common practice in modern stone cutting, but the geometrical conditions of our prototypes—namely, double curvature and interior cavity milling—necessitated our chosen approach (Rippmann et al. 2013). The height of our drums was constrained by the dimensional length of our custom tool. Surface milling from a volumetric blank typically requires multiple procedures of roughing and finishing within machine and tooling constraints (Burry 2016). Milling on all sides of a volumetric blank requires various steps of flip milling and indexing of parts.

The six-sided blanks cut from quarried slabs of Indiana limestone were three-axis rough machined with a 2-mm offset using a 75-mm diameter diamond electroplated bit on a 400-mm extension shaft. Finish milling the top male convex surface of each drum was done with a 19-mm diamond electroplated ball nose bit. The key geometry necessitated specific tooling decisions for machinability (fig. 7).

These drum parts were eventually flipped into a matching fixture to rough cut the inverse side of the part, removing any undercuts missed during the first roughing operation. For expediency, a three-axis scallop finish toolpath completed the top surface to the perimeter filleted edge (fig. 8). A slope analysis of each drum face was conducted to ensure an accurate surface milling of the perimeter male/female key with the ball nose tool without requiring a more complex five-axis toolpath. The result of these parameters was a gentle curve seam between the stacked drums (fig. 9).

Key Geometry

A vacuum system is typical in holding down stock during machining, but with an average mass of 70–90 kg, each limestone drum was secured in place by gravity as well as by the locking mechanism of the male/female key. The key, running the perimeter of each face, also served as the indexing method during the many re-orientations of the part. The key also uses a doubly curved surface as a friction lock to prevent rotational movement of the dry stack joint. It was determined that the greater the oscillation of this key surface, the better (fig. 10).

Key Index Strategy

Successful flip milling requires a precise matching fixture of the inverted non-planar part. Our fabrication process required eight unique machining operations for each drum and 51 orientations of drum parts from blank stock to dry stacked column. Therefore, the embedded indexing key ensured precise re-indexing throughout the process of fabrication, reorientation, transportation, and assembly (fig. 11). Every male convex top drum face had a matching female concave bottom face counterpart, which was leveraged during the flip milling and keying procedure. A consumable master key to fixture the drum parts served as the base coordinate system for each operation. All milling operations could have been performed on each drum part individually, but in an effort to reduce redundancies and expedite the fabrication process, two drums were simultaneously dry stacked for the final two steps. Utilizing a fixed robotic tooling angle in sync with the external rotary axis, the surface milling of the drum flutes was performed as a seven-axis operation.

The robot maintained its tooling angle along the vertical length of the two stacked drums as the rotary axis spun to allow complete 360-degree reach of the part geometry. This strategy with the rotary axis improved accuracy with an indexical step over of 1 mm, producing a digital fluting in reference to ancient Greco-Roman technique. In fact, this method of stacking drums and carving across the seam was a common practice in ancient column carving. Drums were roughed out and stacked; then, once assembled, the flutes were carved, further disguising the seams between drums through shadow relief.

Software Workflow

The software workflow required a series of hybrid toolpath and simulation procedures. SUM3D served as the robotic CAD/CAM interface which was simulated and translated into KUKA KRL code using ROBOmove. ROBOmove also synchronized the rotary external axis to optimize for the appropriate robotic tooling angle. Certain drums required additional check surfaces, containment boundaries, and primitive geometries for establishing tool angles. Roughing toolpaths were created with SUM3D, but the male/female drum faces were scallop-finished with toolpaths extracted from Mastercam. The vertical flute toolpaths of the drum exterior surface were generated using a custom Grasshopper script, which was also translated through SUM3D into robot code.

PROTOTYPES

3D Prints

To validate the most successful method, a 3D print was made for each: Shape Deformation, Mass Carving, and a solid plaster print for control. The validity of the stability analysis was assessed through a series of scaled

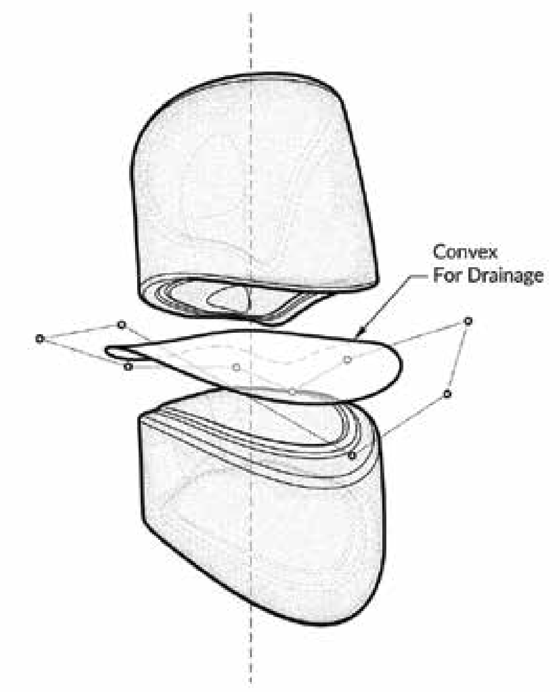

Figure 10: Global alignment condition of drum geometry, parametrically calculated for each matching drum face after the evolutionary solver.

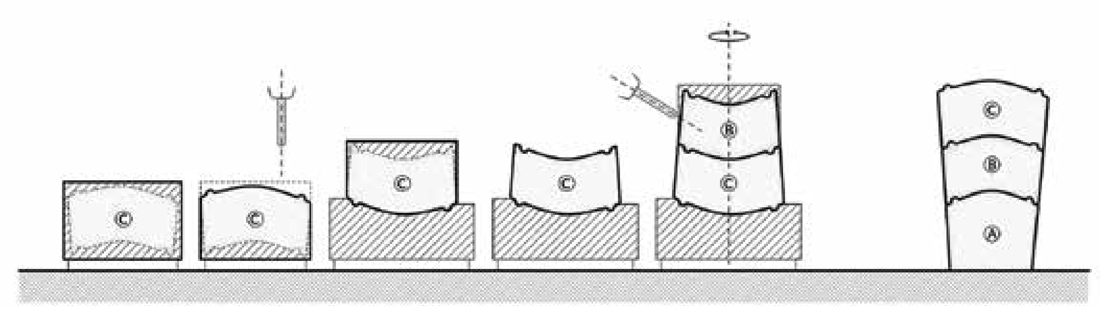

Figure 11: Key Index Sequence during the fabrication process.

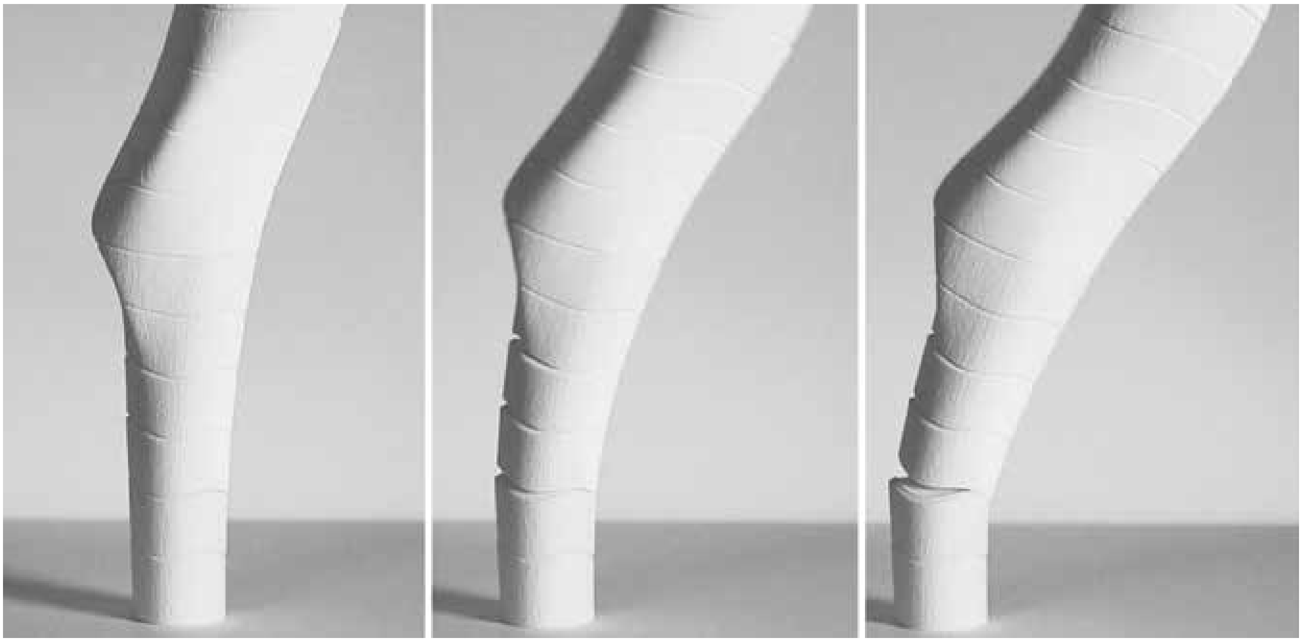

Figure 12: Photos of the plaster 3D prints falling.

Figure 13: Initial drum study for the Shape Deformation method, which led to improvements in the drum face geometry and milling strategy.

physical tests of specific optimization details and prototypes as demonstrated by prior full-scale prototyping in stone. Shape Deformation introduced an unacceptable distortion from the original geometry; furthermore, based on this specific case study, Mass Carving generated a more stable geometry. 3D prints were also used to evaluate different keying strategies of the drums (fig. 12). The 3D-print prototypes provide a rapid way of testing multiple key locking details, eventually developing a 500-mm-tall stackable prototype.

Another realization emerged through the rapid prototyping. A design was computed that, when printed solid, would stand, but when discretized into individual column drums, became unstable two-thirds of the way assembled. While this failure is self-evident in hindsight, the act of prototyping the geometry brought attention to a flaw in our computation approach. The initial approach did not visualize the incremental stabilities and instead calculated for the global COG, assuming the incremental was stable as well. This discovery refocused the computation research to incorporate this condition.

Process Prototypes

To ensure an accurate digital-to-physical workflow, a variety of process prototypes were simultaneously created while the digital tools were developed. At first, individual drums were milled to understand the material, fabrication parameters, and logistics of flip milling. The team realized that machining the drums from the top, as opposed to front and back, was most efficient if the tool was long enough, which led to the decision to fabricate a custom milling tool. This technique also reduced vibrations, which were problematic on smaller parts. On one early drum study (fig. 13), a test was performed using the external rotary axis in combination with a spiral seven-axis finish toolpath while the robot tool maintained a fixed angle. This proved to be inefficiently slow, so the decision was made to develop the Grasshopper script for vertical surface fluting, which minimized machine time.

The first stackable prototype proved the concept of shifting mass but revealed the need to create a more dynamic drum joint to prevent rotation as opposed to the flat stacking (fig. 14). It also led to the decision to invert which drum surface was the convex male and which was the concave female to allow for proper water drainage towards the exterior. Later studies revealed the need to fillet the drum edges to reduce chipping, but more importantly, it encouraged the implementation of a perimeter ring offset from the male/female faces of each drum to precisely lock each compressive drum into each other like a key.

Full-Scale Prototype

The five-meter-tall, dry-stacked "Quarra Cairn" stands as a proof of concept for a computational workflow informing advanced fabrication techniques. Seventeen unique drums equal to one cubic meter of sculpted Indiana limestone, weighing in at 2,450 kg. The stone has 4,000 psi compressive strength and was calculated to have a 700 psi modulus of rupture. A threaded stainless steel rod for post-tensioning runs through the core of the drums and is anchored into a reinforced concrete pile. This added a secondary measure of safety during the in situ dry stacking assembly, which involved cranes with nylon straps for lifting (fig. 15). We decided to only rough mill the interior cavity, which can be viewed through the porthole opening (fig. 16), allowing observers to understand the physics of the column and the secret to the stability even though the column appears unstable (fig. 17). Post-processing of the exterior surface was done with common honing techniques to address any blemishes or inconsistencies in the stone. The full-scale prototype remains at the Quarra Stone Company in Madison, Wisconsin, as a proof of concept for integrating digital workflows with physical fabrication processes.

Figure 14: Flip milling key strategy prototype. The dramatic amplitude of the drum faces confirmed rotational stability as compared to a flat drum face.

Figure 15: Construction of the final column.

Figure 16: Visual connection to the interior cavity of column where mass was removed, looking upwards towards the orifice on the opposite side at the top of the column.

CONCLUSION

This research demonstrates the potential for a computational workflow that allows for the design, fabrication, and assembly of a non-stable global form by ensuring incremental stability at each stage of the process. It also attempts to reconsider the viability of structurally optimized final forms to accommodate incremental fabrication and assembly challenges. While this research successfully designed, simulated, fabricated, and assembled a stable cairn from a non-stable form, a number of other criteria emerged through the prototyping that could become incorporated into the solver logics. For instance, the final form and carving was checked against lateral wind and live snow loads, but only in order to verify the stability post-design. This information was not incorporated into the intelligence of the solver. Coordinating digital and physical workflows was a nonlinear process, which could be an area of refinement for efficiency of digital design to physical production. The research contributes to the potential for construction of unstable geometric forms without the need for falsework.

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Figure 17: Full-scale prototype consisting of 17 unique dry-stacked drums on site.

Submillimetre Formwork: 3D-Printed Plastic Formwork for Concrete Elements

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1 ABSTRACT

Submillimetre Formwork is a novel method for fabricating geometrically complex concrete parts with 3D-printed plastic formwork (fig. 1). This research investigates how 3D printing can be used to fabricate submillimeter-thin formwork. To achieve this, computational methods for optimizing the fabrication speed of formwork with plastic deposition 3D printing are developed, as well as methods to stabilize the minimal formwork during the casting process. Without any coating and post-processing steps, the plastic formwork is easily removable, recyclable and bio-degradable. The implications of *Submillimetre Formwork* are a considerable material reduction, faster off-site fabrication time for the formwork, ease of transportation to site, ease of on-site assembly, and unprecedented design opportunities for free form and highly detailed concrete components.

2 INTRODUCTION

With more than 10 billion tons produced each year, concrete is by far one of the most used materials in the world, second only to water (Olivier, Janssens-Maenhout, Muntean, & Peters 2016). Concrete is ubiquitous in the building industry due to its versatility, wide availability of raw materials, and low embodied energy. It is favored by engineers because it has excellent structural properties, and it is celebrated by architects because it can be cast into any conceivable shape.

But in order for concrete to materialize a shape, it needs a formwork to be cast in, a mold to be sprayed on, or a die to be extruded through. The excellent geometric potential of concrete is therefore limited by the ability to fabricate the necessary formwork.

> *Although reinforced concrete has been used for over a hundred years and with increasing interest during the last decades, few of its properties and potentialities have been fully exploited so far. Apart from the unconquerable inertia of our own minds, which do not seem to be able to adopt freely any new ideas, the main cause of this delay is a trivial technicality: the need to prepare wooden frames. (Nervi 1956)*

For concrete construction, formwork accounts for a significant amount of resources, both in terms of material costs and labor (fig. 2). In particular, for free-form, non-standard parts, formwork resources can represent more than 60% of the whole construction, more than

Figure 1: Prototype for an architectural concrete element cast in Submillimetre Formwork. - DBT, ETH Zürich, 2017

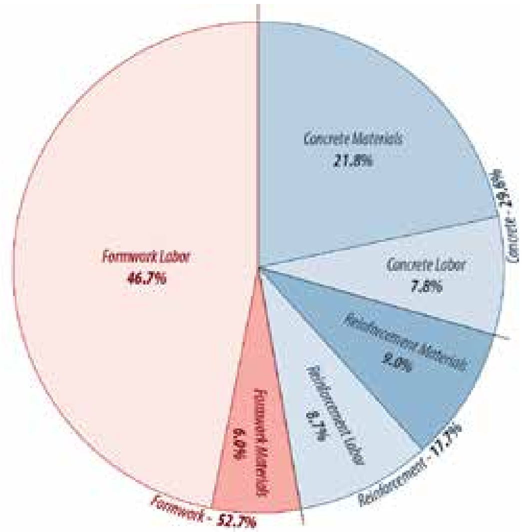


Figure 2: Breakup of costs in concrete production. On average, formwork accounts for roughly half the resources in terms of both labor and materials (Oesterle, Vansteenkiste, and Mirjan 2012).

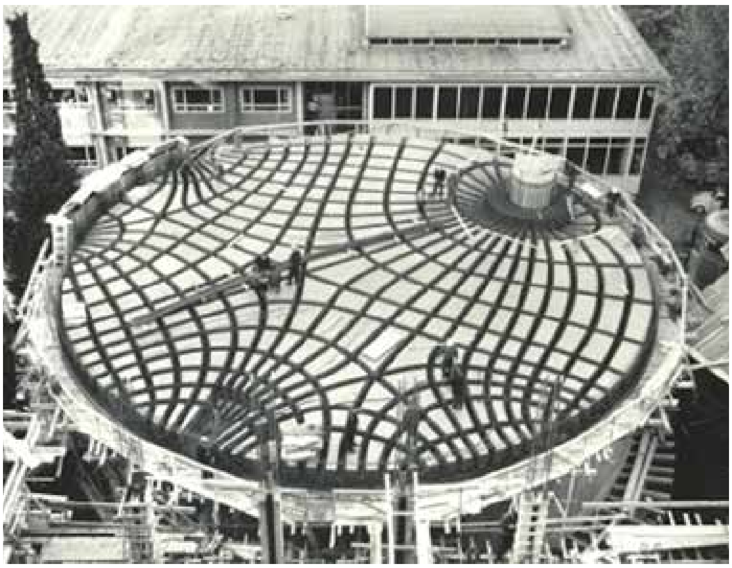


Figure 3: Formwork represented 80% of the construction costs for the slab of the Zoology Lecture Hall of the University of Freiburg, designed by Hans Dieter Hecker in 1969 (Antony et al. 2014).

concrete and reinforcement combined (fig. 3).

The elevated cost of non-standard formwork compared to the low cost of raw materials discourages complex geometries that efficiently distribute material. Geometrical simplicity is preferred over optimal material use because materials are cheap and custom formworks are expensive.

Given the significant importance of formwork in concrete construction, the aim of this research is to minimize the amount of material and labor used for fabricating formwork. The objective is to develop an efficient, automated fabrication method based on 3D printing which can be used for making formwork for large-scale, complex concrete components. This can have further positive effects on: the sustainability of formwork; speeding up formwork fabrication off-site; reducing the cost of transportation; streamlining assembly on site; and facilitating removal and reusability after casting.

Yet the most significant advantage of 3D-printed formworks is their potential to enable complex topologies to be cast in concrete, which can have further indirect implications:

- Considerable material reduction through computational topology optimization algorithms, which result in complex geometries (Jipa et al. 2016).
- Integration of additional functionality, such as surfaces with acoustic properties, thermal activation, insulation, and enclosures for building services.
- Smart integration of construction and assembly logics that streamline on-site fabrication, such as interlocking connections and referencing systems.
- New design possibilities for free-form geometries and high-resolution ornamental surface articulation (Dillenburger and Hansmeyer 2013).

Production of formwork for non-standard concrete elements is done in practice by robotic hot wire cutting or CNC milling of foam blocks (Søndergaard, Amir, and Knauss 2013). Lightweight formwork can also be produced with fabric (Veenendaal, West, and Block 2011). However, these approaches are resource-intensive as regards necessary time and labor (milling tools are slow and fabrics require extensive patterning) and have limitations regarding the geometries that can be produced (e.g. no undercuts for milling, and only smooth, anticlastic surfaces for fabrics).

3 3D-PRINTED FORMWORK

To overcome these limitations, different 3D-printing technologies have already been proposed for formwork (fig. 4). The architect and researcher Philippe Morel of EZCT has experimented with two different technologies to 3D print formwork for concrete. Clay robo-casting produced a rough result, inheriting the coarse layers of the extrusion process. With binder jetting, he created a three-dimensional triangulated truss structure cast in concrete to demonstrate this material's load bearing capacities. The binder-jetted half shells are infiltrated with epoxy resin and assembled to form the hollow tubular mold prior to being cast. The structure has a very smooth surface quality; however, it lacks reinforcement. Additionally, formwork removal limits to some extent the geometric freedom (Gosselin et al. 2016).

A jump in scale and resolution was made with the realization of the Swiss pavilion for the 2016 Architecture Biennale in Venice. "Incidental Space," designed by Christian Kerez, is a 9m-long and 6m-high room enclosed by a 2-cm-thin shell of polymer fiber reinforced shotcrete. Around a third of the formwork parts were binder jetted in sandstone and infiltrated with a release agent. No other known fabrication method would have allowed for the production of this level of detail (Dillenburger 2016).

A further precedent of binder-jetted formwork comes from ETH Zürich, where a 1.8m² topologically optimized slab was fabricated using ultra-high-performance fiber-reinforced concrete (UHPFRC) cast in a 9mm-thick sandstone 3D-printed shell. This showed how the complex topologies resulting from computational optimization algorithms can be fabricated to considerably reduce material in load-bearing components (Aghaei-Meibodi et al. 2017).

In contrast with the first two examples which use binder jetting, Brian Peters from Kent State University tested and patented fused deposition modelling (FDM) for fabricating formwork (Peters 2014). Peters discusses small-scale horizontal elements, and his research shows that there are inherent characteristics of FDM 3D printing that need to be addressed in order to make this technology feasible for large-scale fabrication. Scaling up and applying this process to vertical components such as walls and columns is challenging due to the hydrostatic pressure exerted by the concrete on the formwork.

The research question posed by *Submillimetre Formwork* is how large-scale, geometrically complex structural concrete parts can be produced with minimal FDM 3D-printed formwork.

Figure 4: Precedents of 3D-printed formwork for concrete, clockwise from top left: Philippe Morel, EZCT 3D-Printed Formwork, 2014; Christian Kerez, Incidental Space, 2016; DBT, The Smart Take from the Strong, 2017; and Brian Peters, Additive Formwork, 2014.

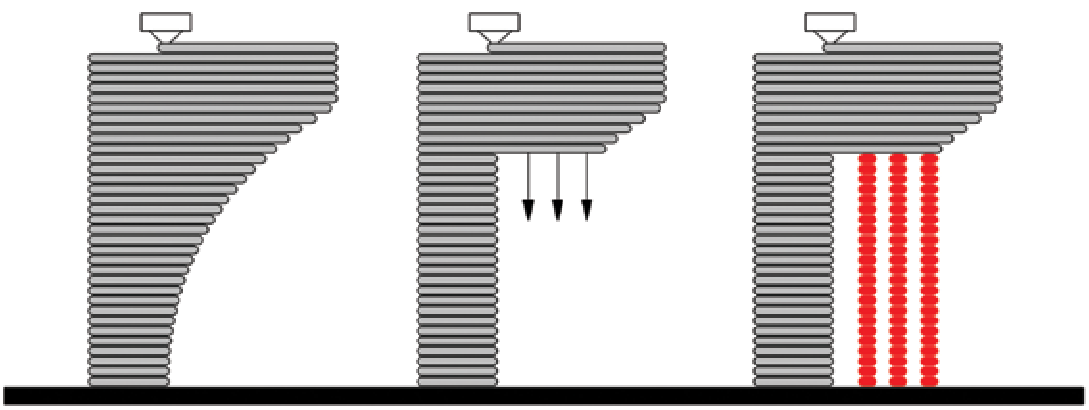


Figure 5: The FDM fabrication process requires auxiliary support structures (in red) for certain geometric features, such as overhangs and cantilevers. - DBT, ETH Zürich, 2017.

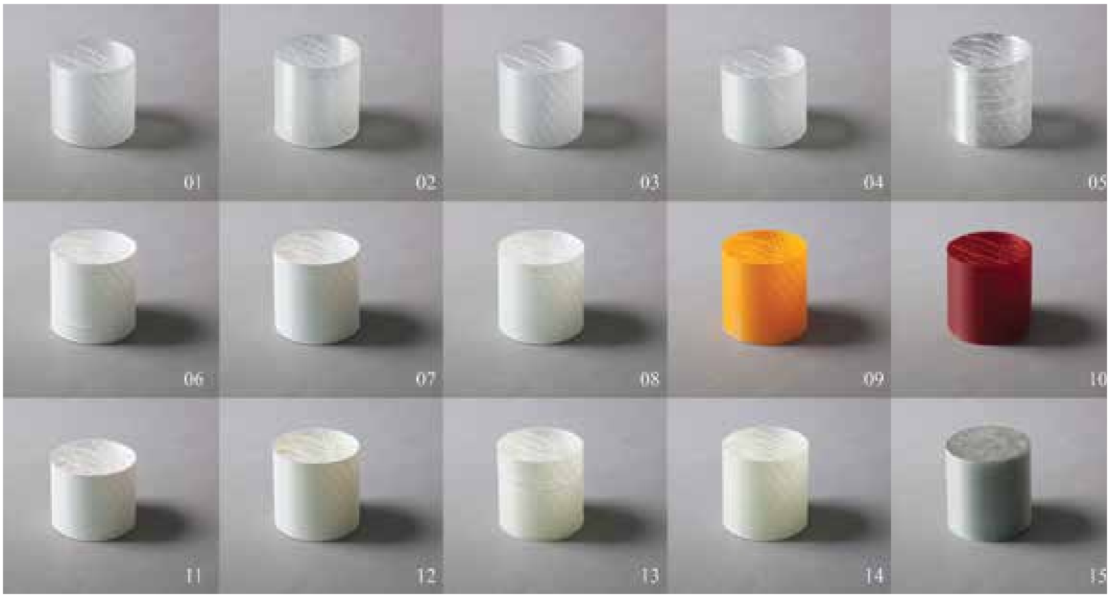


Figure 6: Different thermoplastics tested for finding a balance between printing speed, quality, and shrinkage. From the highest printing speeds achieved to the lowest: natural polylactic acid (01); natural polylactic acid/ polyhydroxyalkanoate blends (02–04), polyethylene terephthalate glycol-modified (05 and 06), polylactic acid with pigments (07–10), polyvinyl alcohol (11), biodegradable plastic Green-Tec™ (12–15). - DBT, ETH Zürich, 2017

4 METHODS

FDM is a widely available 3D printing technology in which molten material is extruded and hardens immediately after the deposition. The deposition happens in consecutive horizontal layers which are generated as slices through a digital model of the part to be fabricated. Despite some fabrication limitations—such as the inability to produce unsupported cantilevers (fig. 5)—FDM is unique among the different 3D-printing technologies for its capability of producing large-scale freestanding parts with very thin geometric features, such as walls as thin as 0.4 mm.

Because of the nature of the FDM process—where the build material solidifies and cools down quickly—a limitation of this technology is determined by the dimensional inaccuracy caused by uneven shrinkage during thermal contraction. Shrinkage is a function of the total volume of plastic:

$$dV = \mathbf{V}_0 \, ß \, dt$$

where dV = shrinkage in m^3
V_0 = initial volume of the formwork in m^3
$ß$ = volumetric thermal coefficient of PLA in $°C^{-1}$
dt = temperature variation in °C.

The overall time necessary for the 3D print is also a function of the volume of formwork:

$$t = \mathbf{V}/Q$$

where t = 3D printing time in s
V = total volume of the formwork in m^3
Q = volumetric flow rate of the 3D print in m^3/s.

By reducing the total volume of formwork material to the thinnest skin possible, both the 3D printing time and thermal shrinkage are reduced to a minimum. This section discusses how the plastic 3D printing and the concrete casting processes can be optimized to enable the fabrication of *Submillimetre Formwork*.

4.1 3D-Printed Plastics for Formwork

FDM is a relatively slow 3D printing process, usually able to produce volumetric flowrates of 15 cm^3/hour and resolve 0.1 mm features. With well-tuned machines, flowrates as high as 100 cm^3/hour can be reached, but this has a negative impact on the resolving power, which increases to 0.2 mm.

A critical factor in achieving such high flowrates is the material used. FDM can extrude a wide variety of plastics (biodegradable, water-soluble, fiber-reinforced, flexible, conductive, low-shrinkage, bioplastics, etc.). In order to achieve a balance between fabrication speed, quality, and shrinkage, different materials were tested, and finally translucent polylactic acid (PLA) was selected for its versatility and low shrinkage factor (fig. 6).

While flowrates of PLA can be further increased through mechanical improvements of the hardware, the focus of this research is to speed up the 3D printing process on the software side, by generating an optimal tool path that controls the movements of the 3D printer tool head.

4.2 Optimized 3D Printing Tool Paths

Tool paths are generated from horizontal slices through a CAD model of the part to be 3D-printed. A custom slicing tool was developed for optimizing the travel distances between the different contours in each horizontal slice. The contours are sorted with an efficient algorithm that minimizes the distances between consecutive contours (fig. 7). In order to compute this optimization problem, each layer is interpreted as a complete weighted graph, where the graph nodes are contours and the graph weights are

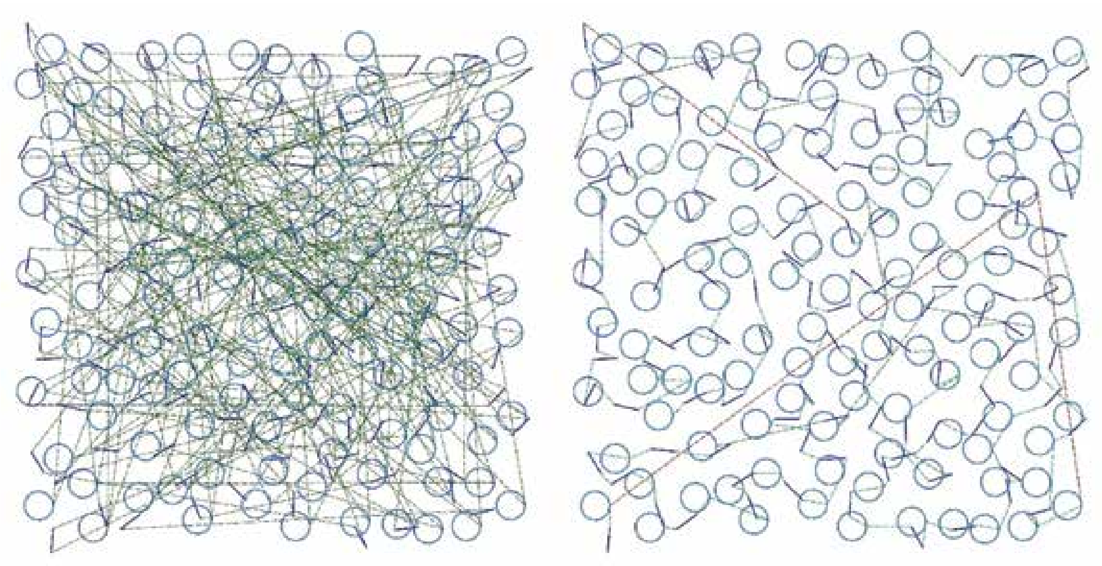


Figure 7: A slice through a CAD model with 100 line segments and 100 circles as contours. In a random order, this configuration generates a very long, inefficient tool path (left). The NNA arranges the 200 contours in an order that minimizes distances between consecutive contours (right). - DBT, ETH Zürich, 2017

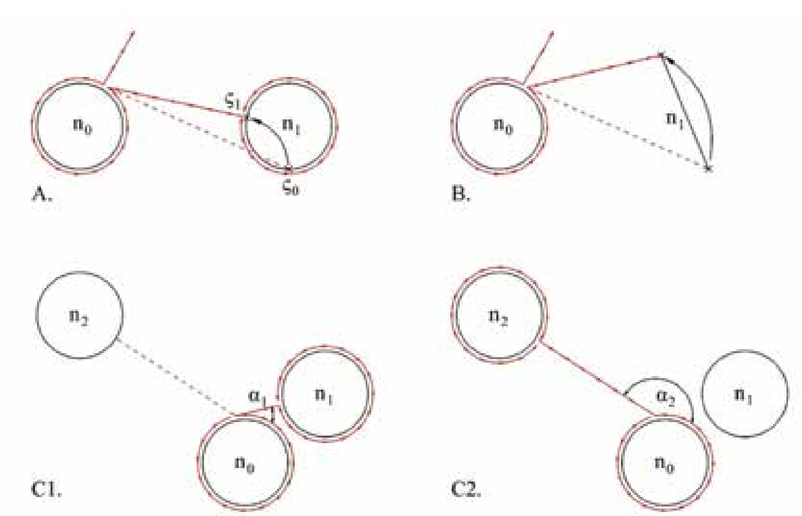


Figure 8: Additional features of NNA. The tool-head first prints contour n0. When traveling to n1, the algorithm can: A) adjust the starting point α of closed contours; B) flip open contours; and C) calculate the loss in speed due to direction changes. Angles α1 for contour n1 and α2 for n2 are factored in the weight of each node. - DBT, ETH Zürich, 2017

distances between contours. The problem is a variant of the classic 'travelling salesman' algorithm where the shortest toolpath (i.e. minimum-weight Hamilton circuit) has to be computed for the given graph (Lin and Kernighan 1973). To compute the shortest toolpath, a heuristic method is used, the nearest neighbor algorithm (NNA).

Calculating and comparing all the possible tool path variations with a brute force algorithm is impractical even for graphs with as little as 12 nodes. With the NNA heuristic, the search can be performed in linear time; however, the global optimal solution may be missed because of the greedy approach of the algorithm which relies on finding the local optimum at each step. Nevertheless, the NNA offers a good compromise between computation time and optimization.

For calculating the tool path, specific features were added to the generic form of the NNA:

- For each graph node that is a closed contour, the seam can be adjusted along the contour in order to find the shortest path at the current step (fig. 8A).
- For each graph node that is an open contour, both ends are compared in order to find the shortest travel distance at the current step, and the direction of the contour can be reversed (fig.8B).
- The cost function contains a factor p that takes into account the attack angle α between the incoming and outgoing direction of the tool head:

$$p = 2 \cdot (1 - \alpha / \pi) \cdot (v_{max} - j) / a_{max}$$

where p = penalty factor

α = change in direction in radians

v_{max} = feed rate of the tool head in mm/s

a_{max} = maximum acceleration of the tool head in mm/s^2

j = jerk federate of the tool head in mm/s.

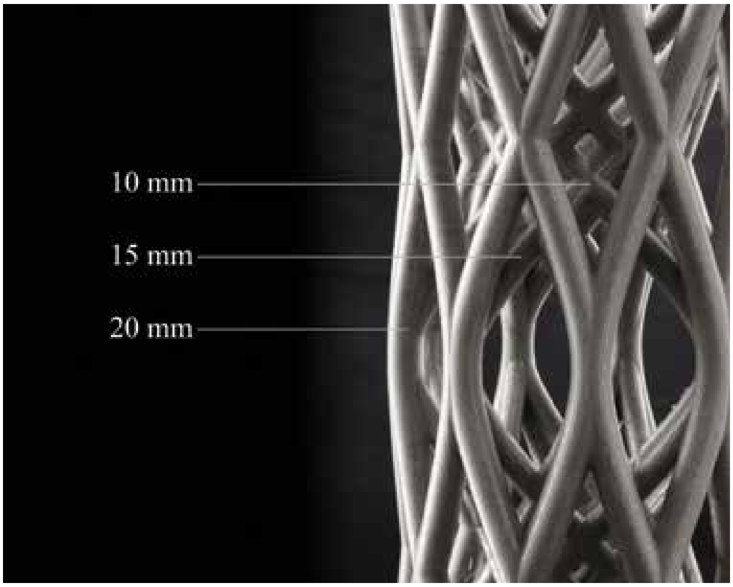


Figure 9: Concrete prototype using 3D-printed formwork displaying micro-tubular structures as small as 10 mm in diameter. - DBT, ETH Zürich, 2017

The factor p accounts for the fact that the tool head has to slow down more to negotiate tighter changes in direction. Negative and positive acceleration times have to be taken into consideration when calculating the total weight of the Hamilton circuit (fig. 8C).

4.3 Concrete Casting in Submillimetre Formwork

Ultra-high-performance fiber-reinforced concrete (UHPFRC) with 10-mm-long steel fibers was used (Aghaei-Meibodi et al. 2017). This satisfied the necessary rheological requirements to flow through the tubular geometric features as thin as 10 mm in diameter used in a series of prototypes (fig. 9).

The early prototypes revealed that one of the critical issues related to concrete casting is the buildup of hydrostatic pressure. The hydrostatic pressure is the maximum stress that is uniformly exerted by the concrete on the thin formwork. Hydrostatic pressure is only dependent on the density of UHPFRC and the depth of the cast:

$$p = \rho \cdot g \cdot h$$

where p = hydrostatic pressure in N/m^2
ρ = density of concrete in kg/m^3
g = gravitational acceleration in m/s^2
h = depth of the cast UHPFRC column in m.

The very thin PLA formwork is unable to withstand the hydrostatic pressure of the dense UHPFRC ($\rho \sim$ 2,350 kg/m^3) for depths larger than circa-100 mm. The breaks in the formwork generally happen along the contact surface between consecutive 3D-printed layers, where there is a weak interface and lower tensile strength. In order to overcome this, several strategies have successfully been tested:

- Submerging the formwork in a bed of sand. The sand acts with a counter-pressure on the formwork that cancels out the hydrostatic pressure from the UHPFRC. Breaks are also neutralized by the sand, which consolidates the part locally and prevents further concrete leaks.
- Submerging the formwork progressively under water. This method also provides a counter-pressure on the outside of the form but has the advantage of keeping the casting process visible throughout. In combination with the transparent PLA, this is an important tool for monitoring the casting process for very challenging, thin geometric features (fig. 10).
- Coating the formwork with organic resins to increase its strength. Clear epoxy or polyester resins have been used to make the formwork waterproof, in addition to the two methods illustrated above.

Following the concrete casting, the PLA formwork provides the perfect enclosure for concrete curing, preventing the development of cracks due to water loss. Forty-eight hours after casting, the concrete is stable enough for removal of the formwork. A heat gun is used to supply moderate heat (~200°C), and the PLA peels off of the concrete on its own (fig. 11). After the removal, the uncoated PLA can be combusted, composted, or recycled.

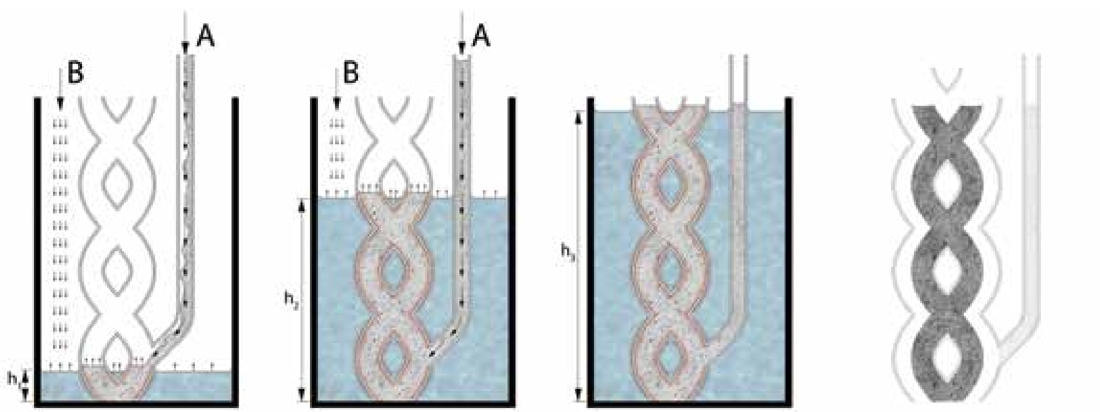


Figure 10: Step-by-step diagram showing the simultaneous infill of concrete through the bottom of the formwork (A) and of counter-pressure material (B – sand or water). The final step consists of the removal of the formwork and casting inlet. - DBT, ETH Zürich, 2017

Ongoing research is investigating alternative methods for the formwork removal, such as using polyvinyl alcohol as a 3D printing material. This can be removed easily because it is water-soluble, but the interaction with the hydration process of concrete needs to be tested further.

5 RESULTS

The method presented above optimizes fabrication times through a custom tool-path generation algorithm for 3D printing. Several commercial slicer tools do exist, but they produce tool paths that take at least twice as long to be 3D-printed (fig. 12).

Using such a thin shell as concrete formwork presents a number of challenges. Apart from the thermal shrinkage and fabrication speed, the research so far has identified challenges where further investigation is needed:

- The focus so far has been on parts which fit the size of a 3D printer. In order to fabricate larger parts, strategies for segmentation and connection need to be considered.
- Rheological limitations of concrete and fabrication limitations of FDM (fig. 5) have been identified empirically. A shape optimization process could address the limitations of the two processes and integrate geometric adjustments that make fabrication possible.

Figure 11: Concrete component displaying high-resolution texture (left) after the Submillimetre plastic formwork has been removed (right). - DBT, ETH Zürich, 2017

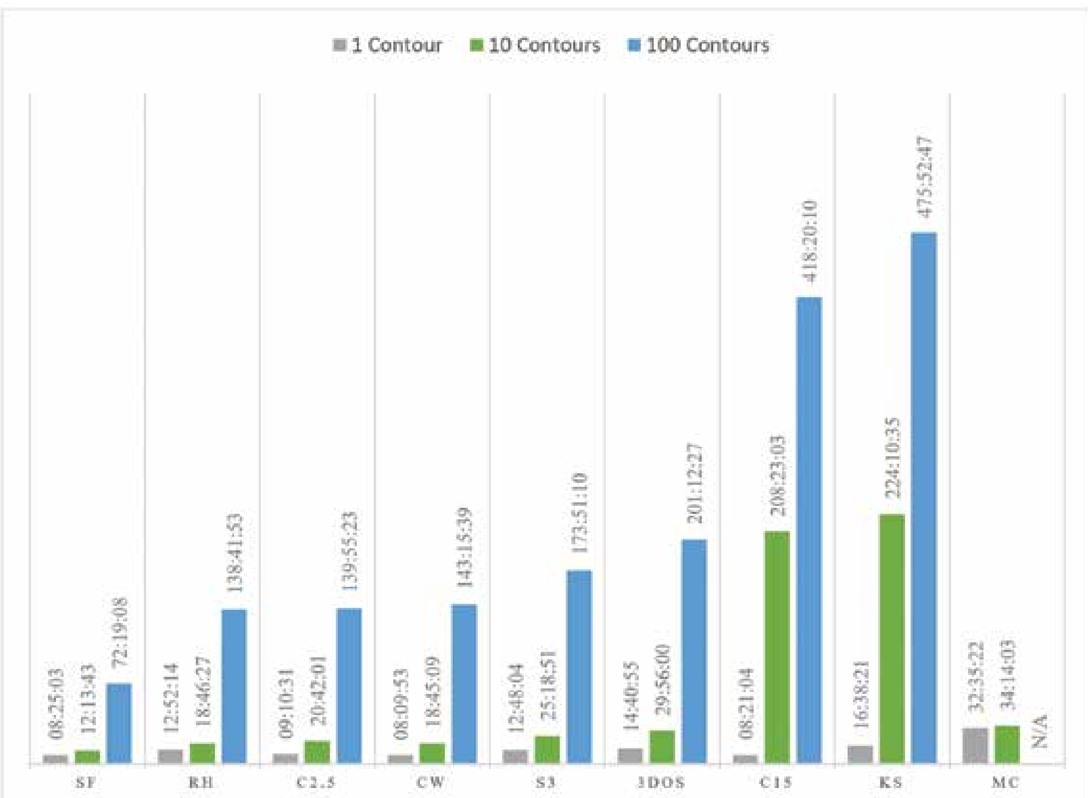
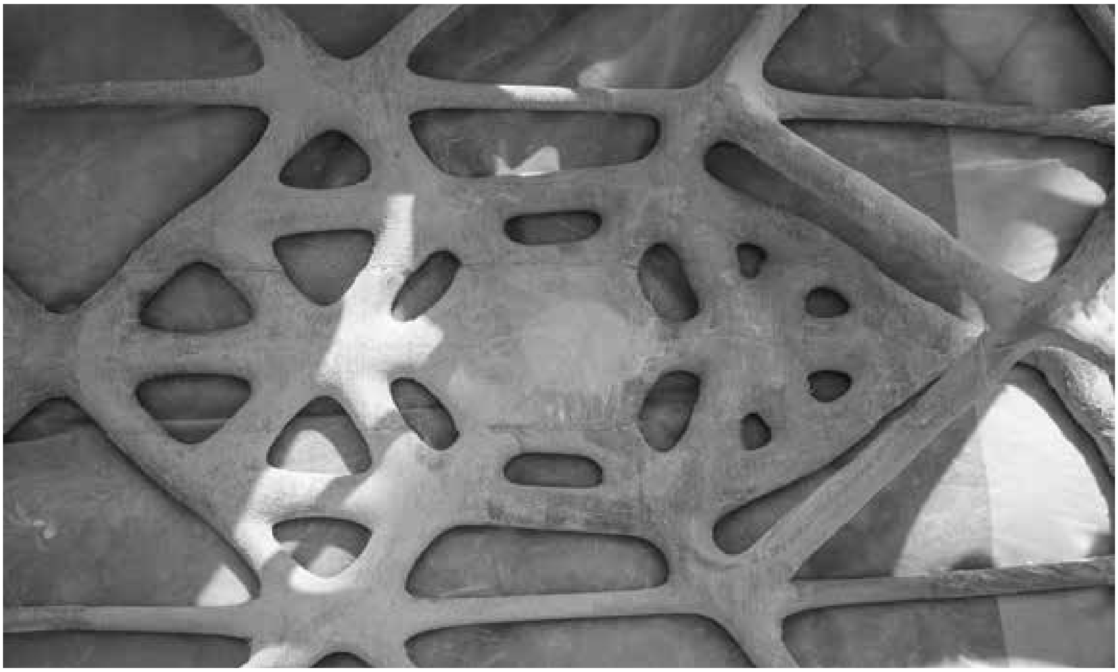


Figure 12: Comparison of printing times (in hours:minutes:seconds) of tool paths generated with different commercial slicers. Three different digital models with 1, 10, and 100 contours each were used for benchmarking. The printing time improvement for the custom slicer developed for Submillimetre Formwork (SF) is significant, especially for the model with 100 contours, where the fabrication is at least 50% faster compared to Repetier Host 2.0.1 (RH), Cura 2.5x64 (C2.5), Craftware 1.14 (CW), Slic3r 1.2.9 (S3), 3DPrinterOS.com (3DOS), Cura 15.04 (C15), KissSlicer 1.5x64 (KS) and MatterControl 1.4 (MC). - DBT, ETH Zürich, 2017

Figure 13: Load-bearing spatial concrete element cast in discretized Submillimetre Formwork. - DBT, ETH Zürich, 2017



- The structural performance of the components needs to be tested. Of particular interest is the orientation of the steel fibers in the intricate narrow tubes. Computed tomography coupled with computational fluid dynamics simulation could give some insight in this regard.

6 OUTLOOK

The next step in the research is to address the challenge of further scaling this fabrication process up. In order to investigate this, a four-meter-long, load-bearing spatial element was designed, optimized for a complex load case, and is being fabricated with the proposed method (fig. 13). This method opens new design possibilities for building elements with functional inner porosity, intricate surface qualities for functional or ornamental purposes, and integrated assembly logic.

7 CONCLUSION

Submillimetre Formwork relies on using 3D printing only for a minimal skin that is enough to ensure the complex shape of a concrete component. The stability of the fragile formwork during casting is provided by an ordinary material such as sand or water that does not require digital fabrication, thus using the precious fabrication process only where it is strictly needed to precisely define the shape (fig. 14).

It has been shown that for producing complex, free-form, and non-standard concrete elements, *Submillimetre Formwork* offers a novel, economical alternative, or even the only possible solution for the fabrication of certain geometric features. The novelty is twofold: on the one hand, an optimized 3D printing process for the formwork, and, on the other hand, a casting process that is suitable for such fragile formwork shells. FDM enables the full geometric and structural potential of fiber-reinforced concrete and promises a more sustainable construction process with no waste material, an easier on-site assembly with lightweight formwork, and a greater design freedom for concrete elements.

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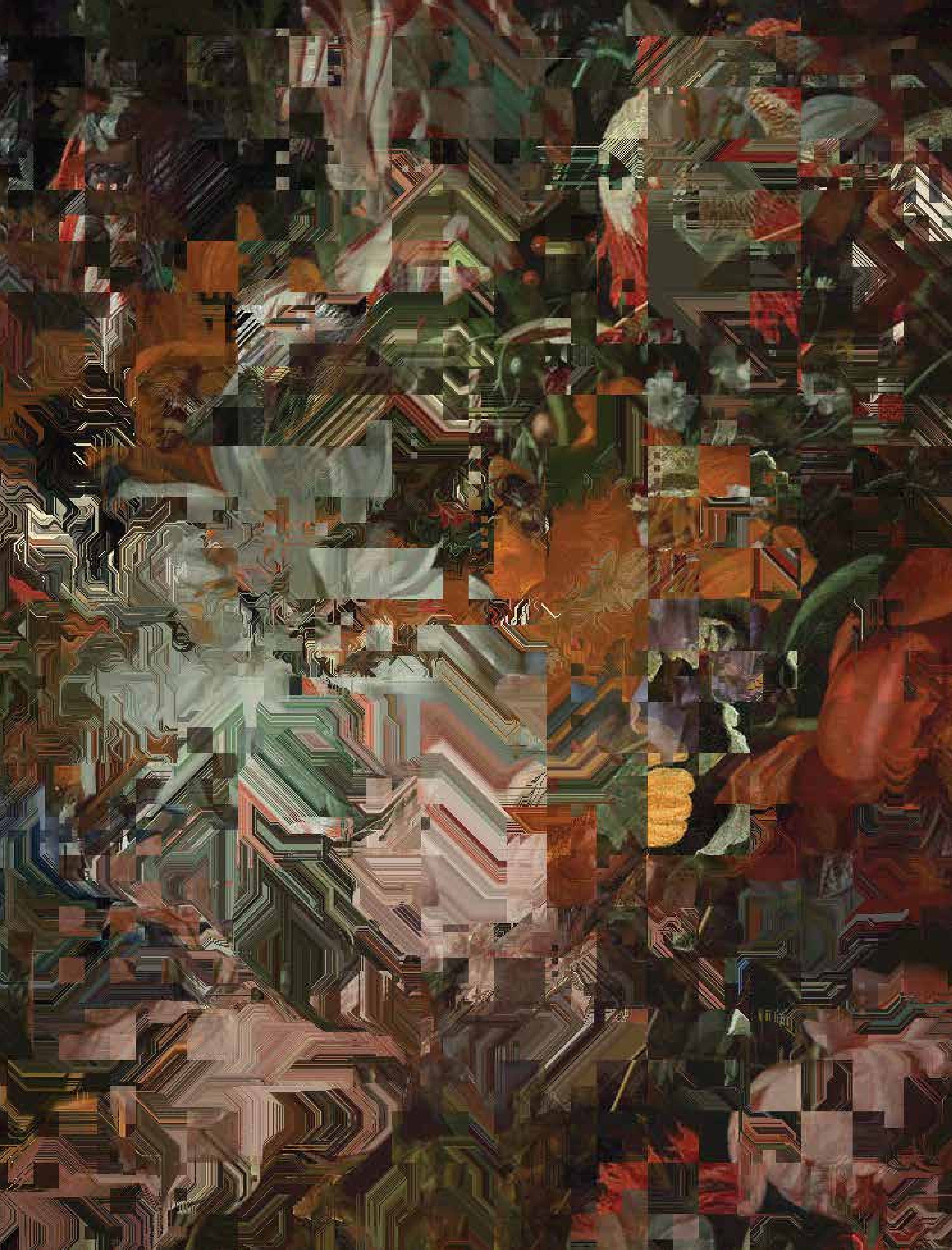

Embedded Seriality: An Anti-Stylistic Reading of Current Modes of Code, Design, and Culture

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INTRODUCTION

Technological advancements typically induce paradigm shifts that reverberate across many disciplines. Architecture is in a moment of such transition both in practice and in the academy. The past 30 years of technological progress changed the relationship between architect designer and design process at an unprecedented rate. The discipline was not prepared for such accelerated movement, and was unsuccessful at expanding its theoretical frameworks to engage with technology in a meaningful way. The unsynchronized advancement of technology and theory became the source of our present condition that is currently dominated by two camps—broadly defined here as computation-based design, and design informed by history and theory; these two camps rarely challenge or contaminate one another.

Technological paradigm shifts often result in another problem: specialism. The rapid influx of advanced technology into the field of architecture in the past two decades has produced a particular type of specialization. Knowledge that is developed in isolation risks alienating those with the most mastery over it. Consequently, the compartmentalization of code-based design operates as an impervious system—with limited meaningful pushback, dialogue, or integration with designers and theorists engaging with visual, formal, and cultural aspects of the field. This lack of integration is an urgent problem threatening the disciplinary legitimacy of both (isolated) camps.

Technology has a tendency to advance rapidly when economic and political climates allow. Technological advancements initiate change in every field. In his "Systems Esthetics" essay, published in *Artforum* in 1968, artist, critic, curator, and writer Jack Burnham illustrates the cultural transition facilitated by technology as moving from an object-oriented model to a systems-oriented one.[1] Academic institutions have the ability to quickly assimilate new discoveries and experiment with them in a pedagogically driven environment. More specifically, over the last 10 to 15 years, the emergence of visual programming (Grasshopper 3D, originally released as Explicit History) and object-oriented programming (Processing) paradigms, open-source computing, and other accessible platforms have infiltrated the architecture school in an accelerated and at times uninformed manner.

FRAMEWORK

The subject of this paper is not grounded in the politics or economics of digital design, despite the difficulty in isolating these factors of technological advancement.

However, it is worth noting the radical shifts in the field from costly computers running proprietary software, to mobile technology, affordable processing power, and open-source platforms. In the 1990s, the digital was strictly available to a select few who could afford the cost of technology. Over time, computers became increasingly affordable, more powerful, and more accessible. Today, every student enrolled in architecture school is expected to own a personal computer. Parallel to the development of hardware in the late 1990s and early 2000s, software development transitioned as well—from large companies developing highly advanced computer programs to a singular person (David Rutten) developing an equally powerful environment.[2] The revolutionary developments in software design processes affected architects, students, and academics alike. One of the most outstanding examples of this development is the shift in the field from Bentley's Generative Components to Rutten's/McNeel's Grasshopper 3D. Individual programmers and small teams unexpectedly found themselves in a position to develop software that could become as influential and widely used as packages that used to be designed by large corporations. This wave of new software and new methods of software development was facilitated by the open-source training model that emerged from platforms such as the workshop, the blog, the online video tutorial, and most importantly, integrated development environments and web-based source code and version control platforms (such as GitHub).

Hardly 10 years after the introduction of the first open-source (architecturally oriented) digital design environments, the contemporary computation-based designer has access to over 200 free Grasshopper plug-ins, 60,000 forum members, 287,000 YouTube tutorials, and thousands of blogs, books, articles, and other forms of user/developer-oriented training support.

From these developments, an entire architectural genre has emerged. Computational Design, once the purview of a select few, has become a field in its own right, with a clearly delineated visual project. There now exists a litany of new Master of Science (M.S.) year-long degree programs being offered by architecture schools all over North America, Europe, and beyond. Advanced Production, Building Information & Systems, Design Computation, Architectural Technologies, Technology of Architecture, Digital and Material Technologies, and Situated Technologies are just a few typical program headings. These degrees promise students a research-oriented environment focusing on technology. However, techniques created for the sole purpose of optimization and fabrication, powerful as they may be, cannot productively engage with the discipline on an aesthetic or visual level. Most Master of Science programs are technologically oriented; they privilege computation over design, and science over aesthetic/cultural concerns. This institutionalized confinement of code-based design practice created a camp within the discipline, an exclusive degree in architecture graduate schools, a specialized department in the architecture firm, and a new branch in the corporate office structure—in other words, a hermetic society couched in hyper-specific, self-emulating design discourses.

In the absence of a developed discourse around the aesthetics of computation design, defaults and clichés have become the norm. At present, there is an overabundance of Voronoi tessellations, hexagonal grids, minimal surface, geodesic lines, box morph, attractor point, and other codes that operate on input geometry—meaning geometry that has been 3D-modeled from parameters that have no relationship with the parameters of the algorithm. Without a deep understanding of specific parameters in both the visual modeling world and the algorithmic one, the designer becomes an operator, unable to create a comprehensive and meaningful relationship between ready-made, downloadable scripts, and independently constructed Rhino surfaces. Designing in this mode—making changes to the parameters of an algorithm that was developed independently from the geometry it is operating on—produces works that lack intentionality. The widespread popularity of this design

Figure 1: Jasper Johns, Alphabet, 1959. Paper on hardboard, 30.5 x 26.7 cm (12 x 10 1/2 in.). Gift of Edlis|Neeson Collection, 2015.121. Photo courtesy Art Institute of Chicago/ Art Resource Center. © Jasper Johns / VAGA at Artists Rights Society (ARS), NY.

methodology has created a specific architectural language and a new style: Computation Design. Typically, architectural movements develop theoretical concepts and evaluative criteria in tandem, but the visual project associated with Computation Design lacks a coherent theoretical and critical project.

The critical inadequacy of the computation project is a new problem, not inherent to technology. Sometime in the 1980s, Deconstructivism started to emerge in opposition to the Modernist demand for flatness and geometric purity. Aided by the emergence of computers and software, this movement focused on developing (what were at that time) complex mechanisms engineered for the production of special effects and atmosphere. The Digital Turn followed Deconstructivism in the late 1990s and lasted through the early 2000s, with the ambition of integrating digital technologies into the design process on a deep, self-conscious level, while critically engaging in philosophical discourse. This era, pioneered mainly by Greg Lynn and Bernard Cache, maintained a serious and meaningful relationship between matters of design, aesthetics, theory, and technology. In the mature period of the Digital Turn, design problems, computation challenges, and new theoretical concepts were developed simultaneously. For example, the replacement of the angled fold with a curved one drew its theoretical (or philosophical) rhetoric from Gilles Deleuze's *The Fold.* [3] The evolution of the fold also tested the utility of the computer and software environments while still addressing issues related to visual studies and aesthetic theory.[4] More recently however (post-2010), Computation Design has been codified as a stand-alone style and an autonomous field of study. A system misinterpreted, computation was meant to service localized design and fabrication problems, not design buildings and urban projects in their entirety.[5] Inadvertently, computation forged its agency as an architectural style with no significant relations to more general (totalizing) issues of architectural design, theory, and aesthetics.

> *"Gradually this strategy transforms artistic and technological decision-making into a single activity."*
> – Jack Burnham, *Systems Esthetics*

The artists and works that Burnham cites in his article are examples of an aesthetic impulse driving technological innovation. He argues that the aesthetic impulse must actively participate and relate to technological means of research and production. Computation Design, as it's commonly practiced today, still largely privileges scientific knowledge, while theoretically/formally-motivated designers address aesthetic issues alone. The Voronoi diagram and the nine-square grid, emblems of the two camps, are equally problematic when used as go-to design solutions. Computation, aesthetics, theory, and cultural issues must all be integrated into a new architectural discourse where each area of study informs the other reciprocally.

ABSTRACT

What follows is a diagnosis of the current state of digital design. Digital design is a problematic and contested term; it is simultaneously loose and very specific. The term is loose in that architecture and media culture no longer operate outside of the digital. It is also specific in that it indicates a particular style wedded to the use of a set of tools and commands directly associated with the computer. The term "digital" further frustrates the conversation by attaching itself to the word design, as it is already difficult to imagine a present or future world where design and culture operate outside of the digital. For the purpose of this study, let's consider Digital Design as a temporary stand-in, on its way to a more fully-realized category of architectural design, one which does not discriminate between the digital and the design aspects of a project, but rather builds on a critical and theoretical framework that accommodates and questions the consequences of the simultaneous collaboration of code and concept.

The following sections focus on three important, related ideas that could contribute to a re-theorization of computation design: the role of style; the construction of critical, evaluative metrics; and finally, the implications of design in our contemporary image-centric culture. This analYsis is illustrated by the work of architecture designers who provide digitally-informed, alternative design models. Among other players, the work of M. Casey Rehm, Gilles Retsin, and Jose Sanchez offer hybrid proposal—working strategies that engage design and computation, code and concept on equal footing.

PART 1: STYLE VERSUS ATTITUDE

In its current state, Computation Design is highly stylized, but it is uncritical about how that style has developed, how it operates culturally (outside of the field), and which disciplinary traditions it is channeling. The purpose of this section is to argue for a visually-oriented, anti-stylistic, procedural approach to Digital Design. To be clear, this essay does not advocate a complete renunciation of style; instead, it proposes a lateral shift, not unlike the way conceptual artists deviated their focus from style, beauty, and personal expression to processes, lists, and raw concepts in the 1960s and 70s.

An early pioneer of Conceptual Art theory, artist and critic Mel Bochner offers an alternative to style in his seminal essay, "The Serial Attitude" (1967). In his essay, Bochner suggests that the "serial order is a method, not a style."[6] This is an intriguing argument if adopted by a design movement in need of a withdrawal from the pitfalls of default styles. Seriality, as a broad term, is generally defined as a number of similar or related things that are structured in a spatial or temporal sequence. For

Figure 2: Narcissism of Small Differences, Kinch, M. Casey Rehm Principal 2014 - ongoing.

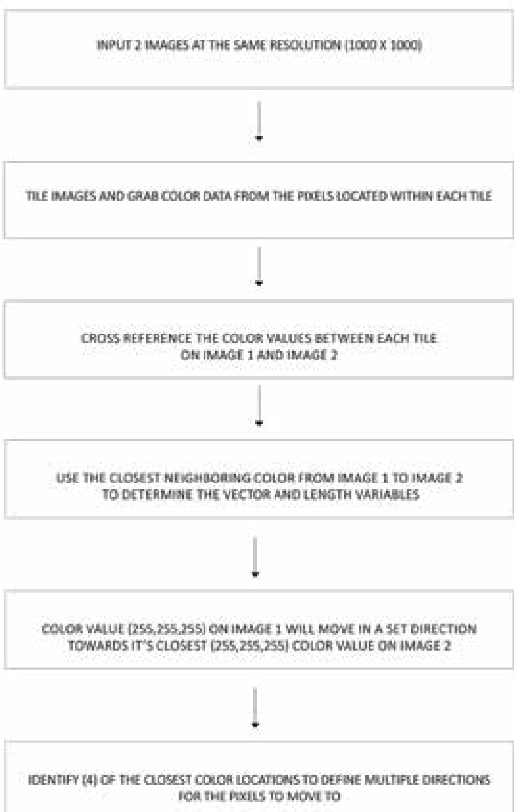

Figure 3: Processing Code Diagram Based on Research Work by Casey Rehm, Viola Ago, 2017.

Bochner, seriality is concerned with the order of things. He further illustrates the role of the serial by separating it into two types: artists that simply work in series and artists that **embed** a series-based methodology within their work.[7] To illustrate, Willem De Kooning's *Woman* paintings exemplify a process in which the work is based on the same theme with different variations. De Kooning paints the same subject, with slight deviations in each instantiation, to create a body of work related to a particular style. Artist Jasper Johns, on the other hand, operates in simple logics. His *Colored Alphabet* (fig. 1) uses a well-known system—the alphabet, which has a fixed amount of elements, a beginning, a sequence, and an end. Johns' use of the alphabet embeds serial logics within the work itself. Bochner advocates for the latter; the aesthetics of seriality employed as an attitude/method, as opposed to a style.

Appropriating this attitude, architectural designer M. Casey Rehm's work directly relates to embedded seriality, wagering an architecture of method as opposed to style (fig. 2). Rehm's algorithmic-based work is not indicative of a particular style, and it cannot be reduced to the mere demonstration of a technique either; it is a balancing act of process and form. In his ongoing research project, *Narcissism of Small Differences*, Rehm uses an image an as input, fragments it, and reorders the fragments into a new composition. There are two main components to his methodology: an image and a process. *Narcissism of Small Differences* begins with two images. Each image, like Johns' *Colored Alphabet*, is a closed system with a finite number of ordered/organized pixels. Regardless of how Rehm restructures the pixel order, the image will always maintain a deliberately organized network of pixels. Rehm's process can be broken down into three distinct operations (fig. 3). First, the images undergo a grid subdivision and cell-based (or pixel-based) color analysis. This information is used to construct a set of vector directions and magnitudes based on constructed relationships between corresponding pixel sets from the two images. After these procedures, the pixels duplicate to a new position guided by the constructed vectors from operation two. This last step repeats consecutively to create a newly processed image. As a result, his work operates on the binary of process and image, movement and perception, where one cannot exist without the other.

Two other examples of serial procedures in digitally inflected design can be found in the work of both Jose Sanchez and Gilles Retsin. Sanchez's and Retsin's bodies of work plug into a similar concept that employs embedded seriality and use discrete geometries to create form by way of combinatorial systems. However, their work is also embedded within a discourse of seriality. In *Suncheon Art Platform* (fig. 4), Retsin creates families of discrete components to characterize form. The structural system here is one that is constructed

Figure 4: Gilles Retsin Architecture, Suncheon Art Platform (2016) Model View.

Figure 5: Gilles Retsin Architecture, Suncheon Art Platform (2016) Parts.

from local as well as global relationships. Although at first the work may seem modular (it uses a basic unit and similar replicas of that unit), it is not the order of these units that modifies the overall form (fig. 5). Rather, Retsin appears to use sequences of units to compose form, using color to index adjacencies between units. To be clear, this illustration is not meant to argue for the designer's intention of the final appearance of the work. Retsin's work does not identity with a particular architectural camp or set of styles. Instead, *Suncheon Art Platform* fuses aesthetic ambitions and process-intelligence by creating interesting relationships within a unitized system. In this framework, the work of Retsin, Rehm, and Sanchez is anti-stylistic as it authors compositions of data and structure.

PART 2: EVALUATIVE CRITERIA – AESTHETICS OF EVIDENCE

The lack of engaged criticism—criteria developed for the assessment of new work—opens the door for arbitrary and circumstantial mass influences to take on that role. The exponential user growth of Instagram, Facebook, design blogs, Vimeo, and other image-dissemination platforms propagates numerous, unaccounted-for styles very rapidly. This is a status of veritable crisis in contemporary architectural discourse. In this critical moment, the serial attitude can provide an alternative to disorienting plurality, a critical lens for architecture as it relates to current

Figure 6: Jose Sanchez, Block_hood Video Game, 2016.

optically saturated modes of social media and image culture. The work of Retsin, Rehm, and Sanchez is not symptomatic of a particular style, and it is not a simple, straightforward response to a technique either. So how does one develop a coherent rhetoric of evaluation for this work?

Here, cultural theorist and critic Sianne Ngai offers another model based on Conceptual Art practice from the 1960s and 70s: an aesthetic of difference. Ngai describes this aesthetic of difference as belonging to variation, information, and forensic evidence.[8] To illustrate, Eleanor Antin's *Blood of the Poet Box* contains blood samples from 100 poets in a wooden box and an associated specimen list. Antin's work has an evidence-based approach that results from the collection of data. Similarly, Ed Ruscha's work addresses the format of inventory-based work. Stains is a collection of 76 mixed media stains created from water, beer, blood, juice, and other substances. It is important to note that both of these artists' works exist as a type of collection, thematically unified as series through the use of forensic information. This inventory-focused method of working was the premise that comprised the Conceptual Art movement. This new paradigm arose from artwork, criticism, and theory that was no longer based on the merits of virtuosity and personal expression, but rather on the neutral, matter-of-fact qualities of lists of data, everyday objects, actions, tasks, performances, and so on.

Lists and other types of data organization comprise the base logics of any type of (architecturally-related) computer programming activity. For example, a digitally-constructed surface is understood and stored by the computer as a list of numerical values. At an abstract level, Conceptual Art strategies are not unlike scripting logics. Comparisons of this nature productively equate works like Sol Lewitt's *Cube Series* to working algorithmically in a permutation-based method. This method of working favors the production of series (composed of many possible variations), as opposed to singularities (one instance of a variation). A contemporary architectural example, Jose Sanchez's architectural video game "Block'hood" (fig.6), operates within a framework of embedded seriality, where the global composition is a unitized system with local moments of novelty and formal interest. Block'hood's system, combinatorial and permutative in nature, operates on a sequence-based methodology. The system Sanchez creates is a game environment, comprised of over 200 different types of units. The game structure is designed as a network of units which rely on a two-phase connection mechanism. In the game, the architectural units contain a finite amount of built-in connectors that differ from one unit to the next. Users are invited to arrange these units, based on their connecting capabilities into localized assemblages that can sequentially build as the permutation logics of the game permit. The ordered approach of the work is one that functions under the varying characteristics of units and the varying localized combination of such units to create larger forms over time. In this sense, the game is inherently mathematical and spatial. Block'hood's serial modes provide the field of architecture with a model for an aesthetic based on permutation and combinatorial logics. In Block'hood, the user engages the city through the cube, the banal, while interrogating global compositions, the city, the interesting.

Sianne Ngai argues that variation in a unitized system has a particular kind of aesthetic agency. The serial method lends itself to Ngai's premise. Seriality offers a platform for the generation of interesting relationships of units based on their information. Ngai further defines the aesthetic of variation as a play between typicality and difference, or, in her words, "standardization and individuation" (terms with capitalistic connotations that refer to logics of industrial production). The image-driven pixel-based organizations in Rehm's work can be understood as a visual analogue to this notion of difference and typicality. *Control* (fig. 7), for example, is made of two systems, one that remains the same and one that changes and generates difference. The final output of *Control* retains original data from the first (of the two) input images. Traces of the untouched, original image (the existing pixels) register a typical condition. However, the work also consists of new or "novel" clusters of pixels (evidence of transformations). These new pixel clusters are transformed by the vectors generated from the initial analysis of the two original input images (similar to those found in Figure 2). *Control* is simultaneously a typical image and an inventory of the work's transformation vectors.

Control productively collapses code and concept, difference and typicality, geometry and image, or in Ngai's words, individuation and standardization. Ngai's theory relates the interplay of seriality and "the interesting" to the rise of new media and communications technology. In her view, new norms of communication have created a sensorially overloaded society in constant need of the next new thing (fig. 8):

> *Low or indeterminate affect, stylistic pluralism and hybridity, and the seemingly endless pursuit, in the felt absence of any totalizing vision, of the next new thing and then the next one after.*
> – Sianne Ngai, *Merely Interesting*

In his book *The Reality of Mass Media* (2000), systems theorist Niklas Luhmann offers a similar theoretical model. Like Ngai, Luhmann describes the media-driven social condition as having a paradoxical

Figure 7: Media Still From Control, Kinch, M. Casey Rehm Principal, SCI-Arc Gallery, 2016.

Figure 8: Diagram for Sianne Ngai's Theory of the Interesting, Viola Ago 2017.

Aesthetics of the Interesting	
Variation of Information	
Interesting Relationships	
Difference	Typicality
Individuation	Standardization
New	Familiar
Variety	Redundancy

Figure 9: Diagram for Current Architectural Practices Camps.

Split Discipline	
Camp 1	Camp 2
Form/Theory Participants	Computation Participants
Incremental Change	Abrupt Change
Medium	Content
Image	Process
Culturally Accepted	Forged Acceptance Over Time

relationship to novelty and repetition. He argues that the economic and industrial influences on everyday culture produce a consumerist climate that depends on two opposing things: redundancy and variety. In Luhman's view, redundancy is integral to the creation of fast relationships between users and products via familiarity, and variety is equally as important in its affirmation and celebration of new things that are always better, shinier, and necessary, in order to sustain a continuous culture of purchased goods.[9] Both Ngai and Luhman contend that this condition results in a specific type of production cycle. Such cycles depend on short-lived recursive products, with slight variations introduced at each moment of reproduction.

PART 3: CULTURAL IMPLICATIONS – THE ROLE OF THE IMAGE

Postwar consumer culture favors small incremental changes over abrupt avant garde paradigm shifts. Anticipating Ngai and Luhman by several decades, philosopher and media theorist Marshall McLuhan, in his book "The Medium is the Massage" (1967),[10] describes a media-induced society psychologically conditioned to depend on a visual apparatus informed by old configurations:

> *Innumerable confusions and a profound feeling of despair invariably emerge in periods of great technological and cultural transitions. Our "Age of Anxiety" is, in great part, the result of trying to do today's job with yesterday's tools—with yesterday's concepts.*
>
> – Marshall McLuhan, *The Medium is the Massage*

The expediency and suddenness with which computation design flaunted its technological flare and procedural expertise when it entered the architectural stage did not account for its reception as a design language. The computation proposal was abrupt, foreign, and purged any previously familiar precedents of architecture. The architecture community, still operating within larger social norms, casually disregarded the emerging computation community and continued to operate with familiar and comfortable design procedures, repurposing old ideas and image-washing (photo filtering) them with temporal digital aesthetics.

It goes without saying that our field is split, with marginalized computational designers on the one side, and history/theory-based designers on the other (informed by the visual history of the discipline and theoretical concepts borrowed from other disciplines). Mainstream designers currently also produce culturally embedded design artifacts at high speeds. The work, generally speaking, occupies the medium of computer-generated images, and post-processed model photographs, declaring a newfound desire for architectural representation. In a similar fashion, this camp, like the computation one, established a style which exclusively produced architectural ideas in service to the image. Baudrillard argues objects lose meaning when they are represented by images. Images are of the aesthetic domain and are evaluated as such.[11] Reducing the evaluation of an object through the utility of the image therefore eradicates meaning from the object. He argues that the image encouraged the common desire to aestheticize form, consequentially removing content from the object that the image is representing (fig. 9).

As this history/theory camp proliferated an endless cache of illustrations of architectural ideas, the computation design group surged into advancing (zoomed-in) problem-oriented techniques and processes; it was all about content. The hyper-focused method of this camp overlooked the importance of representation in architecture, and inadequately replaced it with screen captures of lines of code and grasshopper definitions. The image-medium binary of the first group, and the content-process binary of the second one, developed at different speeds, and in almost complete isolation from one another. While the former immediately proclaimed its role into the cultural landscape of architecture, the latter forged its position over time. The obvious indifference of the two groups to one another led to a hard divide in the discipline—even though what one lacked the other one provided.

There is precedent for work that merges this disciplinary division. The architecture designers previously discussed fuse process, representation, and logics of operation within their work, thereby creating artifacts wedded to the aesthetic, visual, cultural, and procedural modes of architecture. The argument is for progressive collaboration, using modes of seriality, evidence, and image-object conflations as drivers of an alternative project in architecture.

ENDNOTES

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DRONOPOD: Advanced Production Construct and Augmented sUAS Station

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RESEARCH DRAGNET

Projecting into a seemingly inevitable future when small unmanned aerial systems (sUAS) constitute various forms of ubiquitous utility, many of which reside beyond the scope of current predictions, DRONOPOD is an experiment in the advanced production, operational, and interactive potentialities which may be designed and built into such an infrastructural system. Conceived and developed as a prime component within an expansive field of urban deployment, DRONOPOD incorporates large-scale, free-form robotic 3D-printing, drones, and augmented reality (AR) into a spatial, material, and experiential demonstration, and serves as an invitation to both consider this future fabric in a proactive manner, and launch new research and experimental trajectories in advanced production. As is the case with many advanced material and spatial productions, the impetus for this endeavor was sparked by a confluence of multiple streams of exploratory research, experimentation, and inquiry throughout a constellation of interests and operational developments, fueled through a unique opportunity to both cast and amplify the possible reach of a focused collaborative dragnet.

Significant momentum was built up towards the conception of DRONOPOD through a project titled TN-01 (fig. 1), which was the first collaboration between KBAS and Branch Technology, a specialized start-up company launched in 2015 that has been operating at the leading edge of large-scale robotic, cellular freeform 3D-printing with their patented processes and techniques. [1] Soon after having established itself as open for business in Chattanooga, Tennessee, Branch Technology was invited by the Museum of Design Atlanta (MoDA) to contribute a large piece for the exhibition that focused

Figure 1

Figure 2

on state-of-the-art 3D-printing.[2] In turn, Branch Technology invited KBAS to design a "very large" object for this installation, thus initiating a rapid and intensive collaborative burst of design iteration and production in a compressed timeline of four weeks from the start of design to finished installation. The approach taken was that KBAS would serve as a test pilot of sorts, pushing and pulling the geometric and dimensional envelopes afforded by the tools and techniques recently rolled out by Branch Technology in order to discover key provisional limitations, performance boundaries, and design opportunities built into their overall process. As such, the resultant spatial construct was pushed through five key maneuvers, including a minimally tapered fillet, the sharpest achievable continuous corner, and the tightest possible fillet given the constant cell-depth of the print matrix at that time (fig. 2). Consolidating these base configurations into a unified construct with a total height of 18 feet, TN-01 both records and demonstrates the technological performance envelope with which Branch Technology entered the field.

In early 2016, the University of Tennessee Knoxville School of Architecture granted special funding to the author of this paper as a prompt to produce material work at a high digital caliber as a pilot demonstration for the promise of cultivating a new regional channel of such experimentation and research. Coupling this opportunity with ongoing dialogue between KBAS and Branch Technology about a second joint endeavor, and sparked by KBAS research focused on sUAS airspace regulations and industry projections,[3] the Knoxville Bureau of Air and Space was formed as the proxy entity and collaborative channel through which DRONOPOD was ultimately coordinated, developed, deployed, and broadcast.[4]

DRONOPOD MEGA-PRINT

While the core intent behind the conception of DRONOPOD was that it would serve as a research vehicle through which technical advancements may be developed, publicly demonstrated, analyzed, and positioned for further development, it is designed as a functioning drone landing and take-off station that is perched on the side of a historic warehouse building in the Old City district of Knoxville, Tennessee (fig. 3). At the same time, DRONOPOD is a prototype in relation to its own design development as a spatial utility type, incorporating dimensional and volumetric articulations in anticipation of multiple functionalities to be incorporated in future versions. DRONOPOD also works as a large-scale urban marker upon which dynamic information is overlaid and animated through a working AR application that was designed and developed as an integral component of the project (fig. 4).

DRONOPOD is a composite assembly that integrates custom CNC-fabricated thin-gauge stainless steel (fig. 5)


Figure 3

and polycarbonate parts (fig. 6) plus an extensive array of hardware along with its most prominent elements, which are two large, singular 3D-printed components (fig. 7). With an overall bounding box measuring approximately nine feet wide, seven feet deep, and 12 feet high, it is the incorporation of these large 3D-prints and the methods by which they were produced that affords a notably efficient volume-to-weight ratio for the overall construct. Exploiting the momentum gained through significant technical advancements that continued to progress at Branch Technology beyond the completion of TN-01, the production breakthrough that DRONPOD both prompted and relied upon was a fundamental shift in print capability. Whereas the current state of the art utilized for TN-01 was constrained to a 3D-printed shell consistently three cells deep, DRONOPOD provided the opportunity to develop an approach to fill up a much thicker volumetric envelope with an extensive and variably deep matrix of cells and nodes. The drive to achieve this technical feat served as the launching point for what proved to be an intensive burst of collaborative development between KBAS and Branch Technology over the course of several months, as the challenges at hand were both intricate and manifold.

Printing a three-dimensional freeform cellular matrix within a variably thick volumetric control envelope implies the requirement for numerous steps in the overall cell count per layer at strategic moments during the printing process. This is tied to a dimensional spectrum that controls the range of cell sizes and densities achievable within the matrix itself. At one end, the smallest possible cell is limited by the density built up through the thickness of extruded material as it travels

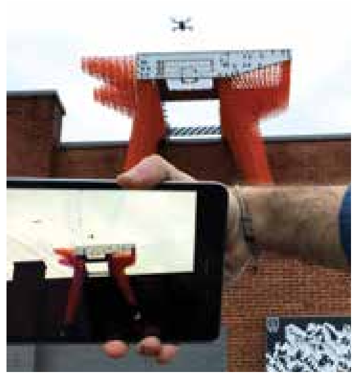
Figure 4


Figure 5

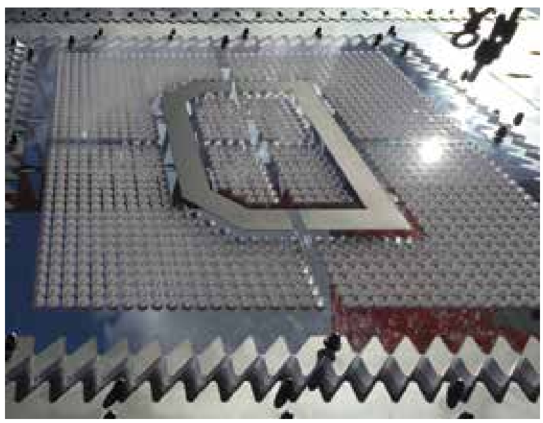
Figure 6


Figure 7

Figure 8

along the edges and diagonals of each cell in relation to the coordination of the extruding end-effector attached to the robotic arm and its motion along the print path. At the other end, the maximum achievable cellular dimensions are primarily controlled by the bridging capacity, the maximum distance through which an unsupported extrusion of material can retain its integrity in space through its localized cooling process and before making contact with a support feature. If any bridging distance is too great for the operations at hand, the printed member will bend or otherwise deform, thus potentially compounding a host of other configurational failures throughout the overall system. Backing away from each end of this spectrum towards an optimal range of cellular densities relatively early in the design process provided the first layer of essential parameters with which the volumetric print envelopes were controlled and iteratively refined.

Working with these quantitative constraints and qualitative comprehension of the processes required to translate a complex envelope into a printable matrix, the author of this paper was responsible for the design and iterative refinement of the volumetric digital models through which potential print paths were developed and analyzed by Branch Technology. While the methods exercised to construct these new types of print paths and the degrees to which these processes were operational innovations remained respectfully protected as proprietary to Branch Technology, a typical round of collaborative iteration would result in the identification of configurational or operational conflicts at key

Figure 9

transitional zones within that version of the volumetric envelope model. In turn, the control geometry would be adjusted accordingly and then pushed back through such analysis. While this back-and-forth working mode may appear to be quite straightforward, every round of geometric refinement required meticulous adjustments to the volumetric control models at hand, each defined by closed polysurfaces constructed with planar quadrilateral faces of varying sizes and proportions, the majority of which are non-coplanar with respect to each other. This configurational type is highly provisional, meaning that any dimensional change to an edge sets forth a ripple of associative geometric operations to resolve the adjustments at play into a newly configured closed polysurface with planar faces. Of course, such operations ultimately impact other localized edge and volumetric configurations, thus creating new conditions that required special attention by Branch Technology and iteratively reordered dimensional priorities towards the final configuration of each control volume. This process played itself out through many rounds over the course of approximately two months, with focus and resolution fully achieved for one of the printed components such that the knowledge gained could serve as a baseline for the refined development of the other.

Another key constraint was directly tied to the total print volume of both components combined. While the number of hours it would ultimately take to develop the finalized geometry and the associated print paths as outlined above was completely unknown at the outset of this endeavor, and all participants were fully committed to whatever that might entail, the amount of time it would take to 3D-print a specific volume was readily calculable by Branch Technology. The logistics of fitting this experimental production into their ongoing workflow of other professional projects drove the starting date and duration for each print. Working backwards out of the projected schedule, it was determined early on that the maximum total print volume for DRONOPOD was set at 44 cubic feet. Coupling this parameter with the goal of fully exploiting the vertical reach of Branch Technology's large KUKA robotic arm and customized 3D-print extruder in one of the components, and the maximum horizontal reach from its base for both components, led to a design strategy that significantly differentiates the

Figure 10

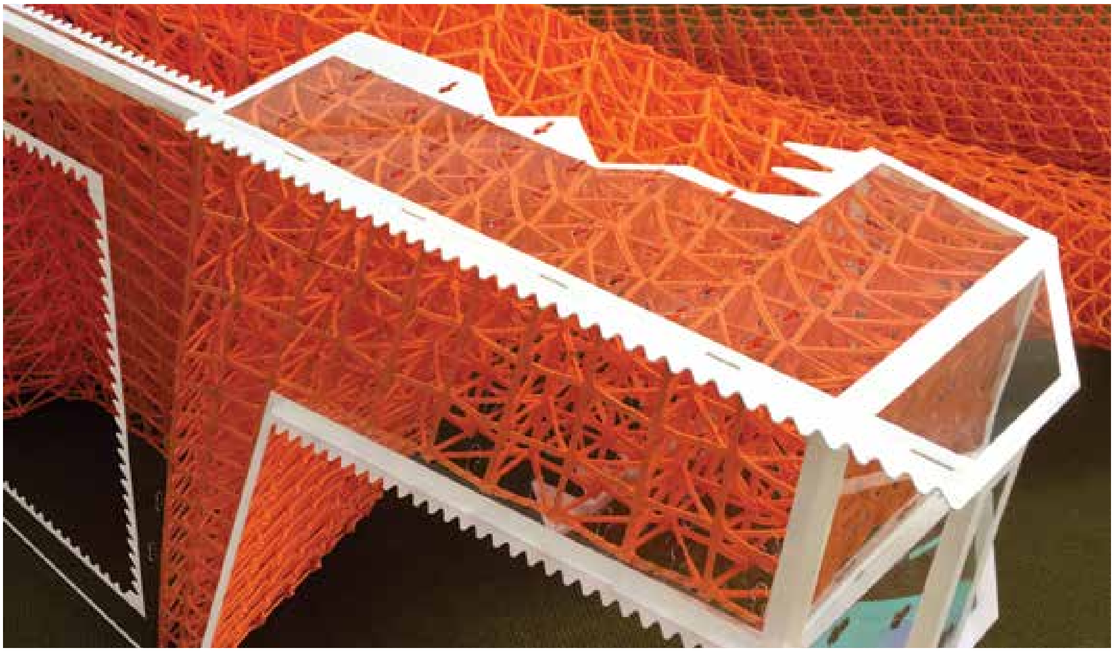

Figure 11

Figure 12

Figure 13

printing configuration operations for each component. One element was printed vertically and upside down (fig. 8), while the other was printed on its side utilizing a folded print bed. The net result of this overall process was the production of two very large and voluminous singular freeform 3D-printed components, the larger of which weighs only 70 pounds (fig. 9). Notably, through iterative developments initiated by DRONOPOD, Branch Technology has developed practices that now fluidly automate the processes by which variably thick control volumes can be optimized with respect to stepped cell counts, refined printing paths, and kinematic precision from initiation geometry through finalized production.

COMPOSITE CONSTRUCT

As both elements were printed with carbon microfiber infused ABS plastic, which is susceptible to UV damage with alarmingly little exposure to the sun, several coats of industrial-grade enamel were applied as a durable protective finish (fig. 10). The next set of challenges involved dialing in dimensional parameters for the design and fabrication of customized stainless steel components and developing a connection system to integrate all components into a composite construct. As the two DRONOPOD mega-prints were the first to be printed in such a manner at Branch Technology, localized and cumulative dimensional tolerance levels were not fully assessable until after finalized production. While a digital version of the printed matrix was available as a preview in the form of a mesh model that thickened the centerlines of the print paths, the actual prints are inherently imbued with localized anomalies that are tied to the orientation of each print in conjunction with the combinations of heat and speed settings utilized through the process, along with specific kinematic sequencing that allows for building up the system of nodes at any moment within the matrix.

For all of these reasons, the anticipated predictive capacity of the digital model with respect to connection sequencing, orientation, and placement ultimately proved to require a meticulous prototyping and verification process for the refinement of the stainless steel components prior to their finalized fabrication (fig. 11). As the nodes are the strongest points within the print matrix and structural integrity is attained through the quantity of nodes, the connection strategy developed for integrating the stainless steel and printed components exploits the sheer redundancy at hand. A system of "keyholes" was distributed along the planar faces of each stainless steel component, such that threaded zinc-plated steel hooks could reach in, grab a node, and be tightened against a rubber pad and washers, relatively perpendicular to the operative plane of the stainless steel component (fig. 12). Variable in length, these hooks grab as many nodes as possible at different depths throughout the print matrices. After numerous rounds of prototyping with clear polycarbonate sheet material, the final dimensions, orientation, and distribution of the keyholes were established and ultimately validated, thus initiating final fabrication for the stainless steel components. While a number of keyholes remained empty upon final assembly, every node that could possibly be encompassed by a threaded hook within the overall system was utilized.

Each of the stainless steel components serves several purposes, from affording self-registering alignment in the sequential and cumulative assembly of all parts into a composite whole, to providing rigidity in key zones within each printed component and setting up the means by which DRONOPOD was ultimately installed on the building. A large steel lever-armature, outfitted with a concrete counterweight, was designed to lightly sit on the roof membrane and reach up and over the parapet to provide the primary interface upon which DRONOPOD hangs (fig. 13). Upon final pre-assembly, which included hardware verification and disassembly into staged components inside the space adjacent to

Figure 14

the outdoor location for its final installation (fig. 14), DRONOPOD was moved outside, reassembled, rigged with temporary stays, and lifted into place via crane in April 2017 (fig. 15). Once all of the top bolts were installed in the primary hanging armature, the stainless steel "boots," located at the bottom of each printed component, were then used as jigs to locate the optimal placement and drill for threaded rods to bolt through the brick wall, thus locking DRONOPOD into place. With all of the stainless steel components, hardware, and the perforated polycarbonate landing pad integrated with the mega-prints, the total weight of DRONOPOD is approximately 425 pounds.

Figure 15

AUGMENTED REALITY

Our team developed three separate augmented reality applications through this project, the most significant of which provides a freestanding interactive experience that transforms DRONOPOD into a new type of urban instrument. By superimposing dynamic information and effects onto live views through personal smart phones and tablets, a viewer sees an animated display of objects navigating along curves that delineate spatial flows through DRONOPOD, thereby rendering the idea that variable operative scales of interest are embedded within the project (fig. 16). Ultimately, the intent of this applied demonstration was primarily two-fold.

Figure 16

First, the notion that such a customized interface can transform the public reading of a specialized object within the urban fabric holds immense promise for innovative design and broadcast strategies (fig. 17). Second, upon realizing the many challenges embedded within such an endeavor, the successful implementation of this augmented reality application was a goal in and of itself. In close collaboration with Jason Anderson (Studio Anamolous / Associate Professor of Architecture, CCA), the AR application was developed over the course of several months, in an intricate workflow that utilized Grasshopper, Excel, Unity, Vuforia and Android SDK. Spatially registering the dynamic model with the oversized graphic AR marker (fig. 18) such that animated views align with DRONOPOD

Figure 17

from up to 150 feet away from the physical construct day or night, and also in close proximity (without requiring the marker to remain within the camera view) required extensive troubleshooting and customized collaborative protocols through every stage of development.

FUTURE RESEARCH

All of the work set in motion by DRONOPOD served as a launching point for extensive research at Georgia Institute of Technology School of Architecture, where two interwoven exploratory tracks are currently in play. One is specifically geared to thoroughly expand the investigation into an array of projected sUAS futures and interrelated utility components, operative systems, architectural typologies, and urban scenarios. This track is set to be bolstered by the initiation of *Atlanta Bureau of Air and Space*, a long-term project to be carried out through successive Georgia Tech Design and Research Studios, which are specialized graduate-level studios directly tied to faculty research, advanced design, and interdisciplinary collaboration.

Another research trajectory places prime focus on advanced production. Experimental spatial constructs and composite material assemblies will be developed with the same operational attitude set forth through DRONOPOD, wherein customized integrations of advanced production techniques, materials, and technologies require procedural innovation and collaborative agility. While conversations with Branch Technology are ongoing specifically with respect to elevating our collaborative momentum into new rounds of research and development, this track also seeks to fold an expanded arsenal of advanced design and production technologies into its operational thrust.

Research sparked by all of the above has recently been initiated to integrate sUAS, AR, and robotics into multi-system design and production workflows, protocols, and environments. While each of these strains was effectively developed and demonstrated under the unifying arc of the project, they remain parallel operatives within DRONOPOD. With the unique opportunity to potentially boost momentum, reach, and impact through interdisciplinary partnerships at Georgia Institute of Technology, a primary goal at hand is to operate within and contribute to this promising field of research.

Figure 18

ENDNOTES

1. For a concise overview of Branch Technology and their capabilities, see Mahesh Daas and Andrew John Wit, eds., *Even When They Do Nothing, Robots Are Evocative: Towards a Robotic Architecture* (Novato: Applied Research and Design Publishing, 2018), 52–54.

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4. Knoxville Bureau of Air and Space, http://www.knoxvillebureauofairandspace.com

IMAGE CREDITS

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Figure 8: Branch Technology

Figures 4 and 15: Breanna Browning

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