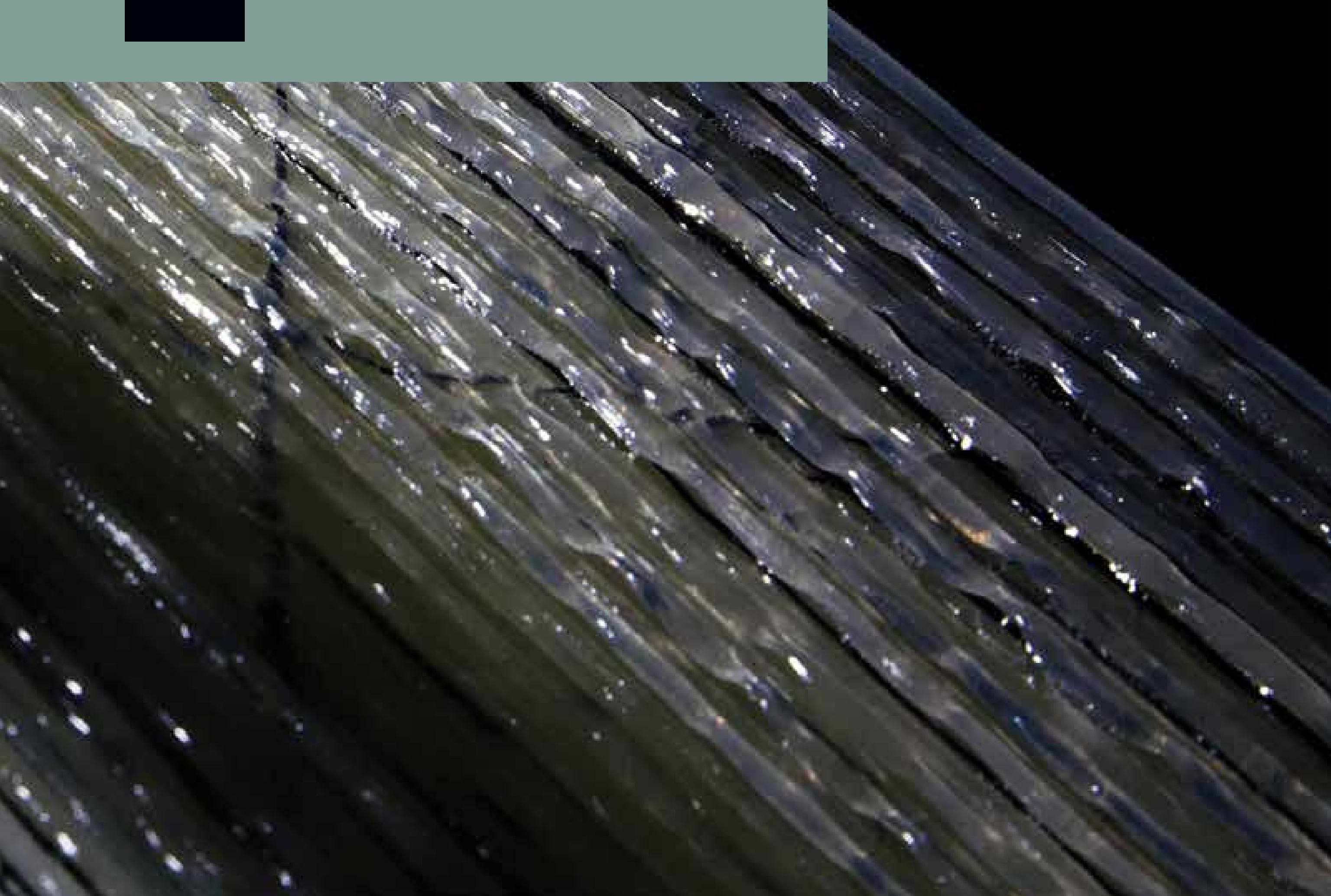
2018 TxA Emerging Design + Technology Conference Proceedings

8–9 November 2018

Held during the Texas Society of Architects 79th Annual Conference and Design Expo in Fort Worth, Texas

Edited by Kory Bieg

Texas Society of Architects



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Acknowledgments: 2018 TxA Emerging Design + Technology Peer Reviewers

We wish to thank the following individuals for their generous assistance in evaluating the abstracts submitted to the TxA Emerging Design + Technology conference in 2018.

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Introduction: How to Make the Impossible Possible

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The papers from this year's conference remind me of a popular topic in academic architecture circles from the 1990s: how to make the invisible visible. Back then, it was about uncovering hidden patterns, behaviors, and forces using representational tools like recordings, mappings, and diagrams. These methods became so widespread that they are now commonplace in education and practice. Architects used these representations to qualify the form of buildings, yet the validity of designs based on these abstract initial decisions were rarely analyzed post construction. As climate change, social equity, and access to healthcare become increasingly urgent issues, there is a renewed interest for making the invisible visible and even the impossible possible. This time around, architects are leveraging new digital and computational tools to bypass traditional modes of representation in favor of a more active and direct approach that welcomes feedback.

New technologies, like augmented reality headsets, are enabling architects to create at-scale, fully rendered digital objects in real environments. While the previous set of tools was used to represent objects indirectly through notation and orthographic projection, this new form of representation removes the need for any translation. Users can see a 3D model materialize before their eyes, or a dynamic particle simulation flow through an existing environment. Technology has enabled virtual objects to exist in the world independently of the laws that govern them. As Mario Carpo has noted, these "new digital design tools ... serve to make something else—something that would not otherwise have been possible."[i]

So what is the difference between the virtual object and the real thing? As far as one's perception is concerned, not much. After all, as Maurice Merleau-Ponty argues, "the perceived world [is] the primary reality" and gives "us the first and truest sense of 'real.'"[ii] To perceive an object is what makes it real; perception is what makes the invisible visible. These objects are presented in full resolution with the physical qualities, textures, and attributes of the things they are meant to become. From our perspective, these virtual objects are just as real as the furniture that surrounds us. The transition from digital representation to digital presentation has shifted "virtual" from a non-being immaterial existence to a new form of being both in and out of the material world.

This freedom—the ability to transcend the laws of nature yet exist within the same space—is the territory explored in this year's proceedings. Augmented reality, and other emerging technologies like automation and artificial intelligence, are entangling the material with the immaterial, forming an even more complex relationship between us, the real world, and the objects we produce. Uprooting the traditional role of drawing in architecture in favor of a virtual incarnation of objects is truly making the invisible visible. By doing so, we might also make the impossible possible and finally achieve some progress on the issues that need our attention the most.

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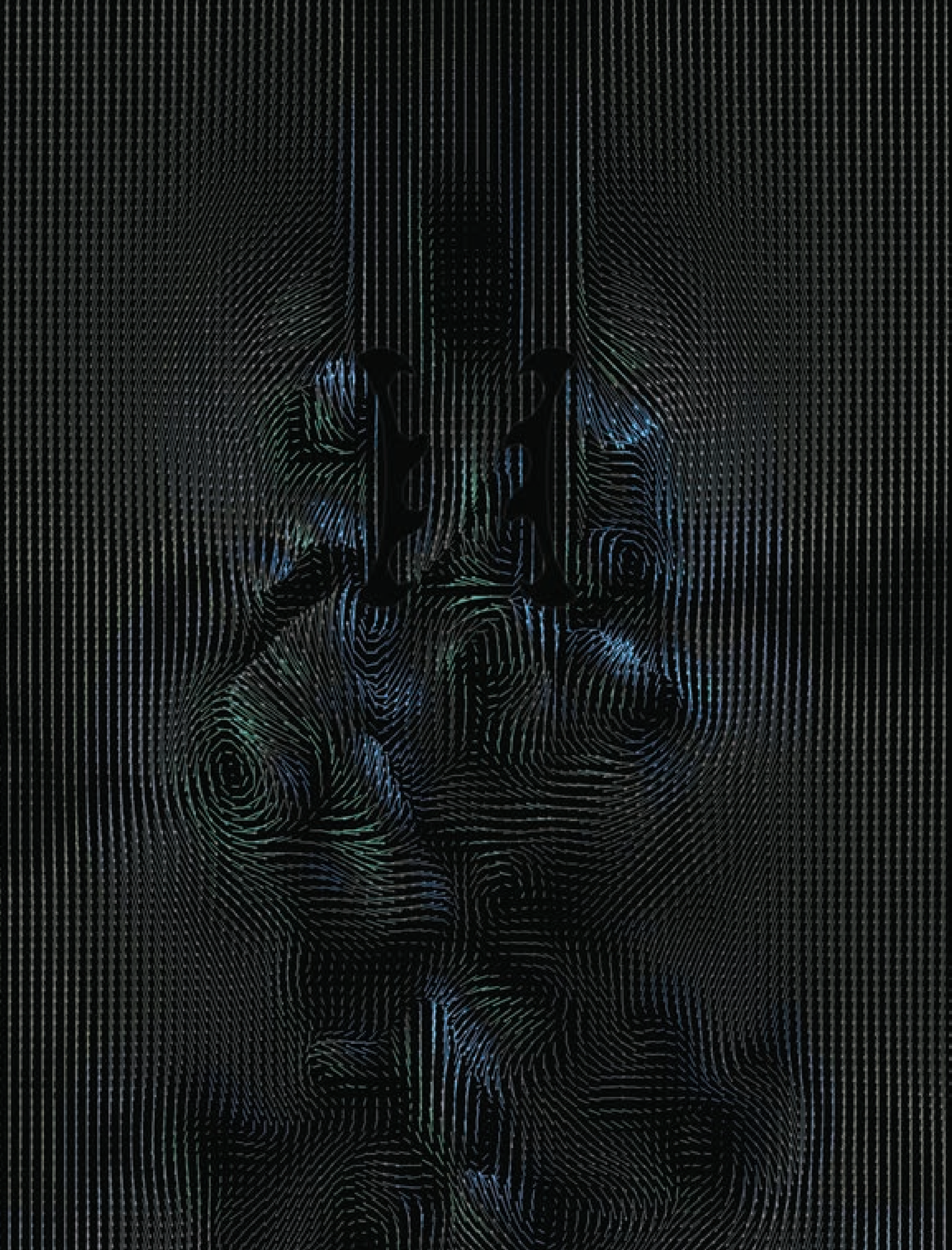
i. Mario Carpo, *The Alphabet and the Algorithm* (Cambridge: The MIT Press, 2011), 36.
ii. James M. Edie, Introduction to *The Primacy of Perception*, by Maurice Merleau-Ponty (Chicago: Northwestern University Press, 1964), xviii.



Aerodynamic Articulation: Recalibrating Micro Airflow Patterns for Thermal Comfort

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ABSTRACT

This research endeavors to increase the performance and capabilities of passive and low-energy design strategies used in hot and humid climates by qualitatively analyzing and instrumentalizing airflow. A multidisciplinary approach is used to explore the design of novel building forms that pattern airflow to enhance passive cooling effects in warm environments. A review of physiological experiments that correlate specific airflow patterns with an increased cooling effect establish the premise of this study. These physiological experiments found that undulating patterns of air velocity create significantly more cooling effect than the same mean velocity at a constant speed. This implies that warm urban environments could be made to feel cooler without using energy to increase the overall flow. To test the applicability of this premise, a series of experiments were performed to establish how effectively surface features and building form could pattern ambient air. These experiments show correlations between specific surface features and patterns of more comfortable airflow. This points toward surface articulation as a method to manage ambient airflow in addition to building mass and porosity. By examining airflow in more qualitative terms, the work also offers new design possibilities in terms of embodied experience.

1 INTRODUCTION

Most rapidly developing megacities are in the tropical region, where the climate is hot and humid. Because of low diurnal temperature difference and high humidity, it is one of the hardest climates to design for passive environments (Givoni 1998). Typically, under such climatic conditions, air movement is one of the most useful and inexpensive methods to achieve a comfortable environment. Despite airflow's critical role in urban comfort, solutions to manage airflow in urban areas remain normative, involving either altering building mass or increasing porosity in urban formations. The objective of this research is to provide an alternative solution to controlling urban airflow through designing or retrofitting building facades and other surfaces with textures. These textured surfaces can be passive or actuated in order control airflow separation in bluff bodies (like buildings), thus patterning airflow to provide a cooling sensation and increase thermal comfort.

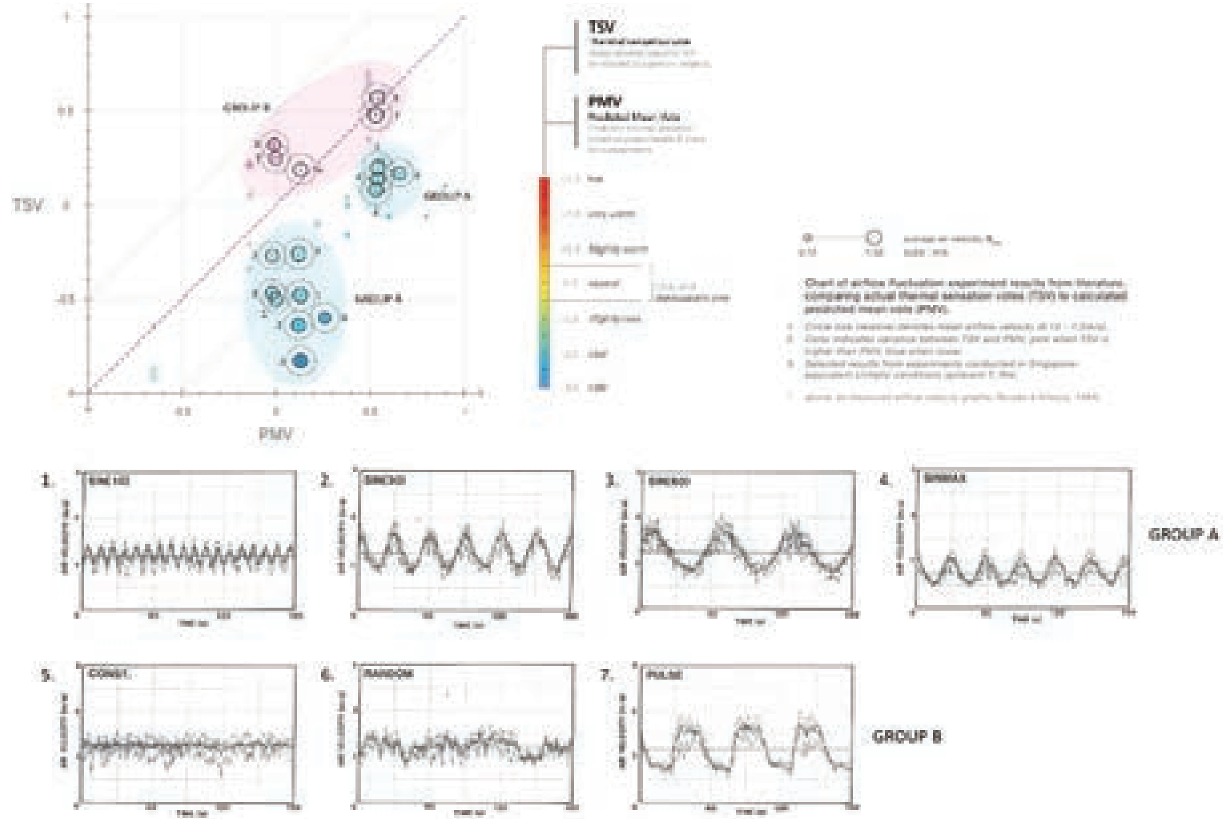


Figure 1: Combined chart of airflow fluctuation results for warm and humid climate. Note: With the same mean velocity of air, the airflow pattern of "SIN(60)" yields significantly cooler thermal sensation compared to the "Pulse" airflow pattern.

This paper will focus on the first phase of the research, where the effects of various surface textures on airflow were studied through a prototypical exterior canopy. The canopy designs were vetted using digital simulation, and then selected designs were physically tested to confirm their performance. In these experiments, computational fluid dynamic (CFD) simulations and particle image velocimetry (PIV) testing were used to examine the flow structures (i.e., airflow patterns). The results show that surface features can change the patterns of air velocity within and outside of the structure tested.

Design of the canopy began with a smooth, double funnel form meant to increase air velocity through the Venturi effect. This baseline form was enhanced with surface textures using symmetrical and asymmetrical ridges and bumps to create vorticity (i.e., spinning patterns), which creates local velocity fluctuations. In the more complex, later iterations, the vorticity created by the textures sheds (i.e., moves downwind) and creates patterns of varying air velocity. In these initial experiments, the research found correlation between the air velocity patterns determined through physiological tests to increase cooling sensation and the patterns created in CFD models.

2 STATE OF THE ART

Thermal comfort studies have been a prevalent area of research in the past decades, and a rich body of research has been conducted to examine the effects of air movement on human comfort. Although mean velocity was considered as the main parameter that contributes to comfort, more recent studies indicated turbulent intensity (Tu), airflow direction, and fluctuation frequency as important parameters for thermal comfort. The influences of Tu on thermal sensation have been explained based on two different reasons. One is that the convective heat transfer coefficient will increase with the increment of Tu, thus enhancing the heat flux of skin. The other, which is from both physiological and psychological studies, is that the increase of Tu value through airflow fluctuation causes the fluctuations of skin temperature, which arouses alarm signals from thermoreceptors to the brain and causes a cooling sensation in warm environments (Zhou et al. 2005). Most experimental research in this area of study includes documenting subjective responses in a controlled climate chamber and comparing these responses against PMV (predicted mean vote). PMV is the average response of a large number of people calculated using P. O. Fanger's equation involving six environmental and physiological parameters (Fanger 1972).

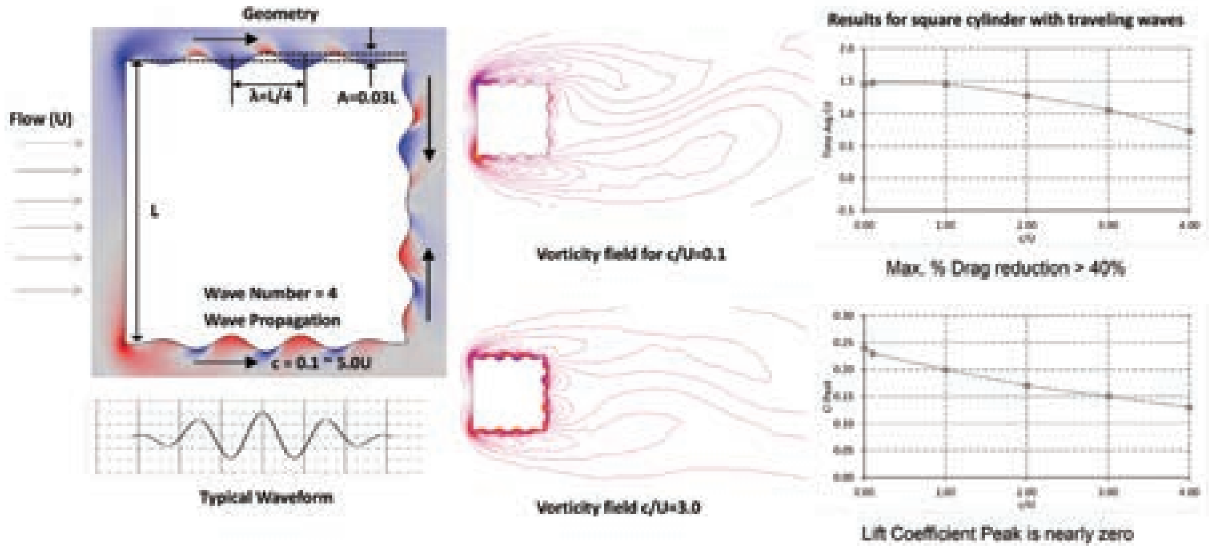


Figure 2: Active wave propagation on bluff body to reduce flow separation control (Dash et al. 2017).

The graph in Figure 1 maps a collection of past documented airflow fluctuation experiments' results at a temperature range of 27–31°C (Tanabe and Kimura 1994, Zhou et al. 2006, Huang et al. 2012, Ugursal and Culp 2013, and Xie et al. 2016). This comparative study shows that, under similar environmental parameters (air velocity, operative temperature, relative humidity), varying just the airflow pattern can significantly affect the subjective cooling sensation or thermal sensation vote (TSV) of test subjects. These studies, as a collective, indicate that specific airflow patterns with dominant frequency distribution increase cooling sensations, especially in conditions where airflow velocity is limited and cannot be elevated.

Patterns that most significantly increased cooling sensation largely follow a repetitive sinusoidal wave velocity fluctuation. Identified as "Group A" in Figure 1, the sine waves with cycles of 10, 30, and 60 seconds produced significantly cooler thermal sensations. Currently, airflow fluctuation frequency is a criterion that remains unaccounted for in empirical models of thermal comfort. The comparative study from past experiments suggests airflow patterns can be considered as another control factor to offset increased temperature in warm indoor as well as dense, stuffy outdoor environments.

Outdoor airflow research on an urban scale has currently been limited to understanding airflow behavior around existing urban environments or by manipulating different generic urban configurations for optimized natural ventilation potential in building, urban, and pedestrian comfort. This is illustrated by Toparlar et al. (2017) in an exhaustive review on the use of CFD for urban microclimate analysis. This review calls for changes in urban geometry and inclusion of open spaces like courtyards, parks, etc. (Toparlar et al. 2017). These solutions involve removing building mass or introducing porosity, which is often not possible in existing hyper-dense populated districts, preserved areas, or in a rapidly transitioning urban economy (Marcotullio 2002). Hence, alternative novel methods are required to address urban ventilation.

One potential applicable new method being developed utilizes static and moving surface features on bluff bodies to control flow separation. Flow separation occurs when a fluid flow becomes detached from the surface of an object and instead takes on the form of eddies and vortices. Per current fluid dynamic research by Dash et al. (2017), the use of static and moving surface features has been shown to greatly reduce flow separation. The recorded experimental results in Figure 2 show that active movement in the form of traveling waves on the surface of a bluff body were able to create a turbulent boundary layer region, which allowed it to reduce drag by more than 40%, and airflow separation was delayed, similar to the popular phenomenon of a golf ball (Chear and Dol 2015).

Controlling airflow field on an urban scale by means of actuated movement of facade features has not yet been explored. If this technique of controlling airflow movement around bluff bodies (like a building) can be extrapolated in urban conditions, it could mean better airflow in congested urban spaces. This type of control could be used to alleviate problems such as wind shear, down draft, and wind shadows while offering the further potential of patterning

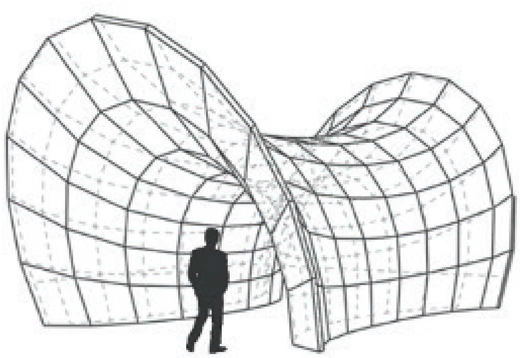


Figure 3: Canopy design for the experiment.

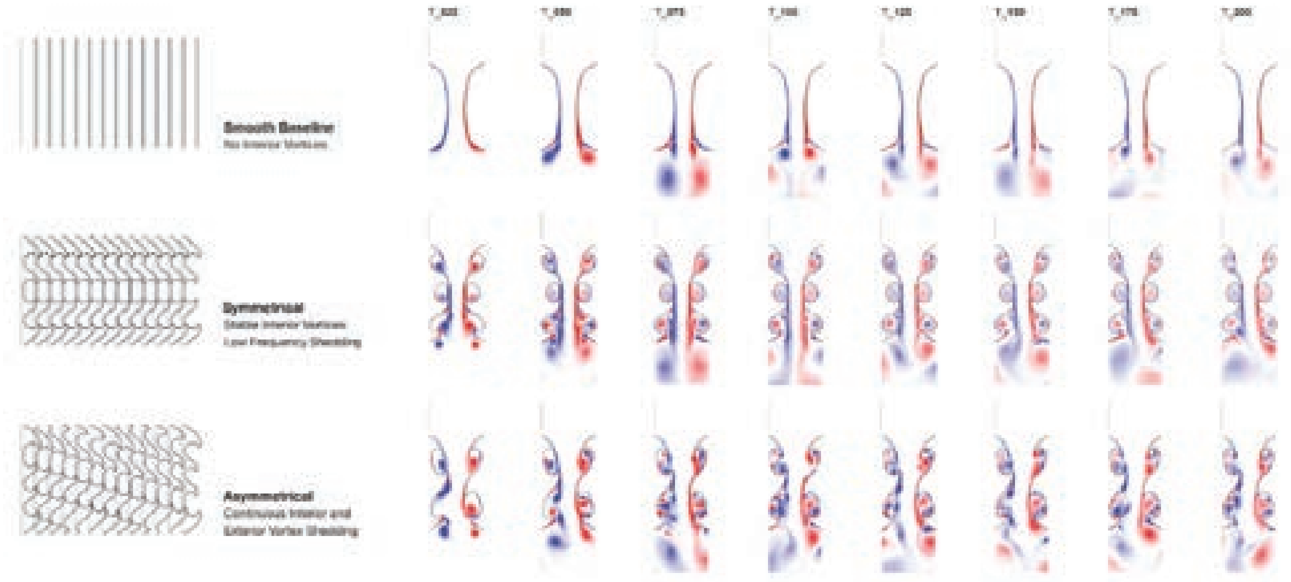


Figure 4: Series of captured instances over 200 seconds of 2D simulation performed on Baseline, Symmetrical, and Asymmetrical waveform arranged in a funnel-shaped urban canopy.

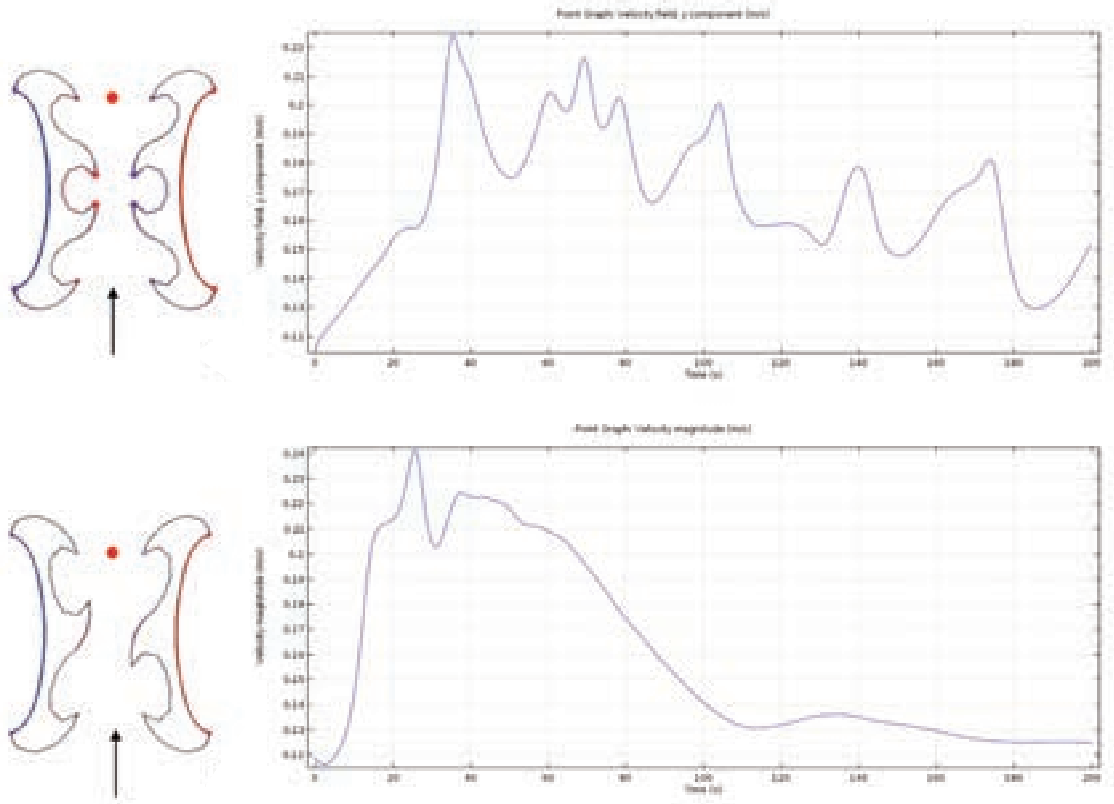


Figure 5: Point graph for the Symmetrical and Asymmetrical Canopy 2D simulation. The red points on the drawings indicate the position where the velocity magnitude was measured over time.

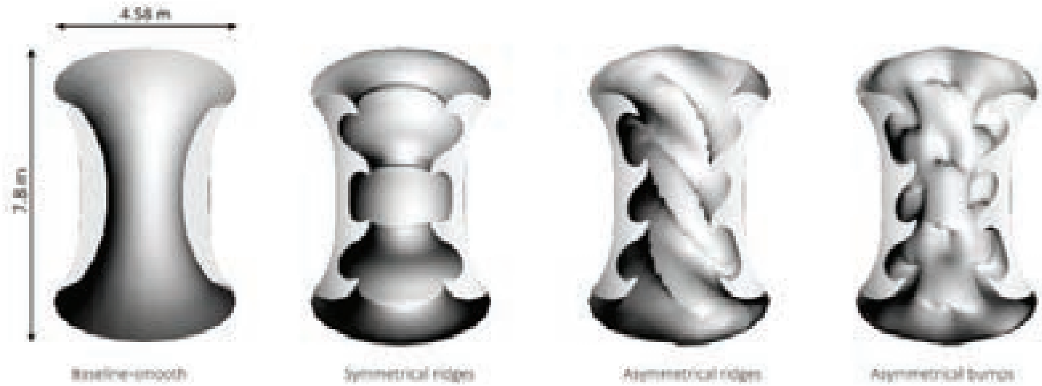
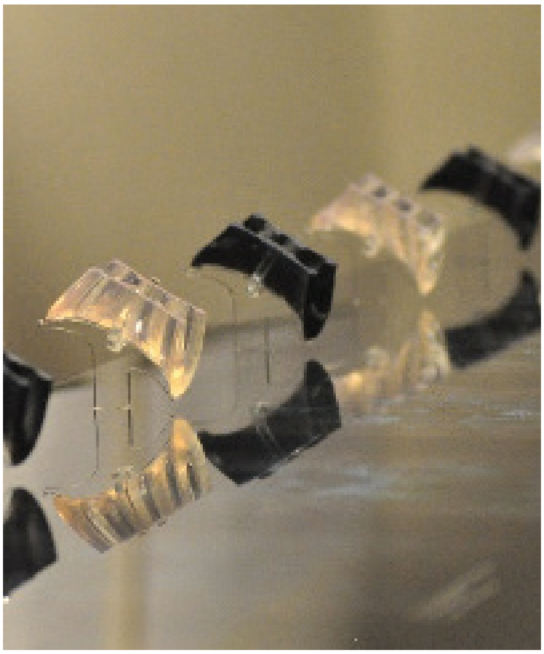


Figure 6: (Above) Final four models used for physical experiments (PIV). (Left) Exhibition showing physical models.



air for pedestrian thermal comfort. Considering this as an initial hypothesis, the authors created various textures replicating waveforms on an urban canopy to investigate their performance on producing airflow patterns. As a first step, these experiments consider static textures to study their effect on patterning air. The urban canopy considered in this study is basically a tunnel-shaped sheltered pavilion that can be used for various outdoor activities suiting local needs of the urban environment (fig. 3).

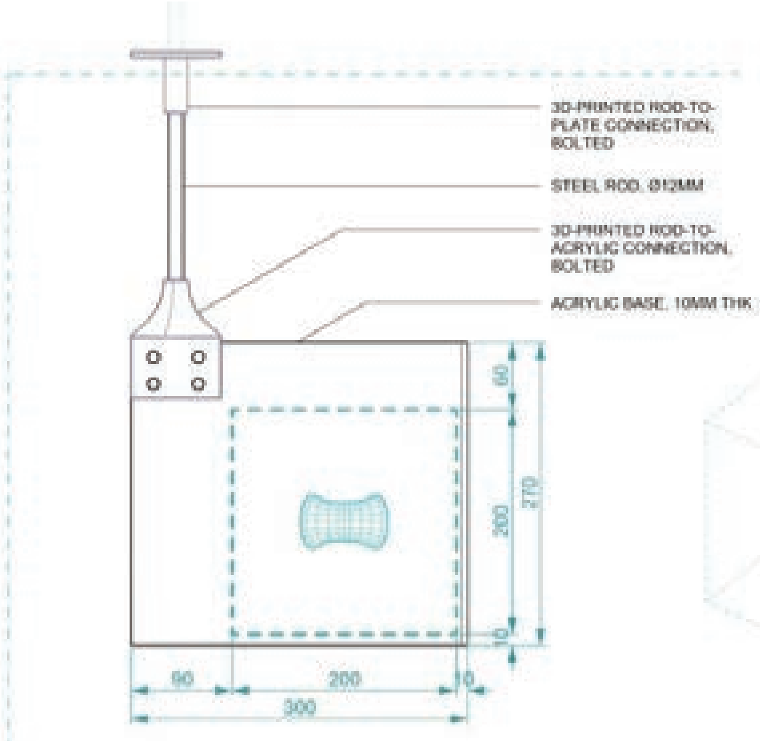
3 METHODOLOGY

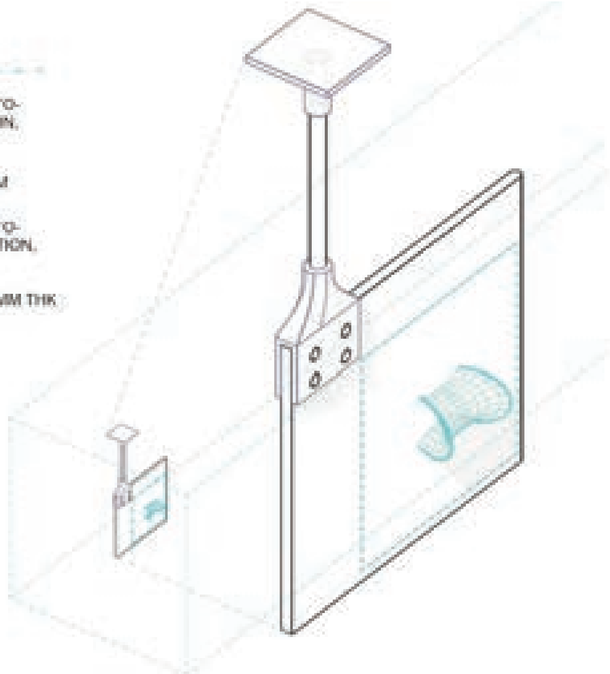
3.1 Design and Selection of Base Model

The baseline for the urban canopy was considered as a double funnel shape (fig. 3), which creates a Venturi effect accelerating the assumed low wind speeds. Simulation tests of the baseline funnel shape urban canopy validate that wind speeds do increase by 25% at the leeward side of the canopy. Adhering to flow separation control guidelines of mimicking a rolling wave form, which would allow for delayed onset of flow separation as seen in the experiments carried out by Dash et al. (2017), a series of waveforms are arranged symmetrically and asymmetrically onto the baseline figure of the funnel-shaped urban canopy (fig. 4).

Then 2D RANS transient models were simulated in order to understand the flow structure around these canopies. This was done using a commercial CFD software—COMSOL Multiphysics Version 5.2a. The simulations were run over a period of 200 seconds, and the velocity variation over time was mapped to analyze the possibility of airflow patterns over the simulated time. The simulation was carried out at a Reynolds number of 100 and with an inlet speed of 0.1 m/s in order to match up with the PIV experiments that were planned to be carried out with these iterations.

The two-dimensional simulation results produce distinctive flow structures between symmetrical and asymmetrical waveform propagation. Figure 4 illustrates a series of captured instances at an interval of 25 seconds. The symmetrically replicated waveform figure created stable interior vortices with low frequency shedding. This is in contrast with the asymmetrically replicated waveform figure that creates continuous interior and exterior vortex shedding. To gain an understanding of how these varying flow structures relate to the fluctuating airflow velocity and pattern, the research group plotted the velocity magnitude at a specified point (marked red in Figure 5) in both canopies. Comparing both experiments, the asymmetrical canopy exhibits some characteristics of airflow patterning, and hence it was selected for further detailed study (fig. 5).





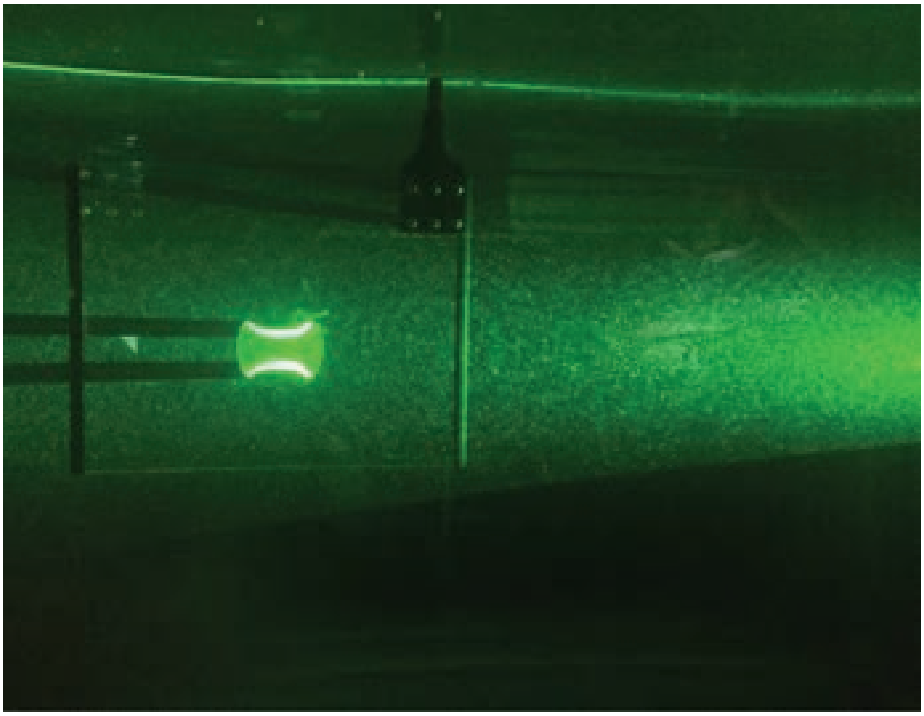


Figure 7: (Above) Setup dimensions for the test canopies and image of how the model is towed on a base board through the long water table, marked in blue dashed lines. (Right) Laser plane through the model illuminating the seeded micro particles (looking like white noise in the image) for flow field analysis.

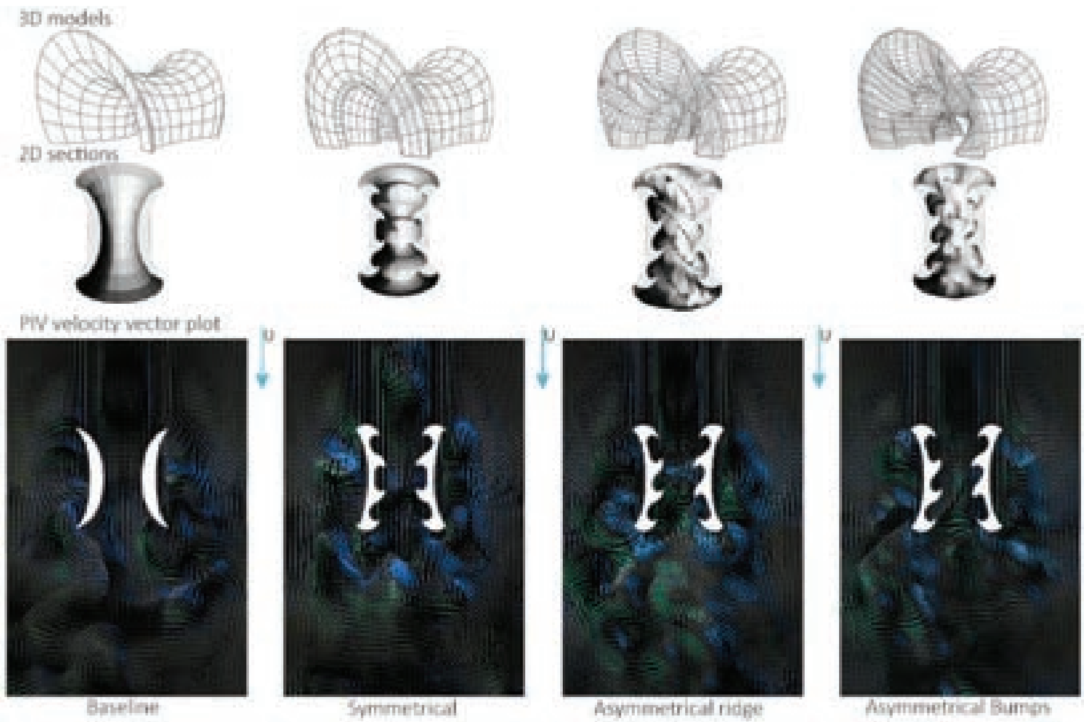


Figure 8: Particle image velocimetry (PIV) test results used to examine the flow structures created by a series of physical models.

3.2 PIV Setup and Results for the Four Iterations

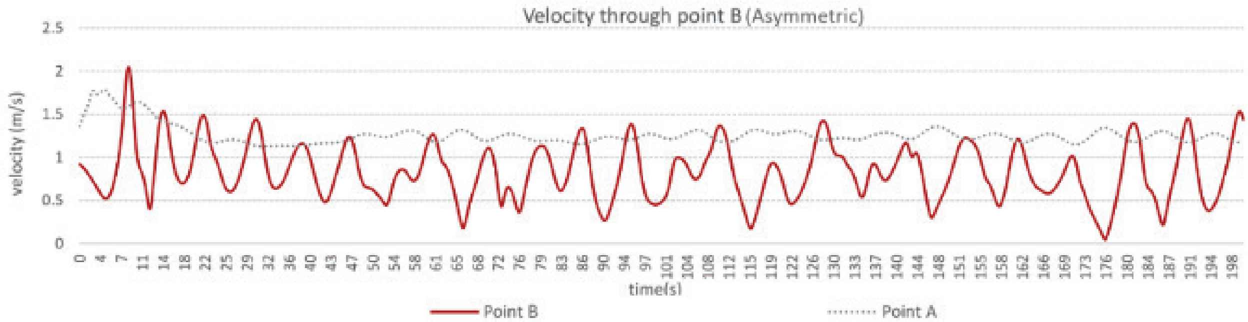
The 2D simulation results in COMSOL were also validated through physical PIV experiments. Three-dimensional models of these canopies were digitally modelled, and the asymmetrical waveform was modelled into two distinct iterations—continuous ridge and alternating bumps (fig. 6).

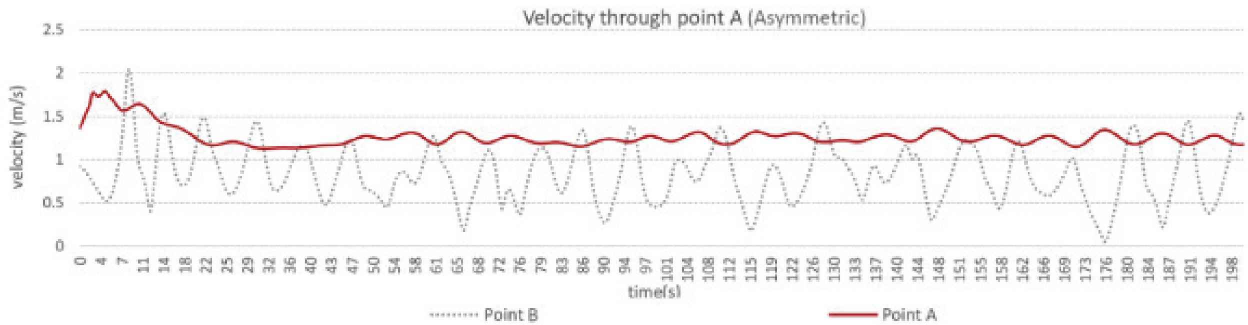
A PIV experiment is a way to physically simulate fluid behavior with respect to an object. The fluid flow is visualized by mixing micron-scale particles in the water tank (light enough not to affect the fluid movement) and illuminating it by a laser plane in a dark space. The particles in the path of the laser are illuminated, and their collective movement reflects the fluid's movement. By tracking the movement of these particles, then, the fluid flow behavior around the test object can be analyzed (fig. 7, bottom). A Reynolds number was maintained at 100 for both the PIV experiment and the CFD simulations because keeping the Reynolds number constant facilitates the simulation of airflow with the help of any other fluid, be it water, oil, or gas, etc. For any two different situations, if the Reynolds numbers are the same, it can be said that the fluid behavior will be the same. For this experiment, the test canopies were scaled to a size of 1:100, towed through the water table (fig. 7, top) at a constant speed of 1 m/s, and, to match the CFD simulations, which were full-scale models, run with an inlet velocity of 0.1 m/s. This reduction in velocity is to compensate for the scaling of the canopies under the same Reynolds number of 100.

The video for the PIV experiment was captured only after the towed canopy reached a steady state condition. For this reason, the time frame for the capture was only two seconds. Although the data was enough to analyze flow field structures and validate the CFD simulations, it was insufficient for extrapolation to a longer time frame (60–180 seconds) for airflow pattern analysis. To overcome this limitation, detailed CFD simulations were then carried out to analyze flow patterning for several minutes.

3.3 CFD Simulation of Selected Asymmetrical Model

Once the CFD setup for the base model and the four iterations were validated with the help of PIV experiments, the previously selected asymmetrical ridges and the baseline canopy model were then simulated again with a higher wind speed of 1 m/s that adheres to a wind speed within a range perceptible to human sensation. Furthermore, the authors wanted to compare the airflow patterning in the canopy simulations with the state of the art (Fanger 1972 and Fanger and Pedersen 1977), where





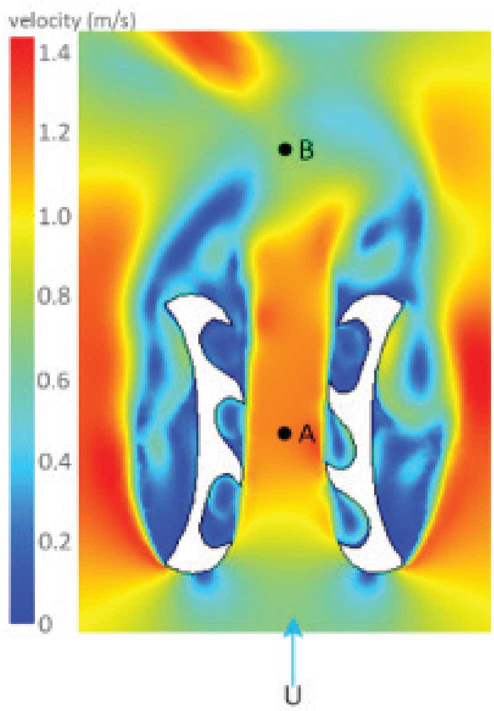


Figure 9: Baseline and Asymmetrical canopy simulation results.

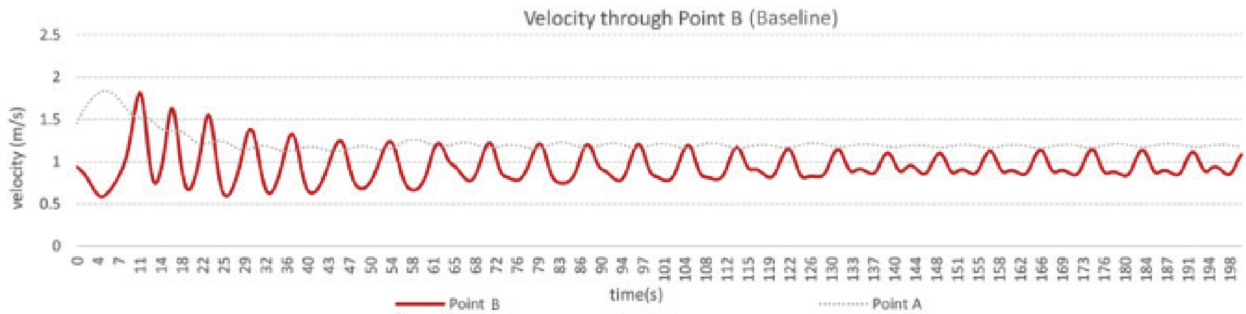
average wind speed was 1 m/s.

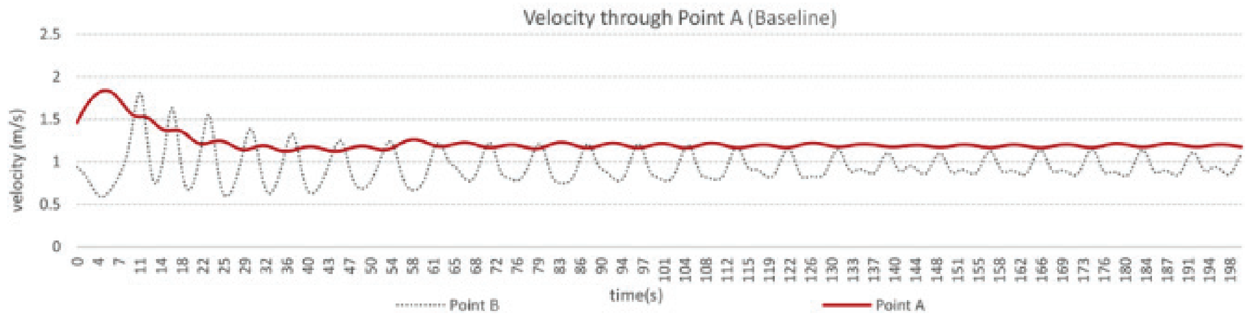
For the 2D CFD setup, again the commercial software COMSOL Multiphysics Version 5.2a was used. A horizontal cross-section through the canopy was considered, and a bounding box sized 20L X 20L, where L is the width of the canopy—5 m) was drawn around it. This would act as the wind tunnel for the test canopy sections. For boundary conditions, a velocity of 1 m/s was chosen for the inlet and a pressure value of 0 Pa was considered for the outlet. The side bounding walls were also given a symmetry condition. The initial conditions were kept the same as the boundary conditions. Since the overall flow pattern was of significance to this experiment, the lamina-based flow model provided similar results to a turbulenc-based model and had much quicker run time. Hence, a laminar physics-based fine meshing was created around the test geometry for all models. The solver was then set to transient simulation with a time step size of 0.1 s and run for 200 seconds. The resolution factor was kept at 0.01. This model setup was the same for both baseline and the asymmetrical models (fig. 9). Certain points, as shown in Figure 9, were considered on the leeward side of the canopies. These points represent the places where a person standing would experience the impact of the static ridges of the canopy on the incoming airflow.

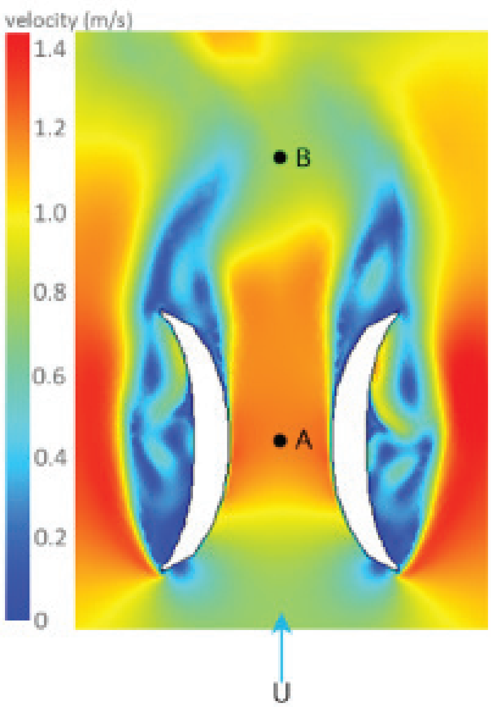
4 RESULTS

4.1 PIV Flow Field

Figure 8 illustrates the four different test cases used for the PIV experiments and their flow field results. The leeward side of the canopy iterations see increasing degree of wake interferences, the baseline being least affected and the asymmetrical ridges having the highest amount of wake structures. Because of this, the vorticity magnitude represented in green and blue







has higher intensity than the baseline. The asymmetrical bumps also seem to continually shed vortexes (inward spiral flow formation), and the phenomenon is more pronounced than in the other iterations of the test canopy. Since the PIV experiment is 3-dimensional, it can be noticed that, at the windward side of the canopy, the incoming laminar-type fluid flow creates a small singular or dual vortex right before it hits the canopy opening.

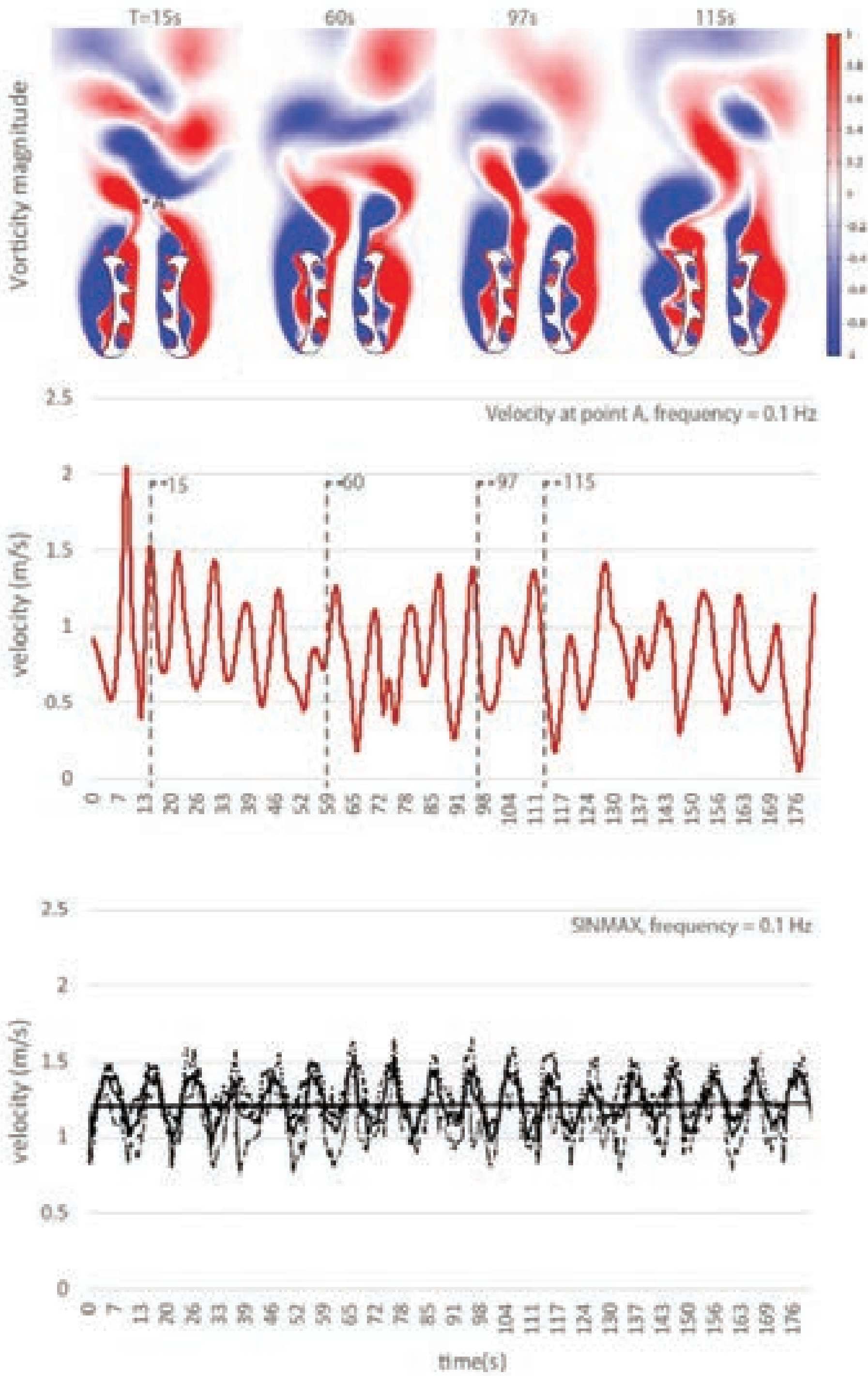
4.2 Flow Patterning in Asymmetrical Ridge Model

Figure 9 illustrates the flow behavior over a period of 200 seconds. The leeward side experiences von Kármán vortex shedding. The points A and B, the probable positions where a person would be standing while walking through such a canopy, were also plotted. This allowed the analysis of velocity fluctuation frequency and airflow pattern to test occupant experiences as mentioned in the state of the art. Point A (midpoint) is located at the center of the canopy. For both the baseline and asymmetrical canopy, we see an increase in the average velocity by 18% and 25% in baseline and asymmetrical, respectively. At the midpoint, the amplitude of velocity variation is much smaller in the baseline (0.03) in comparison to the asymmetrical canopy (0.1). When the test subject moves from the midpoint to the trailing edge, the mean speed decreases to 0.95 m/s and 0.8 m/s for the baseline and asymmetrical, respectively, but the fluctuation and amplitude increase.

4.3 Flow Patterning Comparison With Physiological Studies

The frequency of the wave in the asymmetrical model is in cycles of 10 seconds, and the pattern is similar to natural wind fluctuations. This means that standing around the trailing edge position in such asymmetrically textured canopy would provide for cooler thermal sensations in

Figure 10: Comparison of asymmetrical flow pattern results with Tanabe and Kimura results.



warm and humid conditions, as indicated by Tanabe and Kimura (1994) as well as Huang et al. (2012) in their subjective experiments. Figure 10 illustrates the frequency match with SIN(10), which had cycles of 10 seconds, and also the mean speed match with SINMAX, which has a wind speed average of around 0.8 m/s with a cycle of 30 seconds. SIN(10) and SINMAX also provides a TSV vote of -0.48 and -0.6, which means it has more cooling effect than constant or random airflow patterns for identical temperature and humidity conditions. This confirms the idea that certain specific texturing on building surfaces can facilitate the modification of incoming low constant wind in a sine wave-like pattern, which is studied to provide cooler thermal sensations.

5 CONCLUSION

The experimental results showcase that airflow behavior and pattern can be altered through applying textures on surfaces. These airflow patterns can be controlled to some extent to create patterns that correspond to those found to create cooling sensation to building occupants. These fluctuations are achieved without significant increase in air speed and in complete absence of any mechanical means. This research establishes a direct relationship between surface texture and periodic airflow velocity fluctuations. Though preliminary, this study suggests a potential direction for modifying airflow in cities with relatively small interventions in overall form.

Further studies examining larger buildings in context and using moving/actuated textures are ongoing. These studies hope to establish multidisciplinary (architecture, engineering, and building science) methods for designing more comfortable cities using more qualitative metrics for comfort. In addition to velocity fluctuations, further examination of building airflow problems such as wind shear, wind shadows, and down draught could also establish more uses for this type of aerodynamic design. In the future, active systems like the initial studies by Dash et al. applied at the building scale could refigure airflow on a vast scale in real time. In addition to building science and engineering, these experiments add to a growing body of work exploring the design of flow of energy within and around buildings broadening the range of aesthetic effects as well as efficiencies of future buildings.

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Flat Crush

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ABSTRACT
Flat Crush is an object installation that deals directly with the problem of fabrication and representation in a post-digital era. In recent years, the tools for architectural representation have proliferated and evolved as never before, and some have become commonplace, losing their original novelty. Some of the most widely used tools of representation have generated a real revolution in the perception of architecture, not only among professionals but also among the rest of society. This post-digital condition has influenced how representation in architecture has been able to become a concept for contesting ideas; a proposal for a tender, almost photographic impression; and a combination of playful, quasi-cinematographic scenarios that document projects in 2, 2.5, and 3D, wherein the technique of collage has made it possible to face the digital architecture frustrated reality.

ABOUT THE POST DIGITAL
Post-digital culture is the culture produced by a society that has assimilated the digital into the "natural" world in such a way that the digital ceases to be the supreme medium of the arts or an artistic goal in itself, spontaneously hybridizes with the analogical, and, from that moment, disrupts the analog-digital duality.

Part of the term "flat crush" refers to the classic digital notion of surface, which is not superficial but instead represents the idea of "flatness" as an unstable condition. Flatness refers to the paper or screen onto which architectural images have been projected. The relationship between flatness and surface refers to the combination of conditions of the architectural product and its means of production. *Flat Crush* uses the principle of a simple vertical blind system. The notion of how digital technology has modified global culture is that of flattening real space into horizontal codes of digital technology.

Projects like *Flat Crush* belong to a post-digital discourse in terms of representation and in terms of combining analog with basic digital techniques. However, the post-digital is deeply digital; it simply recognizes our current moment to be different from previous periods of digital preoccupation.[1]

In recent years, the tools for architectural representation have proliferated and evolved as never before. Some of the most widely used tools of representation have generated a real revolution in the perception of architecture, not only among professionals but also among the rest of society.

The concept of "post-digital" was introduced in a 1998 article by Nicholas Negroponte in *WIRED* magazine:

Terabit access, petahertz processors, planetary networks, and disk drives on the heads of pins will be... they'll just be. Face it—the Digital Revolution is over. Yes, we are now in a digital age, to whatever degree our culture, infrastructure, and economy (in that order) allow us. But the really surprising changes will be elsewhere, in our lifestyle and how we collectively manage ourselves on this planet.[2]

Years later, in 2010, when Russell Davies referenced this idea, it was couched in a half-hearted apology:

Post Digital was supposed, if anything, to be a shout against complacency, to make people realise that we're not at the end of a digital revolution, we're at the start of one. The end game was not making a website to go with your TV commercial and it's not now about making a newspaper out of your website. Post Digital was supposed to be the next exciting phase, not a return to the old order.[3]

The question then, is, what does it really mean to be post-digital in architecture and beyond? Gradually, it seems to mean recognizing more clearly that the origins of the essence of this sensibility are increasingly remote in time, but that the computer is the tool that has allowed the reordering of these canons from form to image. The repository of the utopias of each epoch preserved in the depths of culture is transformed into the invigorating and obsessive element that unleashes a revolution, while at the same time providing it with its raison d'être. We must leave behind all those architect gurus of the 1990s who wanted to evangelize architecture and convert it to its postulates by force because that digital project actually failed. This failure can be recognized in the architecture of the last years of the 20th century and the beginning of the 21st century, which seemed only a contingency in an emergency created by professionals worried about raising experiments with techniques, technology, and processes of contemporary design and thought. Some of those aspects continued, but the actual shift occurred when we realized we were all doing very similar common digital operations.

Figure 1: Process

If early digital processes were loud and disruptive, initiating a flood of revolutionary thinking, current technologies spread quietly, without the attention and intellectual development of mainstream digital design. To combat this, this project carefully considers the digital processes we take for granted. Though seemingly trivial, such processes constitute the foundations of architectural design today. The post-digital culture is not a Ludditic disavowal of computation, nor an ironic detachment from it; rather, it's a bid to explore the idiosyncrasies and aesthetics of digital mediums while considering larger cultural questions that have been under-addressed in digital design discourse to date.

FABRICATION/REPRESENTATION

The digital is no longer synonymous with technology, but is instead considered a zeitgeist, or spirit of the current time. When thinking about what approach to take for a particular project, one's methods can be offline, or a combination of digital and traditional methods. Everything belongs to the same reality of small interrelated tendencies that explain a global post-digital context to which organizations of today and tomorrow must respond to rather than fight against. The digital transformation, in this sense, must be increasingly focused on this new scenario. This is the context from which *Flat Crush* emerged.

Digitally fabricated objects have gained a largely technophobic fandom in mass media that harbors little criticality toward the actual objects but an infatuation with the fabrication process. The predominant digitally fabricated "tech aesthetic" in architecture merges sleek minimalism with parametrically subdivided surface logics. *Flat Crush*, on the other hand, responds to a different aesthetic.

Applying a more humanistic rather than artistic tone, this project attempts to rethink the relationship between human beings and technology, now understood through post-digitalism. We reject the implicit reductionism in digital processes while distancing the digitalism of technology; that is, we reject the acceptance of technology while denying the logic that digitalism entails. In contrast, we speculate about a post-digital logic that gives continuity to the human-technology relationship through the integration of the physical and drawing representation, which in a certain way gives unity to our perception of the world. The critical point is not to be dazzled by digital technology, since that will not allow us to link it with its analog counterpart and appreciate them as a continuum that enriches the experience instead of reducing it. *Flat Crush* is a vertical blind that looks at its own representation as a digital reality, its own bump map. The collective engagement in the creation of our surrounding reality will reach philosophy and science, thus resulting in a new understanding of ontology; our reality becomes an ongoing collective project, populated not by static objects but by the immanent process of producing complex assemblages.[4]

This object/drawing goes full circle, going through various iterations of dimensional status and quality of line work and removing from the object its familiarity without sacrificing its integrity as a sort of post-digital abstraction. These low-fi operations or post-digital shifts produce a kind of reconstruction of the object, a drawing machine. These are motivated completely by the vertical planes/drawings as an object, despite the suggestion of the seemingly sculptural end product.

Flat Crush's pivotal moment in the process is the translation from the digital world of a 2D representation to the physical through the CNC. These translations are not merely previous iterations of the former object or representations; they mark the creation of a new object through a restructuring of data, material, and formal qualities. Thus, the typical notion of a linear process, as

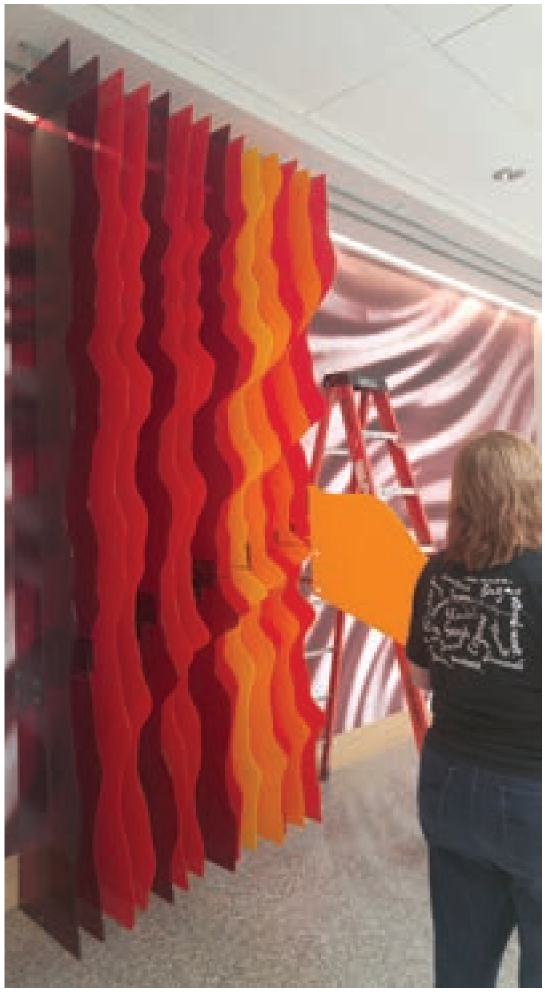


Figure 2: 2.5D installed

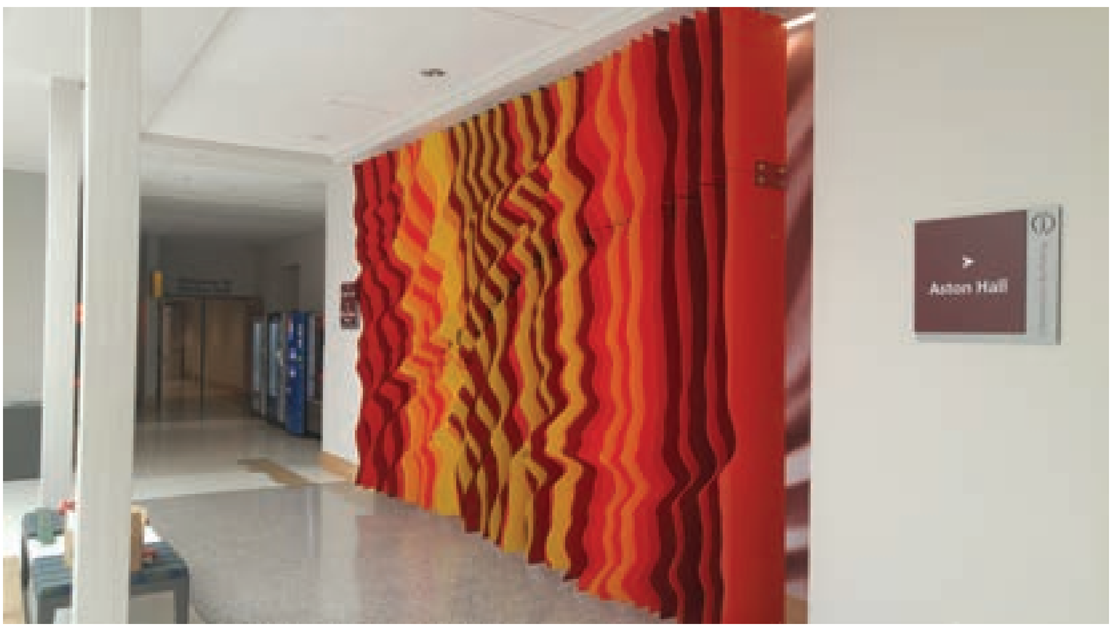
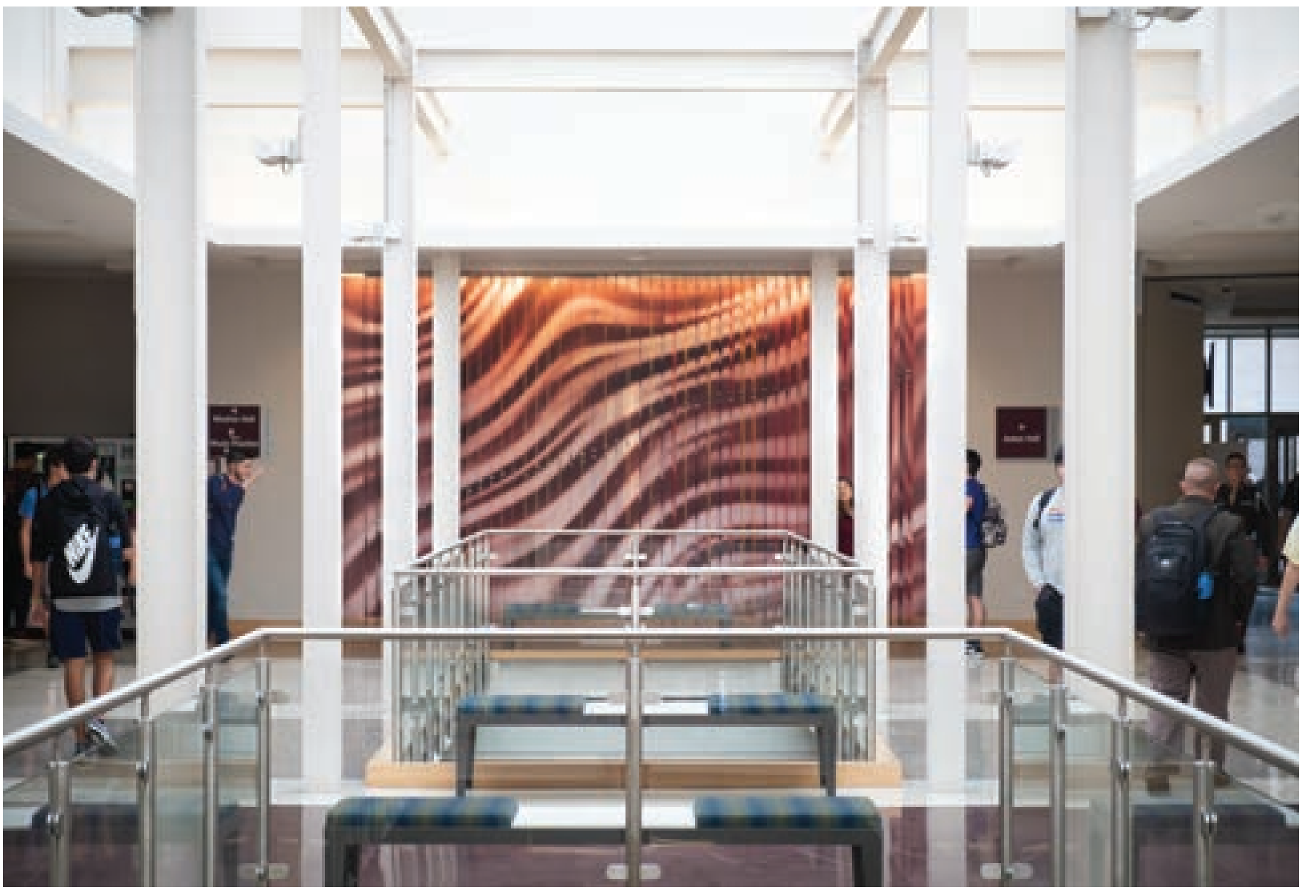


Figure 3: Side View

Figure 4: From object 3D to drawing 2D.



well as representation, is changed. Post-digital design discourse calls for a critical examination of the tools and technologies we take for granted, while simultaneously connecting what we do to larger cultural shifts occurring globally. This is about more than design.

TECHNICAL DESCRIPTION: DIGITAL

This project negotiates the relationship between 3D objects, 2D surfaces, and perception. *Flat Crush* is generated using a digital logic to produce a common object like a vertical blind. The installation was created through three phases. The first phase explored how a 2D image could be transformed into 3D objects. The second phase created an algorithm that transformed the generated 3D objects from Phase One into 2D successive strata. The last phase transformed the 3D objects that were used to create successive strata into an image that could be placed behind the installation.

Phase One: Sculpting Using Displacement Mapping

Displacement mapping is a computer graphics technique that was first introduced by Cook in 1984. Unlike bump mapping, this technique affects the actual geometric position of each point on a surface. The displacement direction is the local surface normal.[5] The term "mapping" refers to the use of a texture map, or 2D image, to manipulate the displacement effect. ZBrush, a digital sculpting tool, was used in this project to perform displacement mapping. A grayscale image of abstract curves was used to create an Alpha map for displacement. A 2D plane, in ZBrush, was subdivided to create high-resolution mesh. The Alpha map of the grayscale image was used to displace or pull each point in or out according to the black-to-white intensity variations in

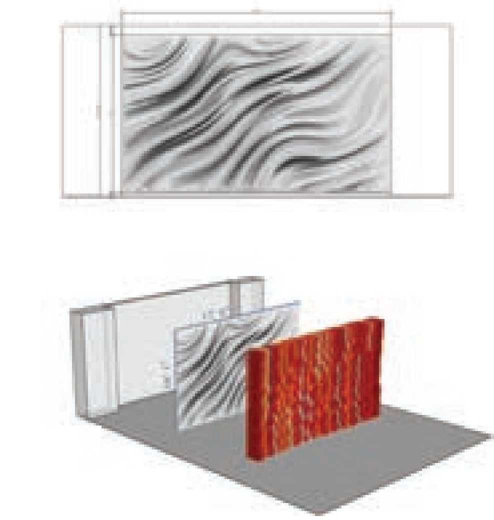


Figure 5: Layers

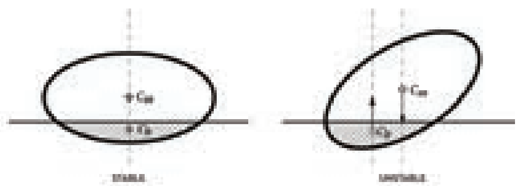


Figure 6: Displacement mapping of a 2D plane using alpha map.

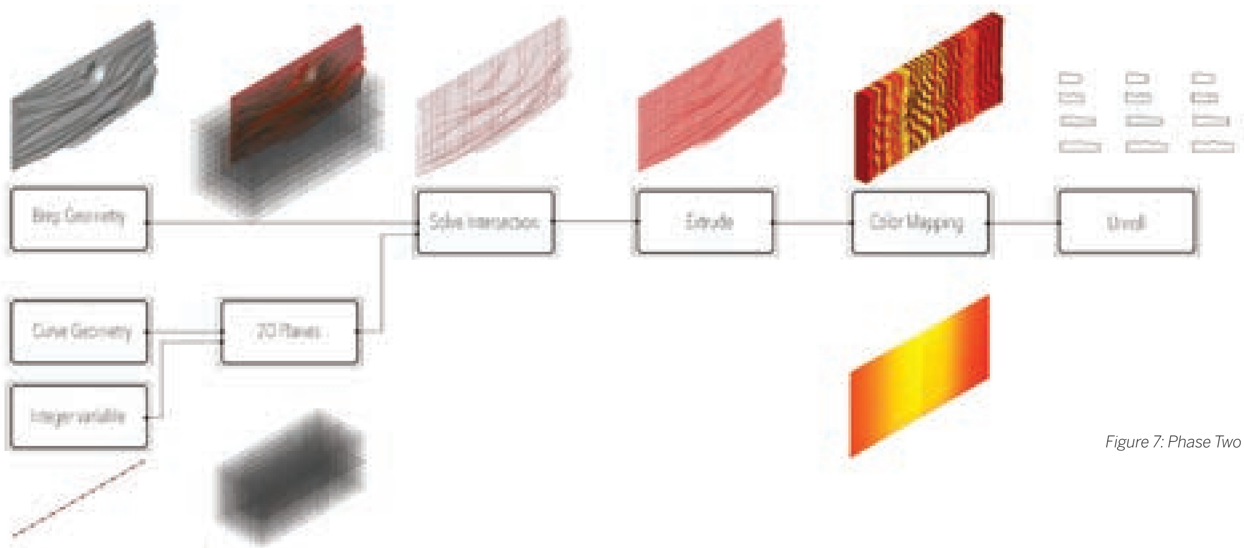
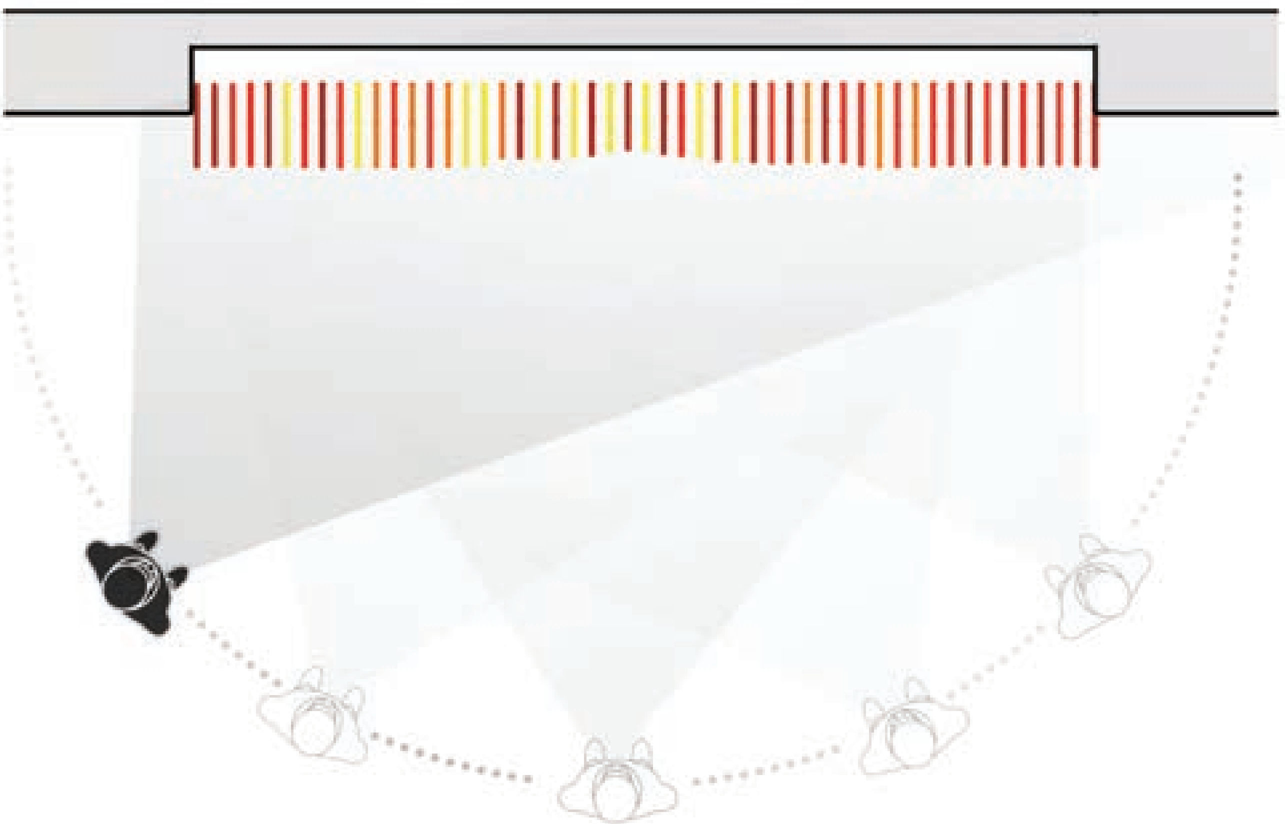


Figure 7: Phase Two

Figure 8: A rendered image of the B-rep geometry.

Figure 9: People's interaction with the installation.



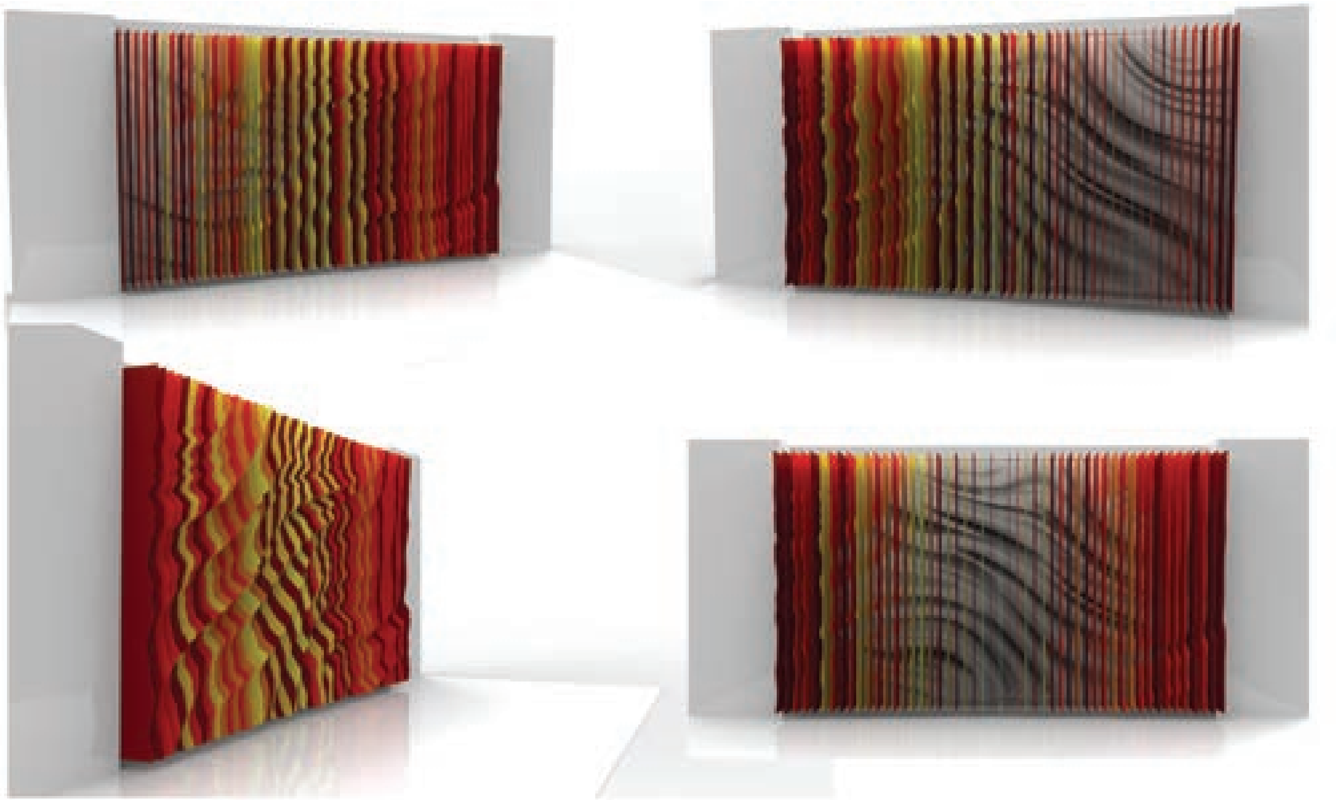


Figure 10: The dynamic experience of moving around the installation.

the Alpha map. As a result, the 2D plane was sculpted into a 3D object through a 2D image, or an Alpha map.

Phase Two: Stratification and Unroll Algorithm
The 3D object from Phase One was imported into Rhinoceros, a computer-aided design tool. Then it was loaded into Grasshopper, a visual programming language, as boundary representation (B-rep) geometry. In addition, a 2D line or a curved geometry was created to define the direction of stratification. A number of equally spaced, perpendicular planes along the curve were generated and controlled through an integer variable. Next, the section algorithm in Rhinoceros was used to create a 2D profile, or lines at each intersection, between the B-rep geometry and the 2D planes. These profiles were extruded to create a 2.5D panel of a Plexiglass sheet. Using a color-mapping algorithm, a red-to-yellow color scheme was used to change the color of each panel. Finally, an unroll script was created to unroll all panels and lay them out for laser cutting.

Phase Three: Rendering (Image Synthesis)
In Phase Three, a rendered image of the B-rep geometry, or the 3D object, was created. This image was printed and placed behind the installation in order to imply a different reading of the same geometry.

ENDNOTES

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2. "Negroponte," *WIRED*, December 1, 1998. https://www.wired.com/1998/12/negroponte-55/. Accessed October 2018.

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5. Robert L. Cook, "Shade trees," in *SIGGRAPH'84: Proceedings of the 11th Annual Conference on Computer Graphics and Interactive Techniques*, ed. Hank Christiansen (New York: Association for Computer Machinery, 1984), 223–31.

Buoy Stone: A Megalithic Simulation of Buoyancy

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ABSTRACT
Megalithic civilizations held tremendous knowledge surrounding the deceivingly simple task of moving heavy objects. Much of this knowledge has been lost to us from the past. It is thought that the bluestones of Stonehenge were floated up the River Avon with animal bladders. This practical solution provokes perception in delivering a floating stone. What would it mean to float a stone today? The *Buoy Stone* is calibrated to rest on its side for a horizontal commute under low bridges, then transform into a vertical figure once pumped full of river water. This paper mines, extracts, and experiments with this knowledge to test what applications and correlations it holds with contemporary digital practice. It describes in detail the design constraints, computation, and fabrication of a prototype. It then analyzes the integration of a custom-developed buoyancy simulation to solve for geometries that perform in water when loaded. These goal performances serve to prove whether the simulation and physical results are in sync. The paper then elaborates on some of the shortcomings and areas of future development. While this way of thinking has great potentials in thinking about structure, gravity, and mass, engaging the geometries of the object to intelligently deploy its own mass to perform tasks has great potentials for architecture.

INTRODUCTION
The greatest mysteries of Megalithic era construction surround transportation from quarry to site and the conundrum of erection (Hunt 2012)(Dibner 1950). It is thought that the bluestones of Stonehenge were floated up the river Avon with animal bladders (Parker 2006). This practical solution provokes perception in delivering a floating stone. What would it mean to float a stone today? The *Buoy Stone* is calibrated to rest on its side for a horizontal commute under low bridges (fig. 1), then transform into a vertical figure once pumped full of river water (fig. 2).

Megalithic civilizations held tremendous knowledge surrounding the deceivingly simple task of moving heavy objects. Much of this knowledge has been lost to us from the past. This paper mines, extracts, and experiments with this knowledge to test what applications and correlations it holds with contemporary digital practice. It describes in detail the design constraints,

Figure 1: Buoy Stone in the horizontal towing position.

computation, and fabrication of a prototype. It then analyzes the integration of a custom-developed buoyancy simulation to solve for geometries that perform in water when loaded. These goal performances serve to prove whether the simulation and physical results are in sync. The paper then elaborates on some of the shortcomings and areas of future development. While this way of thinking has great potentials in thinking about structure, gravity, and mass, engaging the geometries of the object to intelligently deploy its own mass to perform tasks has great potentials for architecture. This silly installation seeks to exercise some of these potentials.

As experiment, this research develops design, computation, simulation (fig. 3), and fabrication methods to perform challenges of a 20-ft-tall megalith. These challenges include floating horizontally and swimming vertically. The *Buoy Stone* is an experiment in calibrating the center of mass of an object to perform in a buoyant state. Through recursion computation, the designer

Figure 2: (Clockwise from top left) Series of images of the erection process. The reservoir is slowly filling and shifting the center of mass to stand vertically.

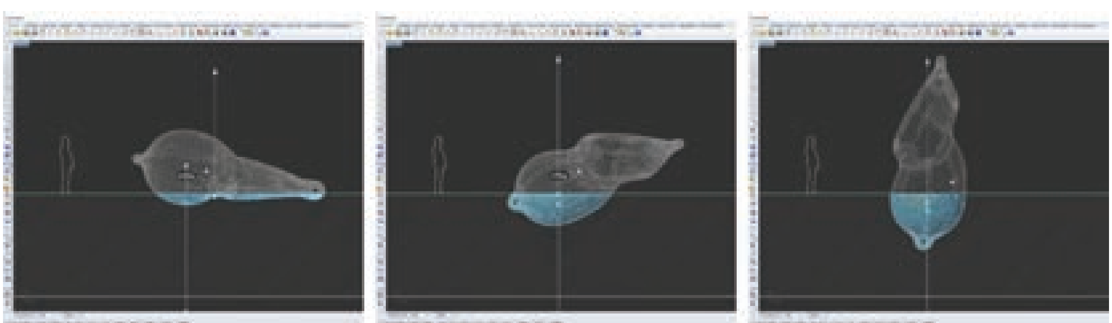


Figure 3: Recursion solver buoyancy simulation process.

is able to develop a design in sync with the physical constraints of buoyancy, or, rather, the equilibrium between the mass of an object and the displaced volume of water.

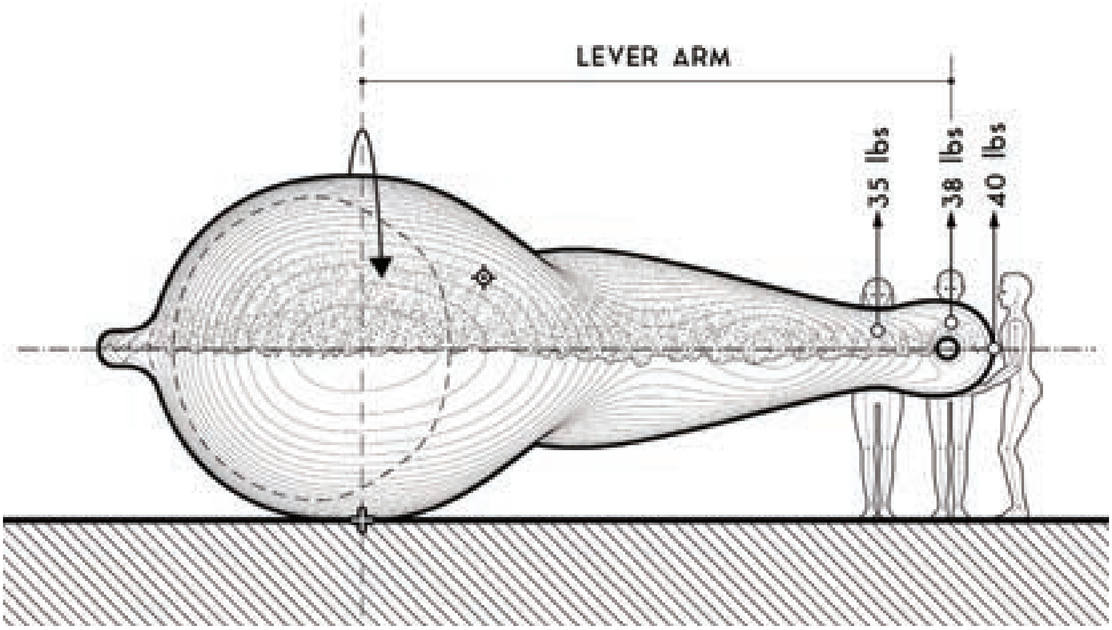
The simple act of beginning in a horizontal position and then standing in a vertical position (fig. 4) is the simple yet complex challenge the *Buoy Stone* attempts to perform. A prior iteration (Clifford 2016) of this research conducted a similar challenge of horizontal to vertical on land, but the constraints of a rigid body calculation versus a buoyancy calculation differ tremendously. As a diptych, they offer a helpful comparison to examine the challenges and shortcomings while projecting alternative possibilities beyond these singular experiments to inform assemblies. This paper describes the means and methods of computation, design, and fabrication. It examines the outcomes of the prototypes and speaks to missed opportunities and variations between the two. It also verifies when the simulated and actual results align and misalign in order to point to possible solutions. In testing this hypothesis, it raises many questions about the relationship between form and the physical world. In addition, it projects practical applications of such reciprocity between architectural desires and the computation of an object's center of mass. While these prototypes test the speculative and spectacular nature of such a way of thinking, they also point to practical potentials in self-erecting architectures.

CONTEXT

This research contributes to ongoing efforts around the integration of physics-based solvers into the design process. While these contributions begin with early megalithic cultures, they have continued through the works of physically minded architects such as Frei Otto (Rasch 1996), Heinz Isler (Isler 1960), and Antoni Gaudí (Burry 2007). Each of these contributors focus on physics constraints as a force to derive idealized form-found solutions. This lineage continued into the digital computation arena with research that incorporated particle-spring systems to resolve catenary forms by Axel Kilian and John Ochsendorf (Kilian 2005), or the ongoing work of the Block Research Group with projects like RhinoVAULT that contribute to the efficient stasis of form through other methods of computed form-finding (Block 2017). Another recent contributor to this space is the program Kangaroo, by Daniel Piker (Piker 2016), which integrate physics into a calculation in a less focused manner, resulting in a plethora of potential

Figure 4: The Buoy Stone in the final vertical position.

Figure 5: A drawing of the fabrication rotation lever arm. This orientation describes the process of rotating the megalith over to the other side so the process of applying the GFRC can cover the megalith.



outcomes. This paper contributes to these efforts by going beyond the assumption of statics as a solution in order to ask questions about what potentials mass can contribute to the assembly and erecting of architectures to come. It engages a megalithic way of thinking that requires an intimate relationship between designer and center of mass. In doing so, it questions conventional disciplinary notions of stasis and efficiency.

DESIGN CONSTRAINTS

The *Buoy Stone* is designed to accommodate a number of design constraints. These constraints include the conventional problems of fabrication, assembly, and transportation, but they also include the performance criteria, which begin with the megalith dipping into the water. These constraints include the problem of launching from a trailer into the water, transporting up the river, pre-loading into a safe condition, standing vertically, and lowering safely.

1.1 Fabrication and Transportation Constraints

One of the largest challenges of the previous megalith is that the form was not designed for the process of fabrication, but rather designed exclusively for the performance itself. In that respect, the *Buoy Stone* attempts to resolve one of the largest complexities of the prior work by engaging the problem of coating the megalith and rotating it over to the uncoated side. This lopsided mass produces a rather violent act. The *Buoy Stone* resolves this problem with a round belly geometry that allows the form to slowly rotate with a set of controlled drops, or rolls. The megalith is calculated so that once it is loaded on one half with concrete, the head of the megalith should be light enough to be supported by three people. At this time, the EPS foam weighs 278 lbs, and the first half of the glass fiber reinforced concrete (GFRC) weighs 486 lbs, for a grand total of 764 lbs. This design constraint determined the maximum height of the megalith relative to the fulcrum point, or the waist of the belly. Figure 5 demonstrates this calculation. In addition, other constraints, such as maximum trailer dimensions, narrow gates, and the CNC dimensions, also played a role in the form generation.

1.2 Performance Constraints

The first constraint of the performance is simply launching the *Buoy Stone* from a trailer into the water on a boat ramp. The *Buoy Stone* is towed by land on its side and thus launched into water in this orientation. The solver verified the approximate angle the Buoy Stone would like to rest in the water, and it was mounted to the trailer at this angle to reduce any violent rolling once the buoyancy took over. The most significant constraints of the transportation and performance of the megalith are determined by the Charles River itself. The launching point is three miles away from the performance location and requires a tow under a series of low bridges, through a set of locks, and to the mooring location, which has high silt. At low tide, the bridges offer 8 ft of clearance from the water to the underside of the bridge. As a result, the *Buoy Stone* is designed to be towed on its side and must not extend out of the water higher than 8 ft. This horizontal towing then resulted in an orientation of the eye-hole to be perpendicular to the face to act as a "rudder" steering the megalith in the water. Once in position, the river is only 10 ft deep before the *Buoy Stone* might hit silt. The concern with this depth is that the silt might hold the Buoy Stone down if the loading sent it deep

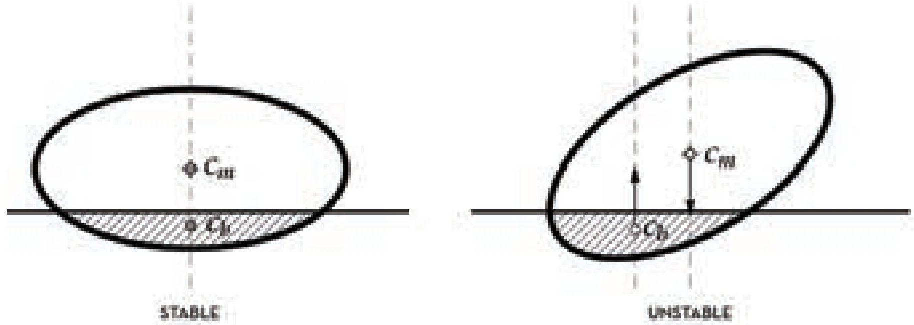


Figure 6: Buoyancy diagram describing the location of the center of mass and center of buoyancy, in equilibrium on the left and displaced on the right.

enough. The calculations ensured that the simulation never reached a depth deeper than 8 ft, to be safe. These general dimensions served to inform the megalith's form and mass throughout the simulations and solving.

A number of self-inflicted constraints also surround the performance of the megalith. The first is inherited from the transportation, and that is that the megalith will begin on its side. It then drinks river water and rotates onto its back with a counterweight attached to its eye-hole. Once in position, this pre-loaded megalith will be released from its counterweight with a release shackle, quickly sending the *Buoy Stone* to its vertical standing position. While these are the intended constraints and criteria for the performance, see the "Results" section to learn how the *Buoy Stone* actually performed.

COMPUTATION

A previous version of this megalith employed a recursion solver to adjust the form of the object to drive the center of mass to a desired location. While that method performed well, it did not simulate the hypothetical performance of the megalith. Instead, physical prototypes were employed to verify expectations and unearth unexpected results. In order to further this line of research, the *Buoy Stone* incorporates a custom recursion solver to simulate the buoyancy of a given form in a variety of loaded conditions.

1.3 Buoyancy Simulation

The principle of Archimedes (of Syracuse c. 287–212 BC) defines buoyancy equilibrium through two forces—the center of mass of the object, and the center of buoyancy, which is equal to the center of mass of the displaced water by said object. If an object were ideally symmetric, like a sphere, a simulation could occur in one dimension. Perhaps simulation is not even necessary in this instance. One could raise or lower the water level relative to the object until the mass of the displaced water is equal to the mass of the object (fig. 6). More complex forms require a form of simulation to resolve their final state of equilibrium because their complex geometries might, if not often, create a center of buoyancy that is not directly below the center of mass, resulting in a rotational moment. This rotation rotates the object in the water until a new center of buoyancy is pulled to the other side of the center of mass, producing what is called a "riding-moment," which corrects for the rotation and sends the object back in the other direction. Given this three-dimensional complexity, a simulation that incorporates momentum and angular velocity is desired to predict the behavior of the object. Beyond this complexity, prototypes proved that where an object is released from will greatly impact the final equilibrium state it reaches. Consider a boat that is simulated upside down: The likelihood that it flips over is unlikely.

The calculation first needs to determine the location and force of the center of mass, as well as the center of buoyancy. The center of mass is determined by a number of forces aggregated. The first is calculated by the surface area of the form multiplied by the density of the GFRC, in order to approximate the centroid of the shell. It then locates the volume centroid of the EPS foam and multiplies that location by the density of foam. It then adds in any other forces, such as the water ballast, in a similar manner and aggregates these masses to find the weighted center of mass of the object. To determine the center of buoyancy, it employs a Boolean union calculation of the object relative to a horizontal that represents the river water, which is assumed to be flat. This Boolean union is occasionally a single volume but can also create two distance volumes. In this event, the calculation has to accommodate the complex hull scenario and produce a new weighted average center of buoyancy of the two or more separate volumes. This brings new meaning to the origins of this calculation.

Once these two forces are calculated, the difference between the x, y, and z locations of these two lump masses is computed, and an angular displacement is created. This angular displacement repositions the object, enters into a loop, recursively recalculates the new center of buoyancy, and repeats these steps. In order to determine the step, an increment is determined to multiply each step by a difference factor, resulting in a simulation that predetermines momentum.

INFORMED GEOMETRY

The *Buoy Stone* rests in three distinct states of buoyancy equilibrium—unloaded, pre-loaded, and loaded. These

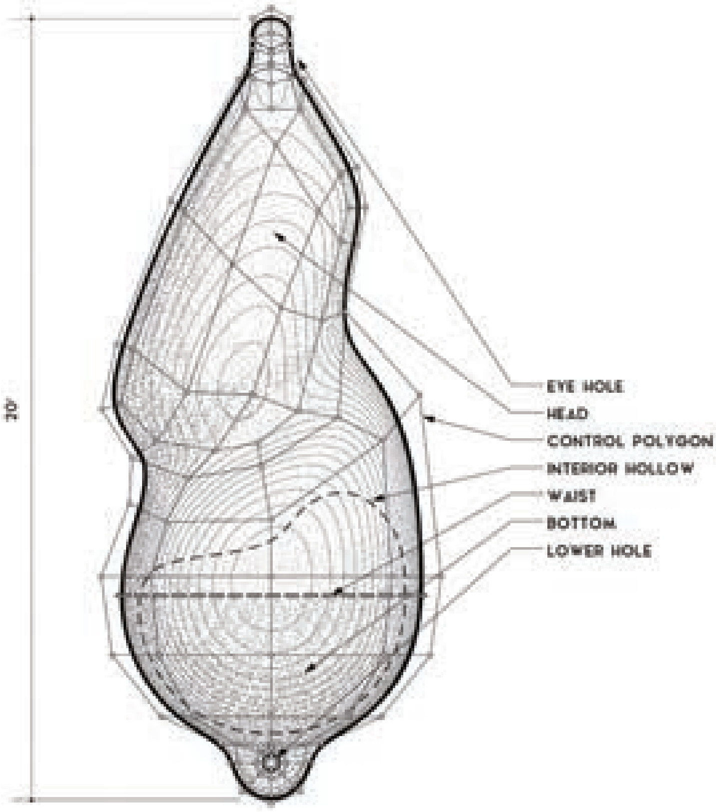


Figure 7: A diagram describing the various geometries.

three conditions also produce three states of being—on its side, on its back, and standing up. A number of geometries (fig. 7) contribute to ensuring each of these conditions meet their own performance criteria.

1.4 Unloaded/On Its Side

In this position, the *Buoy Stone* weighs only 1,250 lbs. This mass was verified after the concrete cured with a set of scales and was re-incorporated into the simulation in order to determine the amount of counter mass required. In this position, the *Buoy Stone* needs to rest as low and as stable as possible. The face is intentionally narrow to provide a large flat surface to continually stabilize the *Buoy Stone* in this orientation. The eye-hole is also designed to serve as a stability rudder during towing. Each of these conditions are simulated and prototyped to check for stability. While this position contributes to a number of the constraint criteria, it is also the easiest to solve for, placing the onus of the burden on the following two conditions.

1.5 Pre-Loaded/On Its Back

In order to re-load the megalith for a quick standing, a counter mass is attached to the top, or eye-hole, while a set of steel shot weights are hung from the bottom hole. These weights offer an additional level of calibration to the process of standing the megalith, as the final mass is not known until it is weighted after fabrication. The most complex geometry to ensure that the performance of this pre-loading rolls the megalith onto its back is the bladder ballast geometry. A hollow inside the belly of the megalith is formed in the shape of a lima bean. Instead of filling this hollow entirely with river water, the Buoy Stone is calculated to perform when partially filled. This is because the water is allowed to slosh inside this ballast geometry to result in a new loading geometry in each of the positions. This internal geometry extends up onto the back side of the Buoy Stone but is rotationally symmetric from the waist down to the bottom. What this means is, if starting on its side, the Buoy Stone fills this chamber of water and the morphed back side sloshes water more to the back, resulting in a rotation force pulling the megalith onto its back (fig. 10), but the counter mass does not allow for the megalith to stand up. Instead, it reaches an equilibrium state that strikes a horizontal, with its head out of the water. Figure 9 describes this position. In this position, the entire megalith, with its counter mass and ballast of water, weighs 6,679 lbs.

1.6 Loaded/Standing

In order to get the *Buoy Stone* to stand vertically in the water with such a significant percentage of the object still outside of the water, in such low depths of water, the lower portion is significantly larger than the upper, by volume. The proportions of the head appear large but are rather flat (also resolving the horizontal stability). This lowers the center of mass considerably and below the waste of the belly when loaded. This low center of mass contributes to the force required to stand up, but the two large issues once in that position are balance and righting. The balance is determined by solving for a head geometry that pulls the center of mass directly over the axis the lower geometry is dedicated to. This solver is identical to the prior research. It drives the center of mass by adjusting a series of control points in the final form of the head. Once this form is determined, the lower portion needs to ensure that a righting moment is produced if the megalith starts to fall in one direction or the other. A very slight flaring to the geometry extends out the curvature continuity and expands the curvature. Figure 12 demonstrates this geometry. The result of this slight variation to the otherwise symmetric base geometry is a rapid righting moment, which corrects for any instability once loaded and standing. In this position, the *Buoy Stone* weighs 6,679 lbs.

FABRICATION

The *Buoy Stone* is fabricated of CNC-milled expanded polystyrene (EPS) blocks that are coated in a

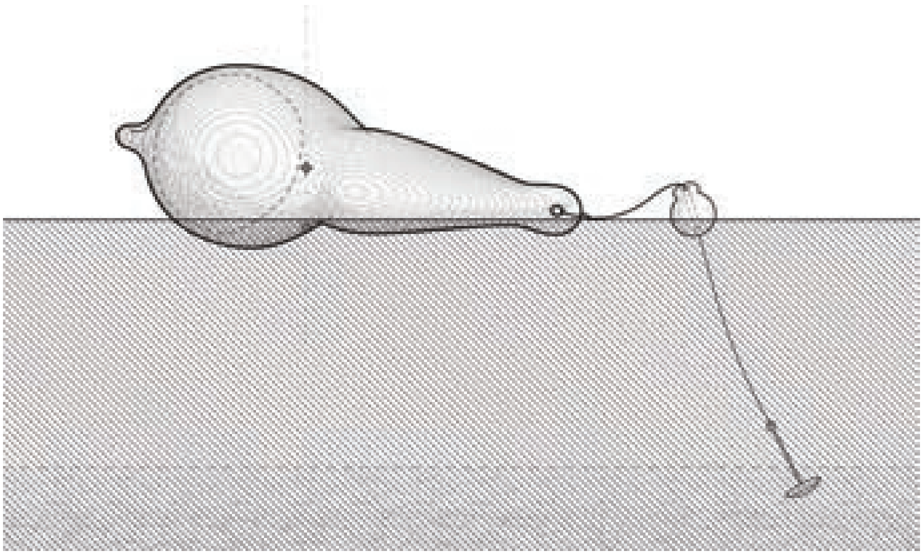


Figure 8: The unloaded, on-side position.

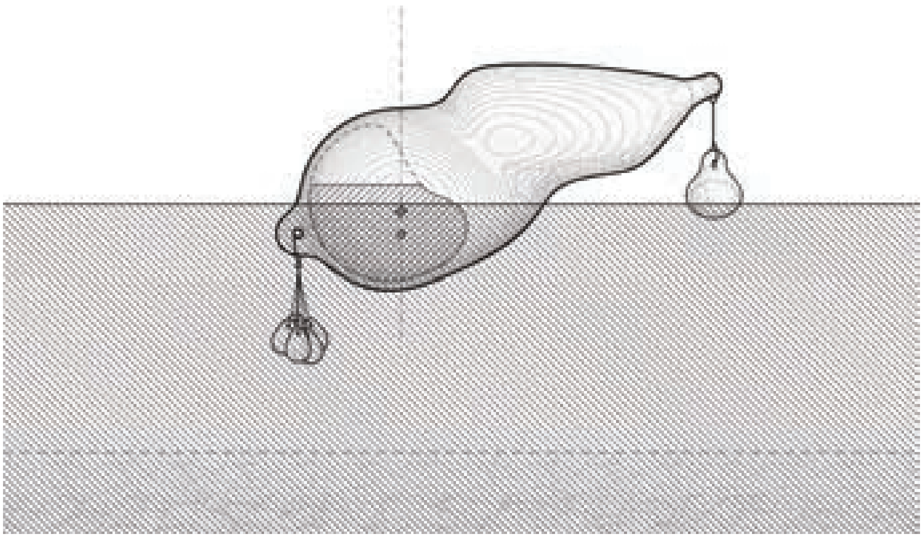


Figure 9: The pre-loaded, on-back position.

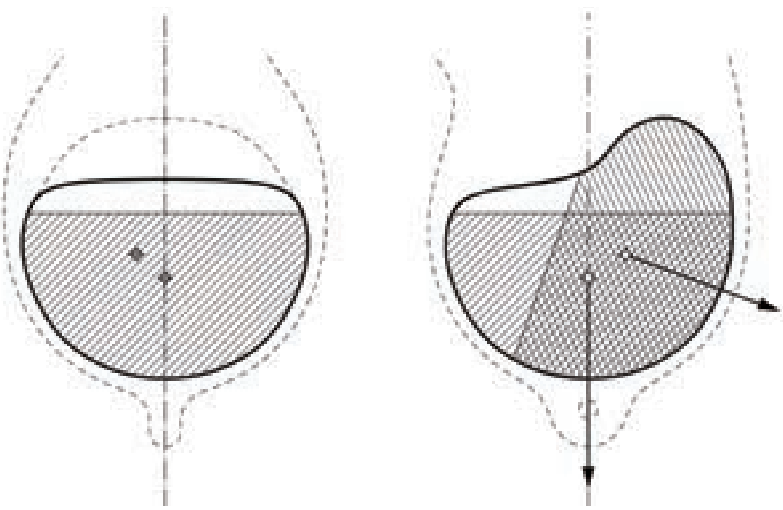


Figure 10: A diagram of the ballast hollow geometry that allows a partial fill of water to redirect the thrust behind the central axis. The right image demonstrates how the center of mass shifts in two different orientations. The left demonstrates those same two centers of mass.

Figure 11: The loaded, standing position.

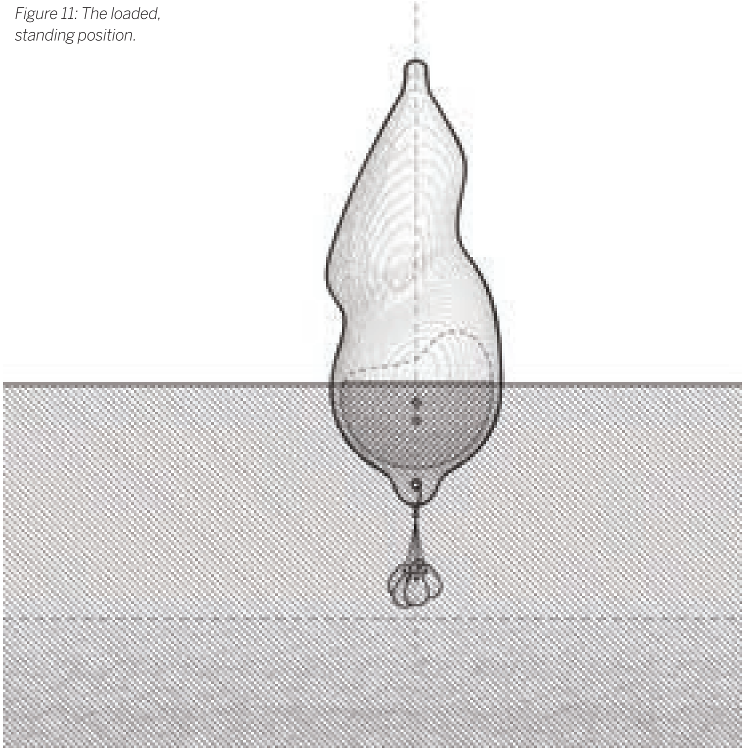
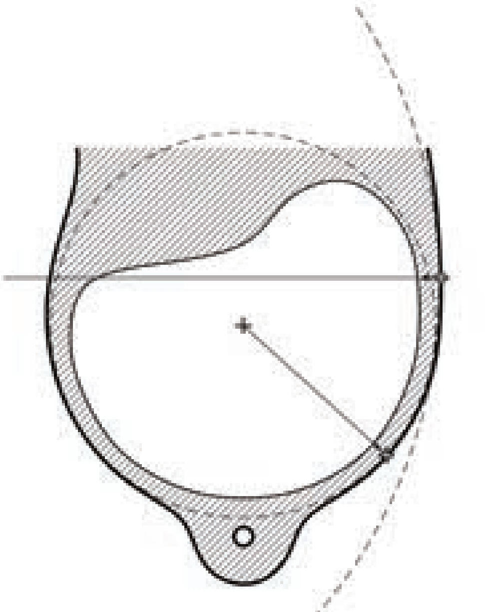


Figure 12: A diagram of the lower geometry that maintains a spherical geometry which flairs outward around the waist to produce a righting moment, thus stabilizing the megalith when standing.



½-inch-thick layer of GFRC. While this process is rather identical to the previous megalith, a difference exists with the interior hollow, which has a waterproofing bladder coated from the interior before the two halves of the megalith are glued together. The seam between these two parts is waterproofed with an expanding sealant during the glue process. As a result of the process, the megalith also needs a way to "drink" water from the river and then "pee" that water back out in order to safely lower back onto its side after the performance. In order to do this, a submersible pump is located inside the hollow and connected to a plug that allows the team to attach a car battery with an umbilical cord to turn on the pump from a safe distance.

RESULTS AND PERFORMANCE

While the *Buoy Stone* performed in significant ways and safely, a number of unexpected results emerged through the full-scale prototype. One unexpected result is the massive shift in cadence in the unloaded and loaded conditions. Naturally, as a result of the incredible difference in mass, the *Buoy Stone* bounced rapidly on its side, constantly being hit by waves and ripples of the Charles River. This produced an extremely animated stone that was also reorienting itself to the mooring depending on the current and wind speed at the time. It acted similar to a bouncy weather vein. However, once loaded, this behemoth in the water acted unlike any boat or object. It was neither static nor receptive to the minor shifts in wave, current, or wind. It slowed considerably, resisting wave impacts. This dramatic shift in character is of interest for further exploration, as it was not incorporated into the simulation. The simulation did not account for waves, current, or wind, but also did not adjust the momentum to account for the differences in mass. Further research could exploit this animate possibility as a design driver through this computation toolset.

Another unexpected result surrounds the ominous erecting of the *Buoy Stone*, beginning with the pre-loaded condition described above. Everything went to plan with the pre-loading. The counterweight was filled with water and attached to the eye-hole with a release shackle. That release shackle was also safely secured to its own lead-line mini-lith. The belly was then pumped with River Water at a pre-determined pace, and a four-hour timer was set to know when the appropriate amount of water had pre-loaded the megalith. At that point in time, the megalith should have slowly rolled onto its back and lifted its head out of the water, striking a horizontal. Unfortunately, this did not happen. Instead, the belly did lower into the water, but it did not roll or lift the head. It appeared as if the megalith was simply lowering into the water. At this point, it became clear that the counter mass was not loaded and therefore not contributing to the safety of a miraculous rapid standing of the *Buoy Stone*. It was detached, and the team retreated as the sun set. The following day, upon our return, the *Buoy Stone* had miraculously started to stand a bit more vertically in the water! It was roughly at a 45-degree angle to the waterline. The team took this as a partial improvement. Eventually, the *Buoy Stone* did stand, but only after more than two weeks. Some real-world factors contributed to this extremely slow erection and were not accounted for in the simulations. The first was that, as the megalith had been towed on its side and moored for a couple of weeks, it has soaked up a considerable amount of water on one half of its face. It had also acquired some nasty river gunk as well as some living organisms that quickly grabbed onto this rough texture.

While the team could see this on the first day, a large amount of this living matter had released overnight, and most of the water had evaporated, lightening the head of the megalith to allow for a bit more of a standing position. This incremental process allowed for a little more standing, and a little more evaporation, until it ultimately found its intended vertical position. While the first megalith was a relatively rapid erection of just a few minutes, the intention of this megalith to be instantaneous through a re-loading resulted in a significantly slower megalith that transformed through time. While this unintended consequence of the complex environmental condition produced a new temporality, future research could incorporate this scale of time to incorporate cycles of the weather as a driving force of self-assembled architectures to come.

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ACKNOWLEDGMENTS

The simulation is created through a custom definition that employs Hoopsnake (grasshopper3d.com/group/hoopsnake), a plugin developed by Yannis Thessaloniki to resolve recursion in Grasshopper (grasshopper3d.com), a plugin developed by David Rutten for Rhinoceros (rhino3d.com), a program developed by Robert McNeel.

Figure 13: The Buoy Stone in the standing position.

Architecture's Digital Divide: Post-Digital Formalisms and the Emergence of Cyberphysical Architecture

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MISAPPROPRIATIONS OF THE POST-DIGITAL

In his seminal 1995 book, *Being Digital*, Nicholas Negroponte talks about the popularity, economic feasibility, and future viability of various consumer technologies of his time. Focusing primarily on media and entertainment technologies of the '90s, ranging from CD-ROMs to cable broadcasting, Negroponte argues that it is futile to insist on a discourse of material intelligence, one that aims to encode information into matter, since all that can become digital will eventually become as such, through replacing "atoms" with "bits." It is the kind of argument that architects love to hate, as it poses an existential threat to many of the disciplinary pillars of architectural production. Negroponte predicts the emergence of immaterial systems of change and transformation, controlled by the collective and momentary decisions of the users, organized in the layered temporality of abstract space. Such an architecture as data is diametrically opposed to the permanent, made-to-last, static notions of what we consider to be designed environments negotiating between nature and the human body. He argues for a future where the artificial construction of space through the disciplining of nature, as experienced through centuries of building practice, no longer prioritizes the organizations of matter but of ideas—a new kind of architecture of information that represents systems rather than nature, presented in experiential interfaces that no longer require the physical manipulation of land and depletion of natural resources but rather constant rearrangement of enclosures as energy, light, motion and information.

Many of Negroponte's predictions about the internet, disappearance of tangible media formats, the ongoing growth of artificial intelligence (AI), ubiquity of virtual reality (VR), and emergence of social media as the dominant public communication protocol have become true. Each of these developments poses a direct threat to the traditional concerns of architectural practice and production as it relates to *representation*, *agency, experience*, and *civic presence*. After the initial excitement of digital design technologies in architecture waned past the '90s, many of these existential questions were largely perceived as unwelcome intrusions into the disciplinary sandbox. Rather than critically considering massive technological developments

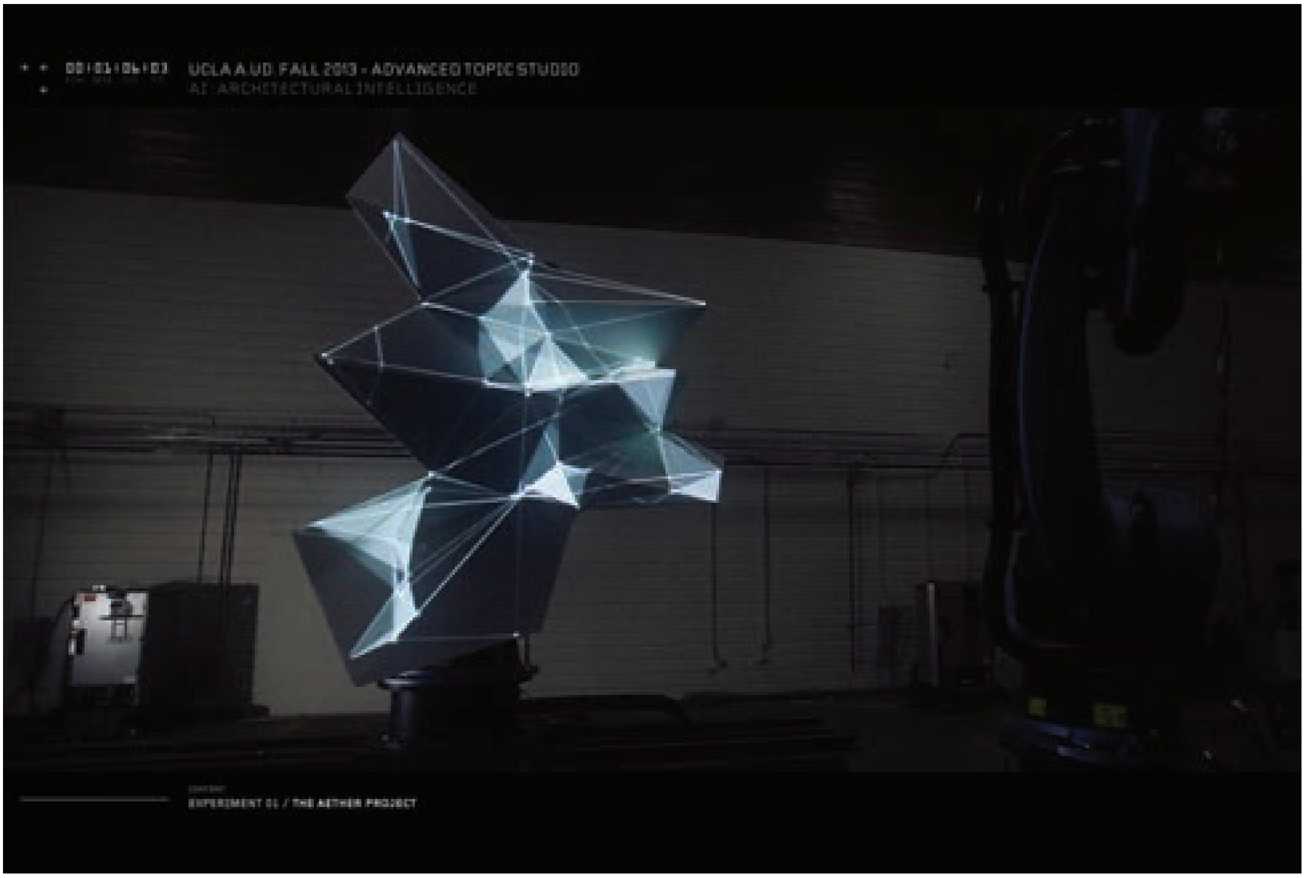
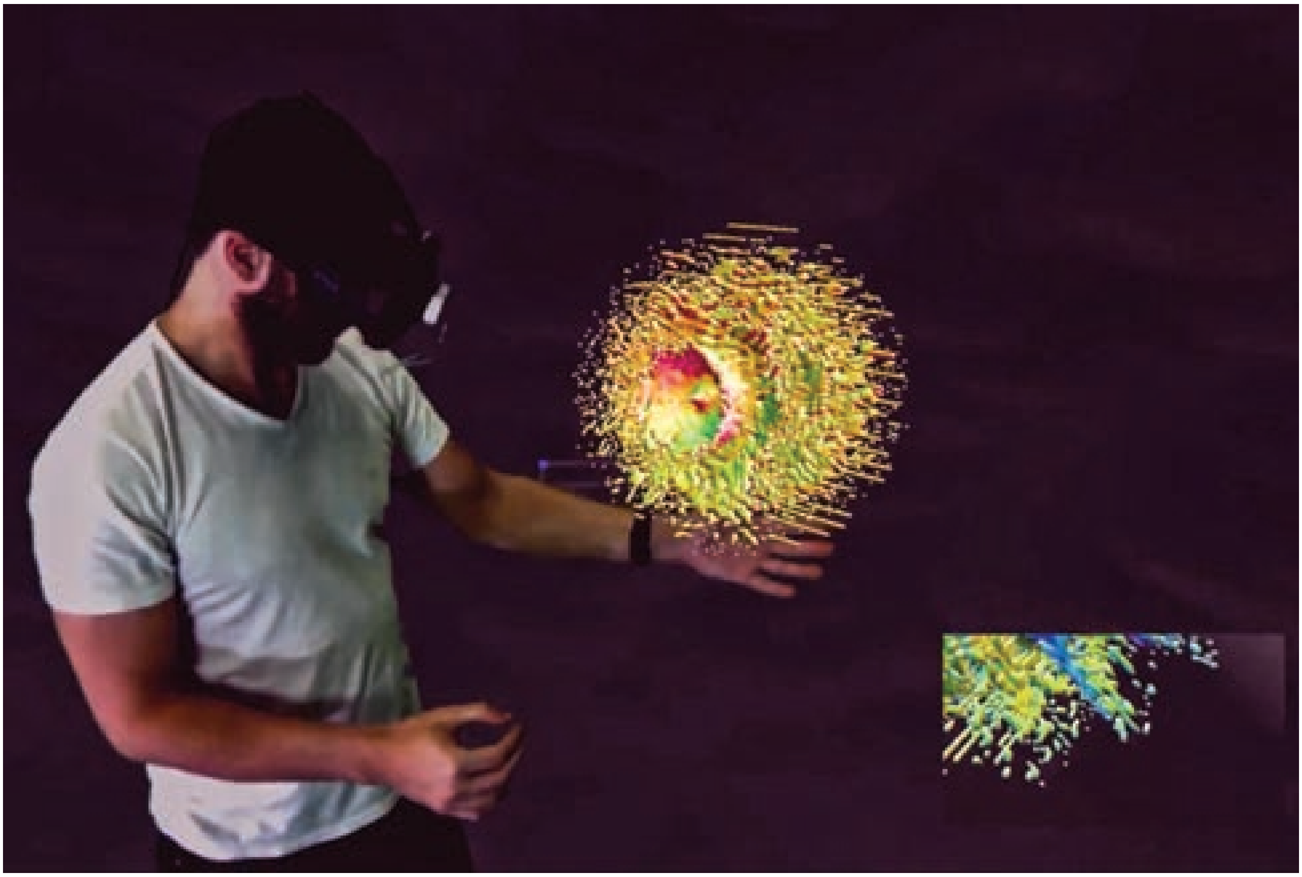


Figure 1: Aether Project, created as a part of "Architectural Intelligence: Exploring Space as an Interactive Medium," led by faculty Guvenc Ozel. Student team: Julietta Gil, Farzad Misfahei, Refik Anadol, Raman Mustafa. UCLA 2013.

as opportunities to transform architecture into a more culturally relevant discourse, the proponents of disciplinary autonomy resorted to the reoccurring operation of "returning to form," where copies of *Complexity and Contradiction in Architecture* were removed from their dusty shelves as the recurrent guidebook for the most recent post-postmodern reincarnation. In this regard, historicism becomes a reoccurring cultural trope that masquerades as radicalism in moments in which an external theoretical foundation that can guide architectural formal production is absent. In these cultural moments, the discipline of architecture is often late to the party and falls victim to misappropriations that are clarified much earlier and with much rigor and intent in other disciplines.

MECHANIZATION OF REPRESENTATION

It is important to note that, in the context of the debate on the post-digital, many other disciplines such as media arts, music, visual arts, and other pursuits use contemporary philosophical and critical devices of technology to break down existing structures with an updated set of tools in order to recalibrate the priorities of their own disciplinary production—since evolution of technology is dynamic and the possibilities, challenges, and opportunities it poses for cultural production are variable. Since the '90s onwards, during the birth and application of CAD and CAM, technologies as they related to production of disciplinary devices (representation, theorization, methodology as it relates to formal production) and production of buildings (BIM, performance and construction simulation, fabrication optimization, and other tools as they relate to the economy of construction) were received as tools consistent with the Modernist ideations of architecture in academy and practice. Technology was perceived as a tool to make the more complex happen—faster, cheaper, and more precise. At that moment in the evolution of technology, contemporary tools and debates surrounding AI, extended reality (XR), and social media were largely absent as these technologies were aspirational and not yet at practical and operational maturation. Once the formal and theoretical possibilities were exhausted—and later on "stylized"—what once seemed original and cutting-edge within the confines of digital formalism started to look derivative, banal, and corporate. As it happened with postmodernism, the post-digital took a historicist turn, but this time, using the new digital toolset to reinterpret and mechanize some of the



fundamental traditional mainstays of architectural representation. As with most things contemporary, it is hard to draw the line where ingenuity starts and irony ends. One thing clear about these projects, however, is their deep mistrust of the evolution of technology and its ability to provide tools for facilitating novel formal and theoretical possibilities. For such musings of the privileged, architecture remains to be a self-referential pursuit that can always turn back time. For the rest of us, the post-digital is a time where the discipline moves forward from mechanizing the production of form and representation and starts addressing issues of presence and interaction in a world that is exceedingly less static and material, and potentially less human.

CYBERPHYSICAL ARCHITECTURE AND THE OBJECTIFICATION OF EXPERIENCE

As the most dominant platform for communication, the internet is often referred to as "cyberspace." Current forms of interface design and organizational logics of information over the internet, however, exist as environments only in the world of allegories, preventing the participants from interacting spatially with these streams of data. One design scenario is to utilize massive amounts of data through simulation tools that would visualize and formalize information flows so that they can be observed, occupied, and experienced. Primarily experienced through architectural-scale media technology application or personalized through virtual reality systems, this method allows architecture to create new experiential environments through computer-generated graphics. This form of "virtual architecture" relies heavily on cinematic methods of representation through aligning simulations with the point of view of the observer and the boundaries of built form simultaneously, often through increasing the scale of the image to an architectural or spatial one. In these instances, the architectural surface is supposed to be devoid of materiality, and media becomes a vestige of cinematic displays for moving images. Often, the empty spectacle of such media mapping schemes suffers from an absence of interfacing with the architectural form in an evocative way since they are not conceived simultaneously as a cohesive design system.

Alternatively, viewed as an ecosystem of technologies rather than a tectonic assemblage of materials, architecture is shifting toward a non-static and non-physical form of experience, opening up potentials for it to be considered as a medium that merges

Figure 2: Virtual architecture as scalable interfaces, varying from object to space. UCLA Ozel Suprastudio 2016. Student: Yuanzhi Li.

the worlds of media and materiality. Environmental sensor systems combined with automated building performance processes coupled with integration of robotics into built form for the actual transformation of environments based on programmatic, occupational, and ambient requirements allow for a "cyberphysical architecture." In this scenario, data collected from the real world is used as a basis to create automated transformations of ambient, functional, and operational modalities. Alternative to material systems, architecture can be explored through environmental applications of media in the form of extended reality, sensor interaction with environments, and real-time control and transformation of spaces as complete ecosystems which prioritize not only visual but also spatial conceptions of architectural experience. The shift in focus from viewing the role of digital tools from the production of form into production of interaction and experience is significant yet disorienting for the architects, since it does not necessarily provide tools for alternative aesthetics. In this absence of tool-enforced aesthetic roadmaps, architecture can instead explore the vernacular of the digital, looking into the culture of media, interfaces, gaming, and similar social manifestations of image-culture for mining alternate formal trajectories.

Figure 3: Cypher is a soft-robotic interactive sculpture. Ozel Office 2018.

Figure 4: Cypher and the VR helmet. Ozel Office 2017..

SOCIAL MEDIA, TELEPRESENCE, AND THE NEW REPRESENTATION OF SELF

Constructing architecture enhanced by and built with media, a post-digital architecture can investigate scenarios where occupants of such architectures travel seamlessly between the digital and physical worlds. Through the proliferation of social media, virtual avatars, sensory simulations, and holograms, current and future forms of technological communications can simulate experiences with precision and without exclusively relying on the physical presence of their subjects. In these radically different new social environments, architecture is conceived as a cyberphysical system, designed not only for the use of people physically present in a particular space but also for the digital occupancy of other beings and their representations. These new environments, occupied by human and non-human entities, take avatars, telepresence of other humans through robotics and XR systems, and other robotic or simulated beings as their new subjects. Although it might sound like science fiction to some, such environments already exist in social media platforms, fulfillment centers, and other emergent environments of the Fourth Industrial Revolution. For such systems of experiential immersion, the actors present in these digital environments no longer rely on image as the sole representation of their participation but on a more profound presence that allows them to initiate change in physical and virtual constructs simultaneously. By questioning the role of representation in the process of designing realities and environments, such an architecture can focus on the potentials of cyberphysical tools to formulate a reformed agenda for the role of the digital in the contemporary practice of architecture.

INTELLIGENT ENVIRONMENTS AND LIMITS OF INTERACTION

In a world where simulations hold equal footing with physical environments, conventional rules that limit human experience no longer apply. Boundaries enforced by the natural world, such as scale, material, and physics, can be bent or broken. Such a world can only be bounded by the precision of presence, as the human subject experiences the physical and digital worlds simultaneously. Therefore, the perceptual boundaries of the human mind and body become the sole restraints for a cyberphysical architecture.

In my UCLA option studio in 2013 called "Architectural Intelligence: Exploring Space as an Interactive Medium," the pedagogical objective was to free advanced architectural exploration from the tyranny of disciplinary conventions of form making and representation by blurring the boundaries of architecture and media art. By setting the scale of production to full scale, the studio speculated on interactive cyperphysical environments that develop intelligent interactions with their human subjects through synthesizing motion, sensor interaction, and media technology.

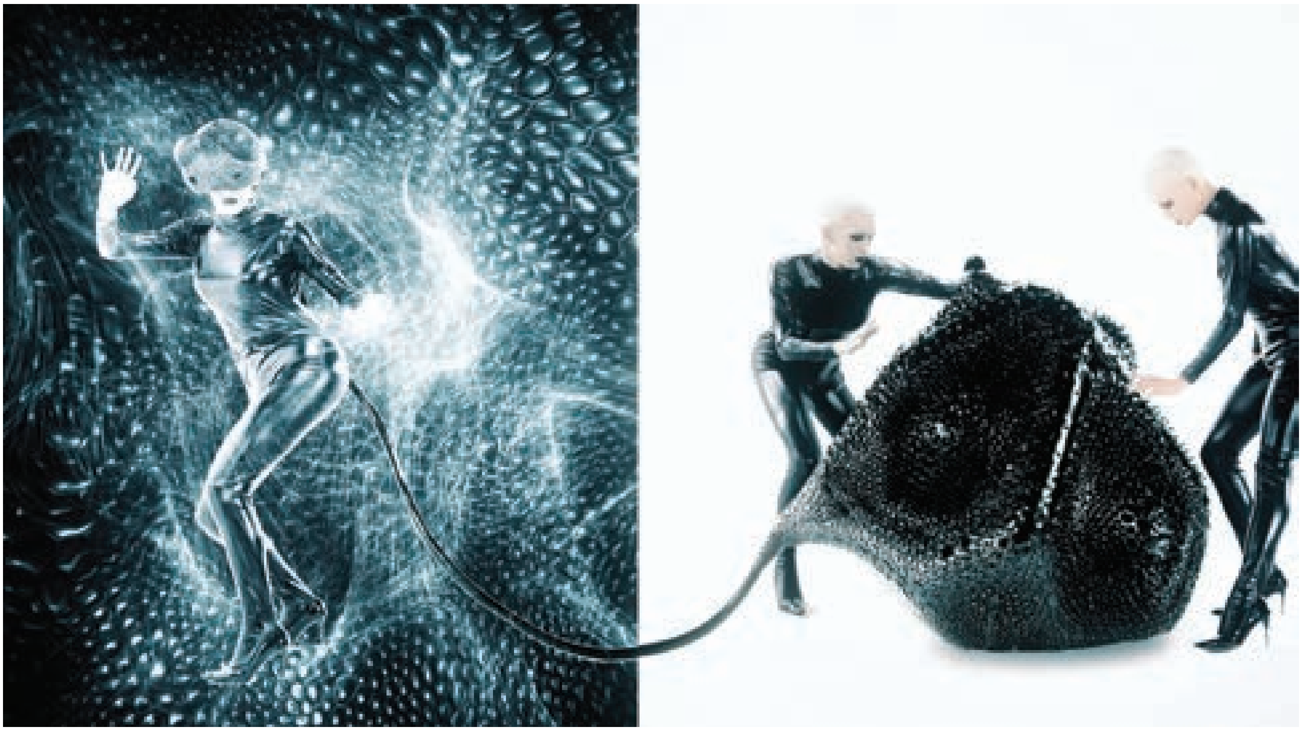


Figure 5: Cypher's teleportation scheme from robotics to virtual reality. Ozel Office 2017.

Each of the multidisciplinary project teams, consisting of architecture and media arts students, were assigned particular scales, actuating and sensing machines, and media devices to create controlled experiments on how the human body would alter and be altered by enclosures that can transform physically and affectively. One team that was assigned industrial robots, real-time projection mapping, and environmental sensors created a scheme that we later called the Aether Project, which synthesized the affects of motion and moving image to elevate and suppress qualities of depth, color, shadow, silhouette, and scale (fig. 1).

In this exercise, what was defined as intelligent was an emergent quality as a consequent output of interaction rather than a given or pre-programmed trait. Machine intelligence was not used to generate formal complexity but rather iterations of behavior as it responds to environmental factors and their surrounding human subjects. This kind of perception of intelligence defined as an advancing trait of a system that has an ability to move, change its properties, and adjust its physical and ambient qualities based on its context had its roots in evolutionary theory. The notion of "experience" was defined as twofold: first, as the cumulative presence of the system existing in the world, and second, as its ability to create variable spatial and aesthetic experiences for its observers. This approach of prioritizing behavior over form became the pedagogical focus of the various research projects and studios I have taught up until now.

Since then, this approach intentionally made a point of differentiating between the performative aspects of machine intelligence and its ability to automate form-making processes. It exclusively focused on formal systems that can respond to outside contexts such as the environment, human occupation, and human psychology. Such programmed behaviors, through systems theory, allow for spaces to interactively respond to conditions as such through sensor interfaces while working in collaboration with formal systems that are conducive to physical and ambient transformation through mechanics and media. It treated the accumulation of contemporary formal systems and styles as pedagogical and methodological repositories which would act as inventories for further formal iteration. This approach yielded productive results in understanding the human presence as it relates to form in motion but has not resulted in unique spatial languages that can be deployed and explored further in order to pose alternatives to familiar models of computational form making, which are heavily constricted by the limitations of parametric design tools. The questions of enclosure as they related to motion, novel material science experiments, and variable modulations to strike a balance between static and dynamic qualities of space were explored through investigating the historic evolution of such forms in architectural and industrial design. The absence of a trajectory for a productive formal strategy became more prominent as we explored virtual reality as a platform for spaces that are not simulations of environments that would be

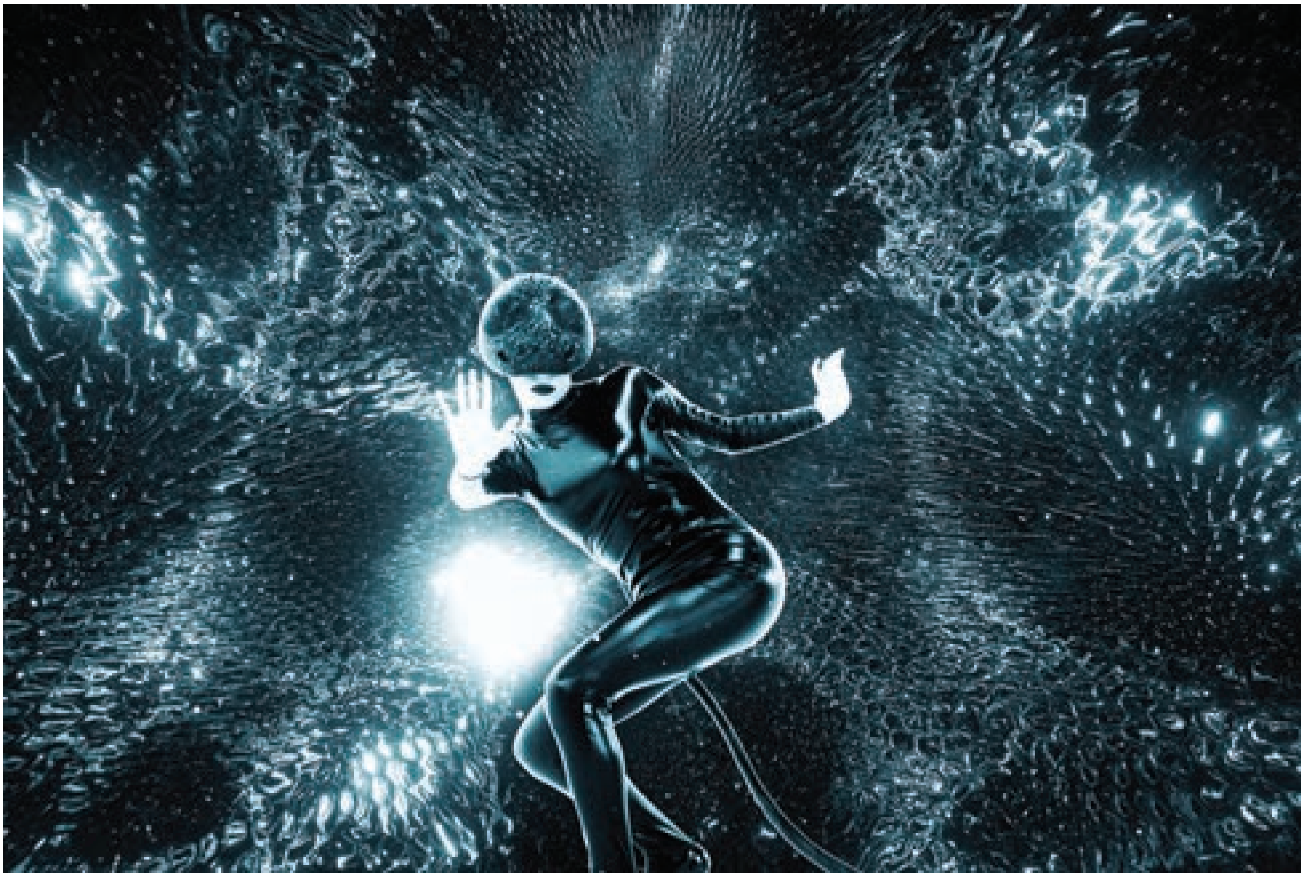


Figure 6: The interior view of Cypher through interactive virtual reality.

physically built in the future but interactive interface architectures that are meant to exist purely digitally, in their own right, in cyberspace (fig. 2).

Recently, in order to overcome this problem, we introduced an additional process to focus on the relationship between human agency and computational iteration by using machine learning (ML) as a design tool. By using basic ML tools in order to classify and iterate stylistic approaches that exist outside the discipline of architecture, we allow for ML to design, coordinate, randomize, and iterate qualities as they relate to pattern, color, proportion, hierarchy, and language. The human engagement in this design process is limited to the initial curation of input data that the ML system can learn from, and also in regulating and choosing the iterations as the final outputs of images such systems are capable of producing. An additional computational mediation process in the form of procedural modeling is deployed in order convert two-dimensional information into 3D geometry.

BRIDGING THE GAP: CYPHER AND THE POLYSEMY OF THE CYBERPHYSICAL OBJECT

The project where we combined machine intelligence both as a tool for formal invention and as an interface for behavioral complexity is *Cypher*. *Cypher* is a sculptural installation that creates an interactive experience through robotics, virtual reality, sensor interaction, and machine learning. By combining an interactive soft robotic body with a virtual reality interface, *Cypher* creates a bridge between the physical and digital worlds, collapsing them into the same experiential plane by synchronizing a virtual reality simulation with human-robot interaction (fig. 3).

Triggered by infrared sensors and a lidar (similar to mapping technologies in autonomous vehicles), the sculpture has an ability to detect the proximity of the audience and change its shape accordingly. The exterior of the sculpture is made of flexible silicon, actuated through a network of pneumatic tubes and linear actuators. Running on a custom-made software, the lidar collects and stores periodic point cloud data from its environment. The software not only uses this data to change the overall mass of *Cypher* based on the proximity of the people around it, but also has integrated machine learning so that the sculpture can develop more natural motion patterns through time.

The appearance of *Cypher* was inspired by the variable skin patterns of many natural creatures, calling into question our aesthetic expectations of robots.

In its initial state, it is angular and crystalline, but as it interacts with humans and other creatures, it becomes curvilinear and organic. By recreating the appearance of an organism artificially, *Cypher* aims to question the relationship between the natural and the human-made, thus further problematizing the interactive and intelligent behavior of the sculpture. The black glossy color is used to enhance the mystique of the object further, therefore blurring the true morphological qualities of the sculpture through a play between absence of light and variable reflection.

The virtual reality headset tethered to the sculpture teleports the user to the interior of the sculpture, radically shifting the scale of experience from object to space. While in VR, the user has the ability to change the shape of the simulation through natural hand gestures. As the user changes the shape of the VR simulation, the robot moves in real time, aligning the physical and digital transformations. The helmet inflates and deflates due to the actions triggered by the user in the VR environment, fusing the user into the spectacular motion of the sculpture. Through this VR interface, *Cypher* blurs the boundaries between architecture, sculpture, and fashion, allowing them to be experienced interchangeably (fig. 4).

The relationship between VR and robotics is further negotiated through machine learning algorithms, allowing the sculpture to develop natural motions by learning to predict the way in which people are interacting with it. The AI component allows for the sculpture to become more "intelligent" the more it is exhibited, using the number of interactions it has with the audience to cumulatively shape its motion and behavior through time (fig. 5). The same application is also used to "evolve" the geometry of the VR scenes. By extrapolating various points in the geometry in synthesis with the archive of the audience positional data, the geometry visible in VR becomes more elaborate the more it is experienced. The gaming engine Unity is used in order to synchronize all the VR, physical computing, and additional custom software. This approach allows the computational system to develop behaviors in reference to all the other actors in the same environment. This method provides a platform to collapse physical and virtual actions into a streamlined interface, creating a continuity of experience between the digital and physical worlds (fig. 6).

With this combination of multiple technological systems working seamlessly, *Cypher* exists simultaneously in the digital and the physical worlds. It has an ability to respond to changes in its environment both as simulation and as material. Through the synthesis of these multiple technologies operating as an ecosystem, the sculpture challenges the notions of what is real vs. virtual, allowing the viewer to travel between multitudes of realities simultaneously. By merging the worlds of virtual reality and robotics, *Cypher* translates concepts and experiences that are traditionally seen as opposite domains: architecture vs. sculpture, object vs. space, digital vs. physical, real vs. virtual, visual vs. tactile, machine vs. organism.

THE ACTUAL SUBJECTS OF THE POST-DIGITAL

When analyzed outside the domain of media art and interactive architecture, spatial reflections of big data are already apparent and prominent aspects of contemporary life. In the form of invisible low-level AI systems, living now already entails a constant interaction with non-human entities, and standard interaction with humans predominantly happens through digital and non-material domains. However, the majority of these systems are engineered to track, document, organize, and eventually streamline public behavior in digital and physical civic realms. In that regard, control and documentation of communal human behavior is the primary subject of the post-digital.

In the world of surveillance capitalism designed to collect and monetize data, digital representations of ourselves and our environments are harvested by CCTV cameras, drones, internet bots, and social media platforms for social, economic, and political manipulation and control. Since the modes of operation for these platforms and how they monetize our actions are opaque, how do we create useful and engaging methods to understand the impact of our digital behaviors? Data is inherently invisible, ubiquitous, complex, and intangible. It has no scale, no materiality, and no perceivable properties through our senses. Its impact can only be measured through its subjectivity and influence in the social sphere. Based on these contemporary questions, our Ozel Office installation called *Deep City* aims to explore the latent relationships between physical and virtual urbanities (fig. 7). Through instrumentalizing architecture and urbanism, the objective of the *Deep City* installation is to demystify the inner workings of the algorithms that hold increasing influence over our decisions, emotions, and sense of self by turning them into media that are comprehensible through our spatial perception. By subverting their innate purpose and objectifying them, the work aims to hack such computational systems of surveillance and control in order to exploit them for their creative potential for artistic production. Based on this premise, the title for the installation, *Deep City*, is a double entendre, one referring to the utilization of deep learning algorithms for their generative potential for creating novel architectural and urban form, and the other referencing a contemporary mode of "deep state" where the data of individuals are constantly collected, archived, manipulated, and weaponized.

As surveillance technologies and artificial intelligence proliferate, the way machines see our environments creates emergent reading of the urban form as it relates to human activity. In this new model of urbanism viewed

through the optical and algorithmic lens of technology, physical elements of urbanity become the canvases and boundaries for data to be forged from. On the one hand, surveillance systems, whether software- or hardware-based, lack the sophistication to understand human constructs such as creativity, history, lifestyle, culture, and other nuanced concepts that are so fundamental to human life. They are geared toward analyzing human activity in the form of images and looking for patterns. The generative quality of such artificial neural networks is to imitate and copy existing outputs of human production, ultimately and ideally to a point of realism where they are no longer recognizable from the original. This notion of "imitation" and "fakeness" is fundamental to the MO of AI. On the other hand, training on vast amounts of data that document various natural and artificial morphologies of our world, such generative algorithms have the capability to decipher a meta-understanding of our physical world and autonomously deduct formal biases about it. These biases hold novel formal interpretations on reading physical objects and carry immense design potential. Through these new technological frameworks, it is possible for machines to imagine images and generate landscapes based on considerations yet unforeseen by the human designer. As a radical diversion from the parametric mainstays of contemporary digital architectural production, these algorithms, called generative adversarial networks (GANs), allow machines to collaborate with human designers creatively, rather than by merely automating design schemes planned by the human designer. In this regard, deep learning algorithms represent the emergence of a "machine creativity," or a machine mind where algorithms have significant autonomy from their human creators. This emergent reality allows for an unprecedented human-machine collaboration to create novel design agendas.

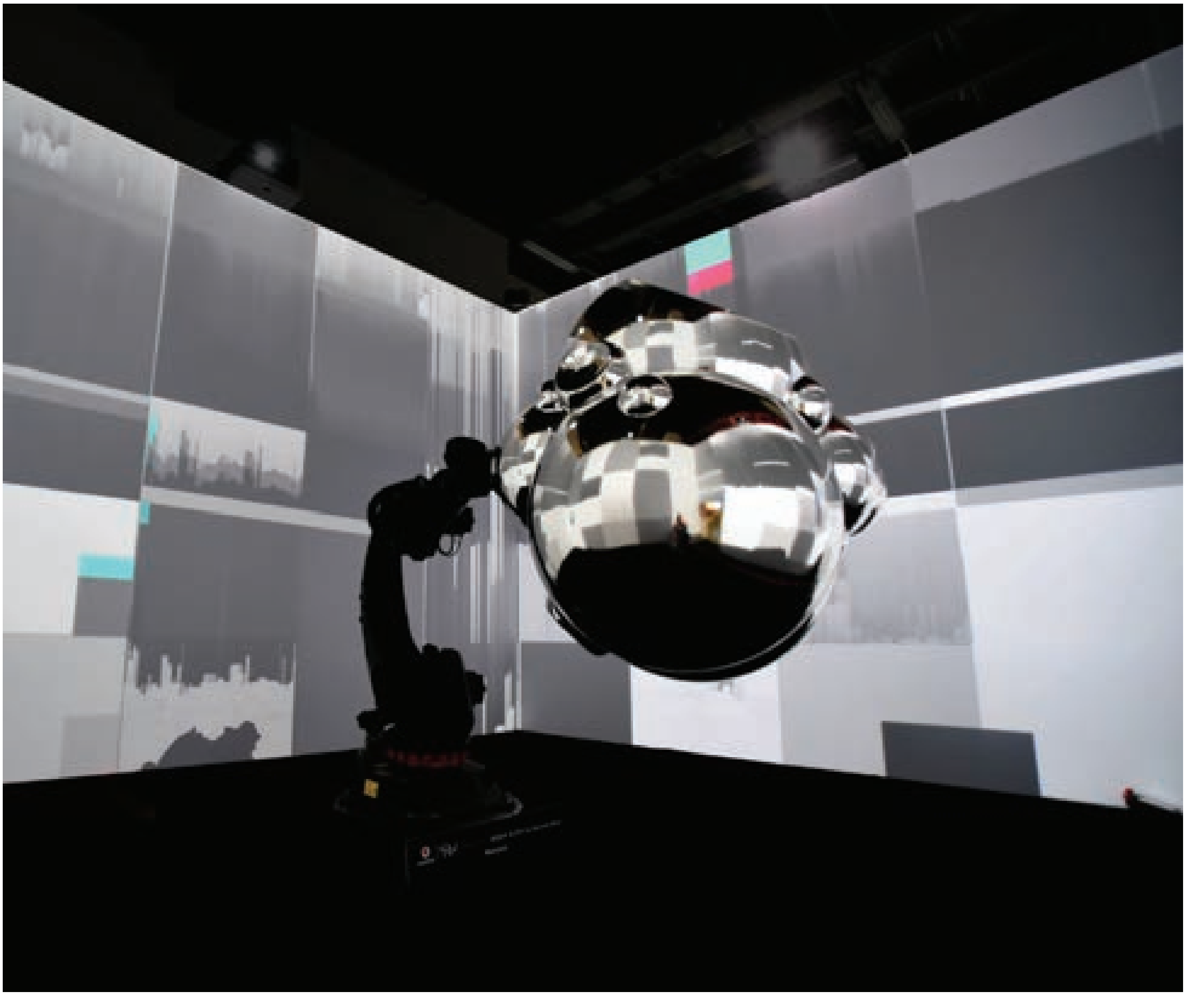
Based on this political framework of the city as image and data, *Deep City* is a cyberphysical ecosystem of robots and media where the audience experiences an immersive depiction of algorithmic and optical modes of surveillance and control in contemporary urban

Figure 7: Deep City consists of a reflective sculpture actuated by an industrial robot. Ozel Office 2018.

environments (fig. 8). The work allows the audience to occupy a fictitious space between the "mind" and the "body" of the machine surveillance apparatus where artificial intelligence and robotics intersect. The project is based on the creation of a surveillance database consisting of four world cities with different socioeconomic, demographic, architectural, and urbanistic identities: Istanbul, Hong Kong, Rome, and New York. Hours of drone footage, CCTV videos, animated 3D models, maps, and other visual data from these cities are used to train deep-learning algorithms to generate a "meta-city," a fictional urban environment that is resultant from the way AI perceives and interprets the various formal characteristics in its dataset. The algorithm is able to deduct semantic generalizations regarding the architectural and urbanistic features of the city. This video shows an idealized deduction of the city's characteristics, stitched into a continuous synthetic panorama, as a result of how AI perceives and interprets the various architectural and urban patterns in its dataset (fig. 9).

Working in synchronization with the video, a mirrored sculptural object with various reflective and optical properties is actuated by an industrial robot in an orbital trajectory. This shiny and seductive object, much like a mobile phone, constantly competes for the attention of the audience, demanding their narcissistic engagement. The more attention the audience gives, the more their data is collected and monetized. Positioned between the projection and the robot, the participants can see their own reflection on the moving sculpture—altered, distorted, and composited into the synthetic landscapes of the "Deep City." Through this spatial setup, the project allows for developing speculative and experiential approaches toward seeing our cities as machines do in the world of surveillance capitalism.

Figure 8: Deep City at the Contemporary Istanbul Art Fair, 2018.



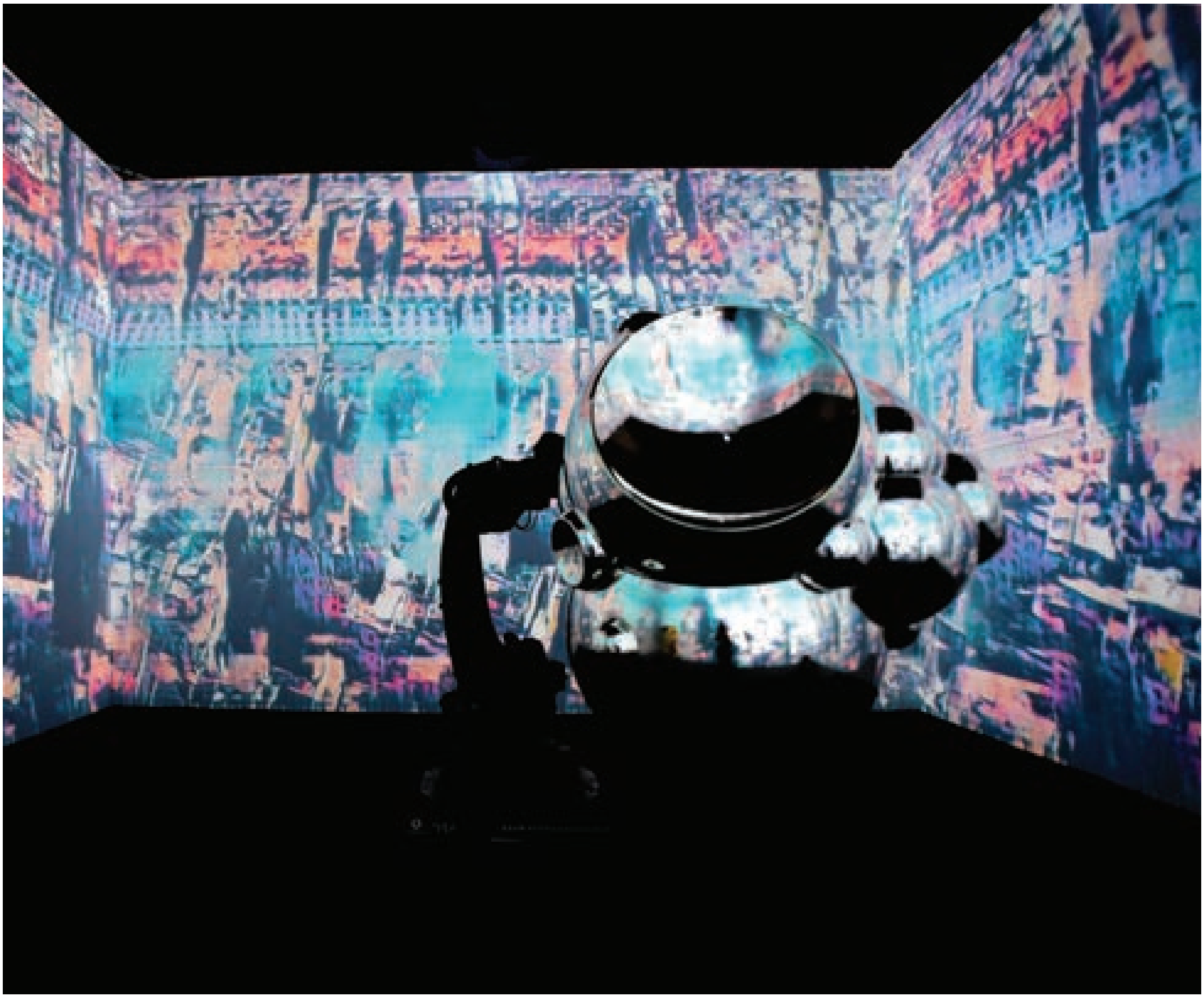


Figure 9: Deep City at the Contemporary Istanbul Art Fair, 2018. "Synthetic Panoramas," or GAN-generated cityscape imagery as projected on the walls.

THE POST-DIGITAL AND ITS VARYING OBJECTS OF DESIRE

Contemporary sociology of technology refers to the "digital divide" as the gap of access to internet and other digital technologies in the human population. Determined by geography, political contexts, and other localized socioeconomic and ideological parameters, the "digital divide" might result in two contemporary societies with exceedingly hyperbolic trajectories. A similar kind of digital divide, this time by choice, is starting to materialize in architectural discourse within the context of the post-digital. The contested meaning of the term reflects two diverting ideological approaches toward what the role of technology should be in the ideation and construction of environments for human occupation. The contemporary challenges that automation, artificial intelligence, and extended reality pose on existing economic, social, and political structures are unprecedented. Rather than hiding in the confines of disciplinary echo chambers, architecture's current fight for survival requires an active and critical engagement with these ever-evolving techno-cultural forces.

This contemporary divide is perhaps the last cry of the heroic architect, a decaying stronghold of territorial individualism that has plagued creative production since the invention of architecture as a distinct discipline. This form of tribalism uses style as a way to divide and limit approaches to the particular confines of practice methodologies, seeking common ground with an exclusive few that have the luxury and interest to entertain theoretical priorities of bygone eras. For the rest of us, we need to march on to prepare for a future that might not need architecture as we have known it, a future where physical space might not even be necessary at all, let alone the biological bodies that are supposed to occupy it.

Augmentations of the Real: A Critical Interrogation of the Relationship Between the Actual, the Virtual, and the Real / The Column as Spatial Marker

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Augmentations of the Real presents itself as an occasion to critically interrogate the opportunities that augmented reality (AR) present for the discipline of architecture.[1] The problem was illuminated from different angles, reaching from aspects of the augmentation of spatial experiences through articulation and ornamentation, to aspects of AR[2] as an aid in advanced construction methodologies. Special attention was given to the fact that these techniques seamlessly fuse aspects of symbolic culture with considerations of materialism.

Augmentations of the Real is profoundly embedded in speculative territories. Moments of uncertainty collide with aspects of precision and control. The result is not an imitation of the former but rather a contemporary interpretation. The foundation can be discerned in the possibility to overlap various experience levels, which allows mining for potentialities in contemporary ornamentations.[3] In this extent, *Augmentations of the Real* can be considered part of the discussion on post-digital discourse in architecture—an era in which computational tools are part of normal reality and other aspects of digital design are positioned center stage. Not the toolsets become the main actors, but the cultural agency produced by the toolsets.

I just mentioned *other* as being one of the goals of the examinations of *Augmentations of the Real*. It is easy to propose *other aspects* as an option without going into detail, so instead of wading into vague hyperbole, I will explain it along the example used for the exhibition *DigitalFUTURES 2018*. In this example, the architectural icon of the column was un-shelved to serve as an object of contemplation. It is astounding that, browsing through tomes of recent architecture theory, the column does not make an appearance even once[2]—a testament to the massive aversion toward the column demonstrated by modern and post-modern movements. Two examples, under many, for this aversion come to mind: Coop Himmelb(l)au's desire to erase the column, impressively demonstrated, for example, in their BMW World[3] building, and Peter Eisenman's use of the term "grid," which in fact can be read as intersecting colonnades—a series of columns penetrating through spatial volumes, as, for example, in the Wexner Center in Columbus, Ohio.[4] Apart from the column's importance as a technical device

Figure 1: Closeup of the digital Hypostyle, as shown at the DigitalFUTURES exhibition, Tongji CAUP, Shanghai, China, 2018.

Figure 2: Student comparing the toolpath printed by the robot with an overlaid virtual model of the toolpath.

in the architectural canon—negotiating the transport of loads from one floor to the next—it is loaded with symbolic value, without any technical efficacy. From the totemic poles of Native Americans to the Stylites[5] of Christian mythology, to the pillars of Hercules and the monumental Trajan's Column in Rome—columns are deeply ingrained in the texture of architecture's contribution to the ecology of symbolic culture.[6] As Manuel DeLanda describes,[7] there can be a differentiation between material and symbolic culture, but they are both connected and influence each other like communicating vessels. In the same realm of thinking, we can position Gottfried Semper, whose observations on the nature of columns and their origin can be considered inspirations for the work on the installation *Augmentation of the Real*. Semper's rigorous examination of the qualities of stereotomic constructions, as well as his well-known feud over the fact that Trajan's Column was originally colorfully painted.[8] Of course, this presents an opportunity for an interesting provocation today. The Polychromic wars certainly inspired the colorful nature of the columns in the exhibition. As the subtitle of the installation already suggests, the installation can be considered a *critical interrogation of the relationship between the actual, the virtual, and the real*—three distinct categories of thinking about the nature of our relationship to the rest of the universe and our possible, or impossible, position therein. To explain all three categories in depth would fill an entire tome, but I will say this: As mentioned before, the project is aligned with considerations of a post-digital age of production. In this universe of thinking, the discipline of architecture has surpassed the first cycle of obsession with digital toolsets and is searching for the cultural contribution to our contemporary age. In a world where digital tools are ubiquitous (from autocorrect to Instagram filters, to AI robocalls that pass as humans) and cultural production is not a priori defined by the original piece of art—or originality for that matter—novel tools of observation come into place. At the same time, it allows us to speculate about the value of the actual,[9] the virtual,[10] and the real.[11]

Augmented reality[12] per se is defined by the application of symbolic gestures as interface between the material and the symbolic realm of computational environments. In a sense, augmented reality applications (fig. 2) propose a synthetic ecology that is primarily defined by their inherent properties, such as simulation, enhancement and intelligence gathering, overlapping two levels of information, which operate between physical environments, and computationally driven information.

The testbed for the examinations executed in *Augmentations of the Real* was found in the archetype of the column. Ornamented[13] columns have a long tradition as freestanding stela, specifically designed as

Figure 3: Series of patterns utilized as triggers for the AR application. The application could be used with conventional tablets and mobile phones.

Figure 4: Teaching students the use of a HoloLens.

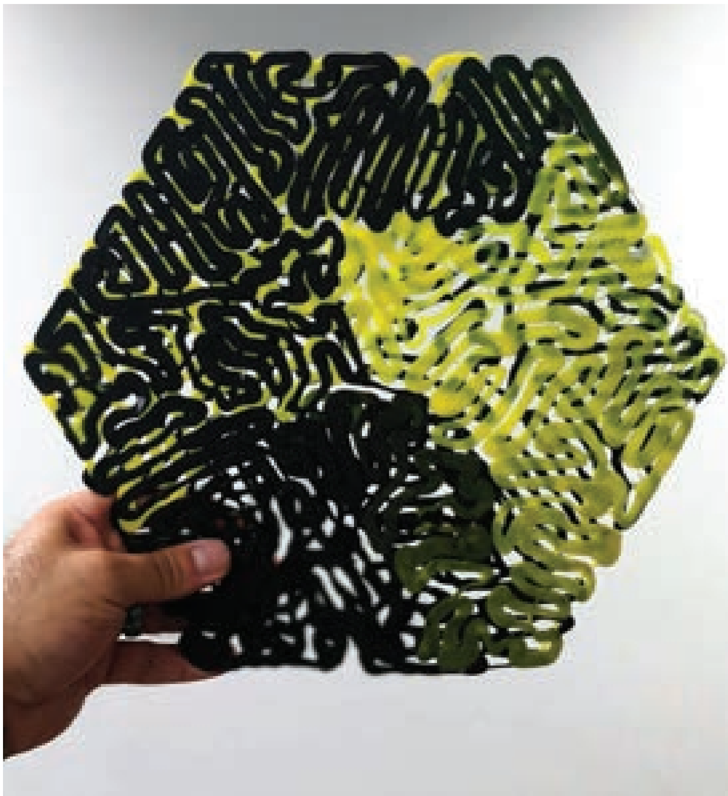
memento, marker, and memorial. The application of AR is able to extend the narrative qualities of the archetype of the column. The combination between one real concrete column, three ornamented columns, and 18 virtual columns produces a forest of columns, a weird hypostyle hall, oscillating between the actual, the real, and the virtual.

THE APPLICATION OF AR IN ROBOT-HUMAN FABRICATION

In the previous section, I described how augmented reality (AR) was utilized as a method of representation within the exhibition setting of the *DigitalFUTURES* exhibition at Tongji College of Architecture and Urban Planning in July 2018. The application of AR with the use of conveniently available means, such as tablets and smartphones, opens up opportunities to create a spatial environment saturated by a multiplicious level of sensorial impulses or stimuli. This was only one part of the application of augmented reality in the context of the *DigitalFUTURES* exhibition. Augmented reality describes a method in which the environment is still perceivable but is overlaid with 3D information; this, of course, opens up an entire array of possible applications, of which the use as representational tool is the most obvious, the most evident, and probably also the most boring.

A far more interesting application can be found in the possibility to introduce AR applications to the construction site. The benefits of this move are quite evident—in the scenario where the architect has to convey complex information to a construction crew, for example. By demonstrating the exact positioning of elements and components to the laymen, the margin for error can be significantly lowered. This alone would justify the use of AR; however, it goes beyond this, as applications such as Fologram do not only convey static information, but also allow one to demonstrate processes, meaning that the information seen through the holographic device not only shows the final stage of a fabrication process, but also the way to get there. The workshop *Augmentations of the Real* made use of the AR application Fologram in order to overlay virtual with real artifacts. Using a HoloLens, students were able to perceive the montage points for the panels (fig.4).

Figure 5: Test panel produced for the Salamander Column, DigitalFUTURES exhibition, Tongji CAUP, Shanghai, China, 2018.



DIFFERENTIAL GROWTH ALGORITHM

The panels were based on application of a space-filling curve algorithm devised from Grasshopper. More specifically, it was a differential growth algorithm that was applied on a simple rectangular plane in order to fill the space with a single line that never crossed itself. The main aim in avoiding self-inflections and a continuous line was to develop a fabrication protocol that supports the use of fused deposition modeling without inflating areas of the deposition by overlapping the toolpath. Due to the fact that the path did not intersect, the integrity of the panel was not given. A single layer rather responded in a very elastic way. By applying two layers, in different directions, the stability increased profoundly (fig.5), providing a high-integrity panel with a low material consumption. No specific structural analysis was done during the short workshop, but it certainly would be interesting to optimize the process by making the differential growth algorithm respond to specific pressures, such as gravity, loads, or wind pressures. This could be a result out of the workshop which would command further exploration in larger scale, for example, for load bearing facades. Also of notice is the use of coloration during the fabrication process. In recent years, SPAN has been experimenting with the use of continuously changing colorations in the fabrication process, as evidenced, for example, in Sandra Manninger's fabrication courses at Taubman College of Architecture and Urban Planning, or in Matias del Campo's studio at RMIT in Australia. In the case of the Augmented Realities workshop at Tongji, a specific color palette was selected: black, yellow, and transparent. This combination allowed for multiplicious effects, such as slow transitions between the colors, the gradient change from opaque to transparent, etc. The color palette was also the inspiration for the name of the

Figure 6: Printing of the large shell panes of the Salamander Column. The glass pane ensured that the panels were straight and even.

column, which we called the *Salamander Column*. A salamander is a small lizard-like creature that populated the Austrian Alps and whose outstanding characteristic is the yellow and black spotted skin—a warning sign due to the toxicity of the skin covered in dangerous samandarin. To keep the production of the column under control considering the tight schedule, the decision was made to reduce the column to a minimum of six components, consisting of three panels that constitute the shell of the column and three support fins in the inside. The consistent materiality and coloration ensured that all these components could be implemented in a seamless fashion.

The students produced the panels for the *Salamander Column* utilizing a KUKA KR 160 robot outfitted with a Dohle micro extruder DX283 as end effector. The extruder acts akin to the extrusion head of a 3D printer, with the only main difference being that the diameter is much larger. The 3-mm extrusion nozzle is able to extrude around 600 g of material per hour. In comparison to larger Dohle extruder heads, it is not a large amount of material, but, due to the morphology of the panels based on a continuous line defined by a differential growth algorithm, the material consumption was reduced to start with, so much so that it was possible to produce an entire panel for testing purposes without falling behind in the time schedule. One specific approach was to print the panels on a glass surface (fig.6). The combination of thick glass pane as printing surface with a heated surface underneath reduced the risk of warping so that the final result of the panels was straight and undistorted.

ASSEMBLY UTILIZING AR

Instead of utilizing augmented reality as a mere mean of representation, this workshop made use of AR as an aid in the construction of the column. This served as a proof of concept to demonstrate the opportunities within AR as a methodology for the construction site. In the workshop, students were trained in the use of the Microsoft HoloLens for two main purposes:

1. To evaluate their designs of the virtual columns that were going up on display in the gallery.
2. More importantly, to use the HoloLens as an aid in the construction of the 3D-printed column.

The assembly of the column only took three hours as the holograph helped in exactly positioning the supporting fins in 3-dimensional space (fig.7). This ensured a precise assembly of the components in space.

CONCLUSIOn

In conclusion, it can be stated that the workshop *Augmentations of the Real* served as a successful proof of concept for two specific criteria. On the one side, the application of AR as a mode of exploration for the enhancement of spatial experiences, as exemplified in the virtual hypostyle hall presented in the exhibition. The focus of this aspect of the application of AR is on the potentialities as a mean of expression within 3-dimensional space. The combination between real, actual, and virtual columns presents itself as a commentary on the lineage of the column as technical mean of production as well as cultural signifier. The virtual column, at the end of the day, is most likely the epitome of a column as a pure cultural signifier, rather than just a support structure. This approach allows for a critical interrogation of the column in our contemporary context, and, more specifically, within the realm of computational design.

Figure 7: Using a HoloLens and Fologram to precisely position the triangular supporting fins of the column.

The second criteria examines the use of AR within the construction site, by applying it in small scale in the fabrication and montage of columns. Special attention is given in this case to the implementation of human ingenuity and pattern recognition talent within a robotic fabrication setup. The workshop participants used a HoloLens and Fologram setup to precisely position the components of the *Salamander Column*. This ensured not only a precise setup of the components but also quick progress with a low-error margin.

In a next step, this approach will be applied to a more complex model, consisting of more components. The main aim, however, is to apply this technique not only in the safe environment of the fabrication laboratory, but also in the wild—the construction site.

ENDNOTES

1. See also: "The Materialism of Architectural Automations – A Critical Interrogation of Automation, Accelerationism and Ornament." Matias del Campo and Sandra Manninger, 2018.

Figure 8: Great Hypostyle Hall, Karnak Temple Complex, Precinct of Amon-Re, 19th Dynasty (ca. 1290–1224 BC).

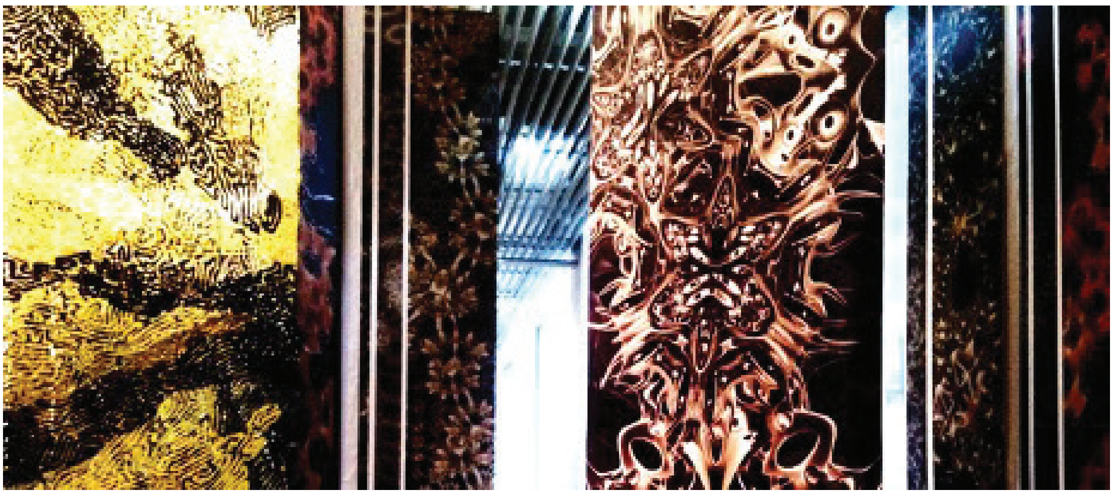


Figure 9: Augmentations of the Real, Hypostyle installation, DigitalFUTURES exhibition, Tongji CAUP, Shanghai, China, 2018.

2. Examples include: Kate Nesbitt (ed.), *Theorizing a New Agenda for Architecture: An Anthology of Architectural Theory 1965–1995*, and A. Krista Sykes (ed.), *Constructing a New Agenda, Architectural Theory 1993–2009.*

3. Coop Himmelb(l)au, BMW World, Munich, Germany, 2007.

4. Peter Eisenman, Wexner Center, Columbus, Ohio, 1989.

5. Stylite: A stylite (from Greek στυλίτης, *stylitēs*, "pillar dweller," derived from στῦλος, *stylos*, "pillar," Classical Syriac: [illegible] *'asṯonáyé*) or pillar-saint is a type of Christian ascetic who lives on pillars, preaching, fasting, and praying (Wikipedia, accessed November 6, 2018, https://en.wikipedia.org/wiki/Stylite).

6. Adolf Loos has made a contribution to this universe of thinking too: The columns in the entrance of the Haus am Michaelerplatz—a wonderful set of columns cut out of Euboean Cipollino marble—are only there to mark the entrance and have no structural function at all. The well-trained architect's eye may notice right away that the striation of the marble is actually in the wrong direction, and that the columns would very likely crack vertically if stressed by loads.

7. Manuel DeLanda in his seminar *ARCH Theory II: Philosophy of Materials and Structures*, PennDesign, University of Pennsylvania.

8. Gottfried Semper, *Der Stil in den technischen und tektonischen Künsten oder praktische Ästhetik: ein Handbuch für Techniker und Kunstfreunde* (Band 2), Frankfurt a. M 1860, p. 399.

9. Not surprisingly, there are eight different terms when translating the term "actual" into German—*eigentlich, tatsächlich, wirklich, effektiv, wahr, real, gegenwärtig, derzeitig*—all of which have a very distinct meaning

attuned to specific situations, circumstances and lingual precision. In the frame of the considerations of this essay, I would argue that *eigentlich* and *gegenwärtig* fit the bill the best in that they describe a moment in the presence of our reality without penetrating the area of "realism," which has a distinct different meaning.

10. Virtual: In this realm of thinking, the term "virtual" references two worlds. On the one side, the way the Henri Bergson and Gilles Deleuze considered the virtual to be an approximation to an aspect of reality that is ideal, but remains just that: an aspect. Or, in the words of Marcel Proust: "real but not actual, ideal but not abstract." On the other, it pretends to be as if it was real, but not in fact—a notion that fits well with the possibilities of contemporary computational design.

11. Real: As with the term "actual," there are at least eight ways to translate the term "real" into German—*echt, real, wahr, tatsächlich, wirklich, eeigentlich, richtiggehend, effektiv. Echt* and *wahr* serve as auxiliary terms to explain the ambition of the usage of the term in the frame of this piece. *Echt* can be translated as real, authentic, and embedded in the material experience of the world; *wahr* denominates aspects of truthfulness, honesty, and reliance. Somewhere between these two poles can be found a material truth to existence, or reality (*realität*).

12. Augmented reality (AR): An enhanced version of reality created by the use of technology to overlay digital information on an image of something being viewed through a device (such as a smartphone camera); also: the technology used to create augmented reality. (Merriam Webster Dictionary, retrieved on July 6, 2018, https://www.merriam-webster.com/dictionary/augmented%20reality.)

13. Le Corbusier once described Adolf Loos's Streitschrift "Ornament and Crime" as a Homeric cleansing. The lecture, first held in the Sofiensaal in Vienna in 1911, castigated the ornament as a "waste of the lifetime of the workers." It can be argued, however, that this argument has no validity anymore, as a whole family of computer-controlled machines primarily executes the production of articulation. On the contrary, in the wake of the words full automation, it could be argued that the return of ornamentation could provide for jobs, which would otherwise disappear entirely. On a further note, it has to be said that Loos's argument is entirely engrained in the sentiments of his lifetime, with its respective cultural, economic, and political ideas—with no value whatsoever for our contemporary age, in which we rather need to investigate changing our relationship to work at large.

Figure 10: Final installation at DigitalFUTURES exhibition, Tongji CAUP, Shanghai, China, 2018.

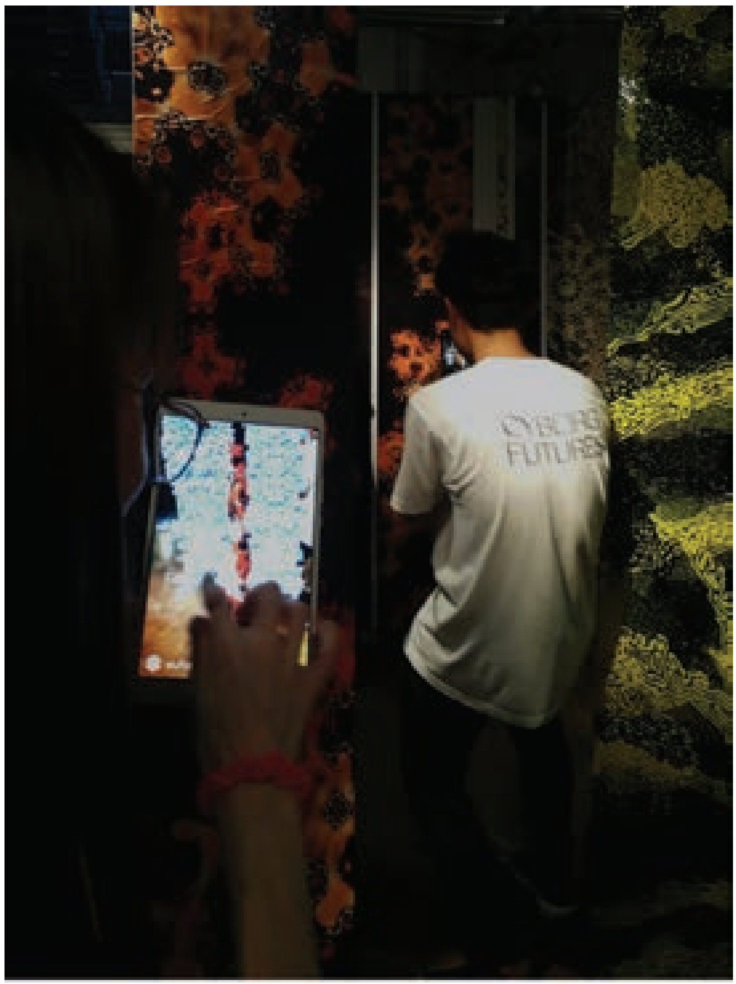


Figure 11: The virtual column becomes visible as part of the installation through an AR app. The application is triggered through the pattern on the physical columns.

An Integrated Robotic 3D Printing System for Carbon Fiber Composite Building Elements

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ABSTRACT

This paper presents a novel method for fabricating lightweight composite building components by integrating possible strategies of fused filament fabrication (FFF) 3D printing (3DP).

Due to the versatility of the FFF molten material extrusion process, the fabrication method can vary in the deposition, spatial-extrusion, and multi-material add-on. For an efficient and effective FFF of large-scale freeform building elements, this research proposes to integrate these three strategies into a single 3DP process: the deposition of the surface shell for structurally-sound enclosed artifacts, spatial-extrusion infill for faster fabrication, and add-on continuous carbon fibers for structural reinforcement. This research includes the development of an integrated robotic fabrication system and the exploration of a material efficiency strategy by grading materials of plastic and carbon fiber.

Two prototypical large-scale elements, a beam and a sandwich panel, are fabricated. The prototypes show the potential of integrated FFF through features which include multi-material gradation, complex geometry, lightness, and structural integrity under rapid manufacturing.

BACKGROUND

Plastics are established materials with decades of successful use in architecture due to their excellent material properties: high-formability and lightness (Engelsmann, Spalding, and Peters 2012). Fiber-reinforced plastic composites, in particular, are well suited for lightweight building applications. Composites are defined as materials in which two or more elements are combined to form a new, useful material (Jones 1998). Notably, carbon fibers have a very efficient weight-to-strength ratio in comparison to other fiber materials, such as glass and aramid, and are 40% lighter and 10 times stronger than steel (Mallick 1997). Despite these beneficial properties, carbon fiber-reinforced plastics (CFRPs) have the limitation of often producing expensive molds, especially when the design of artifacts requires unique shapes (Kwon, Eichenhofer, Kyttas, and Dillenburger 2018).

Recent innovation in fabrication through 3D printing (3DP) has the potential to eliminate the need for a mold, which has been the main cost driver of conventional

CFRP manufacturing. At the same time, 3DP technologies boost up the formability of plastics further, allowing the fabrication of unprecedented freeform shapes and highly complex geometries with ease (Ryder et al. 2002). Moreover, 3DP also allows the single-process fabrication of multiple materials, enabling the efficient creation of composite building components with highly detailed and accurate placement of materials.

The interest of this research lies in plastic 3DP technological processes that can directly build up both polymer and continuous carbon fiber. Among the existing technologies, fused filament fabrication (FFF) satisfies this condition with numerous advantages. FFF is a widely available 3DP technology in which molten plastic material is extruded and hardens instantly after extrusion. FFF can use a wide variety of thermoplastics with fibers, and its hardware setup is simple and accessible. Furthermore, due to the nature of the versatile extrusion process, FFF is unique among the different plastic 3DP technologies for its ability to broaden the methods of the fabrication process, namely through layer deposition, spatial extrusion and add-on.

In architecture, this ability could allow not only the fabrication of complex shapes but also the integration of different structural types, such as spatial or porous structures and double-shell structures, to be fabricated at once in an uninterrupted procedure.

Furthermore, FFF 3DP can enable material gradations, i.e., different plastic material densities and varying carbon-fiber orientations. By placing the plastic and carbon fibers only where needed, the 3D-printed components can be efficiently adapted for specific load cases, achieving smaller dead-loads, and the amount of required material can be reduced, enabling efficient use of resources.

In this context, the paper reviews state-of-the-art methods of FFF 3DP in architecture, highlighting the specific advantages and challenges of each, and describes the development of an optimal and integrated strategy of 3DP for the efficient fabrication of composite building components.

STATE OF THE ART

This section presents an overview of recent developments in FFF 3DP for architecture.

Fused Deposition Modeling

FFF 3DP in contours, also known under the term fused deposition modeling (FDM), is the most popular method of plastic 3DP. FDM works by laying down material in layers; a continuous raw filament is fed through a heated extruder head and is deposited on the growing work.

FDM can produce artifacts to large scales (~26 m^3) with fabrication speeds of up to 50 kg/h and flexible resolution (0.1 mm to 9 mm in extrusion diameters) (Duty et al. 2017). However, a reasonable speed for the fabrication of architectural components can only be achieved when the resolution is relatively low.

In architecture, the KamerMaker, developed by DUS Architects, uses a thick diameter extrusion nozzle (6 mm) with a 17 m^3 print volume. This 3D printer has been used to build a Dutch canal house out of large-scale prefabricated components (Holloway 2013). This method showcases how a faster process can be achieved while improving the structural capacity by having thick wall features.

Spatial Extrusion

Due to the versatility of the molten plastic extrusion process, FFF can also work spatially by drawing molten plastics in the air and cooling them down instantly. In addition to the fast fabrication achieved through thick extrusion, spatial extrusion can also extend rapid fabrication further.

Spatial extrusion has been investigated in architecture by two groups, Gramazio Kohler Research at ETH Zurich and Branch Technology (Hack and Lauer 2014; Molitch-Hou 2015). Their processes have been specifically developed to achieve lightweight engineering and fast fabrication for the manufacturing of molds for concrete and/or foam casting.

However, the spatially extruded structure alone has a considerably low structural capacity due to its

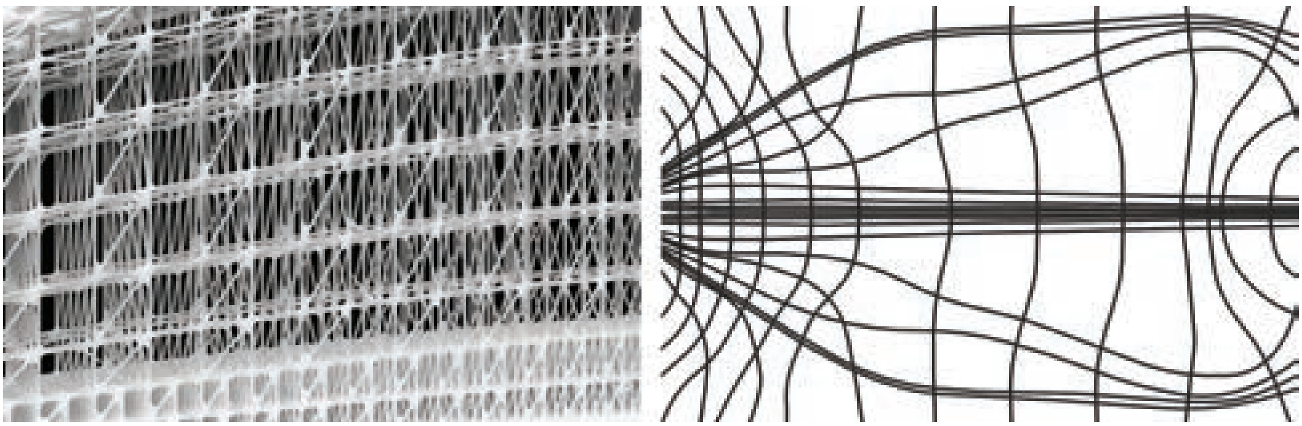


Figure 1: (Left) Example of varying the density of porous structures for the spatial-extrusion plastics; (right) exemplary stresslines for the add-on of CFRP.

low-density characteristics. To improve the structural integrity of the spatially extruded plastic structures, the CurVoxels group at Research Cluster 4 at The Bartlett School of Architecture UCL explored computational design methods. The methods show how a computational tool allows the gradation of the material density of porous structures. These processes can achieve both the rigidity of the structure and a reasonable fabrication time (Kaleel, Kwon, and Li 2018).

Furthermore, by filling the internal geometry with light, low-dense spatial structures, spatial extrusion can act as an efficient infill structure for contour FFF 3DP (Ai Build 2016). These minimal tension connections allow faster 3DP while maintaining the stability of the building components.

Add-On

Nevertheless, most FFF 3D-printed artifacts can hardly be used alone for any applications in architecture due to their limited bending strength resulting from the weak bond between plastic layers. Due to the nature of the stacking procedure of FFF, the adhesion along the vertical axis of every layer is weak (Peters 2016). However, building components require strength in various directions.

As a possible solution to address this limitation, multi-directional FFF 3DP, otherwise known as add-on fabrication, has been investigated. By using multi-axis robotic arms, the add-on process works by applying additional material onto the previously FDM 3D-printed artifacts in a direction that is opposite to the vertical axis of layers. This method has noteworthy implications for improving the bonding strength of 3D-printed components, achieving equivalent structural behavior (Petch 2016; Tam et al. 2016).

Furthermore, the add-on method can also be used to apply carbon fibers allowing the reinforcement of 3D-printed artifacts, resulting in CFRP structures.

This section presented the state of the art of freeform FFF 3DP strategies. These three methods, with complementary characteristics, need to be combined for the efficient fabrication of composite building components in regard to fabrication time, material use, and structural integrity. Therefore, this research investigates the integration of all three strategies into a single 3DP process for the efficient FFF of large-scale freeform plastic elements: the FDM shell for the structural integrity, achieved through a relatively thick material deposition; the spatial-extrusion infill for the reasonable and efficient speed of fabrication; and the add-on to provide the necessary structural reinforcement through multi-directional material extrusion.

APPROACH: AN INTEGRATED FFF SYSTEM

In order to 3D print CFRP components with structural integrity in a time- and cost-effective manner, this research investigates: 1) an integrated fabrication strategy combining these three methods of FFF, and 2) an efficient strategy of locally differentiating material compositions of plastic and carbon fiber. Specifically, the following approach is conducted:

- *Fabrication process development.* Integration of successive planar layer deposition and spatial extrusion; integrated subsequent add-on process with strands of continuous high-performance CFRP material.
- *Computational design.* Path planning: Generating the uninterrupted path for deposition, spatial extrusion, and add-on processes. Plastic material gradation with the data from finite element analysis (FEA): By applying specific load cases, the amount of stress is calculated in the voxel field, and each voxel is then deformed and/or subdivided according to the stress-value, allowing only structurally weak areas to be densified (fig. 1, left). Carbon fiber material gradation with the data from FEA: The system allows the accurate placement of the CFRP in a structurally informed manner, generating stress lines as the tool path of the CFRP add-on, reinforcing along the stress vector fields, and discretizing multiple materials according to their functionality (form and structure) efficiently and accurately, hence reducing the amount of carbon fiber (fig. 1, right).

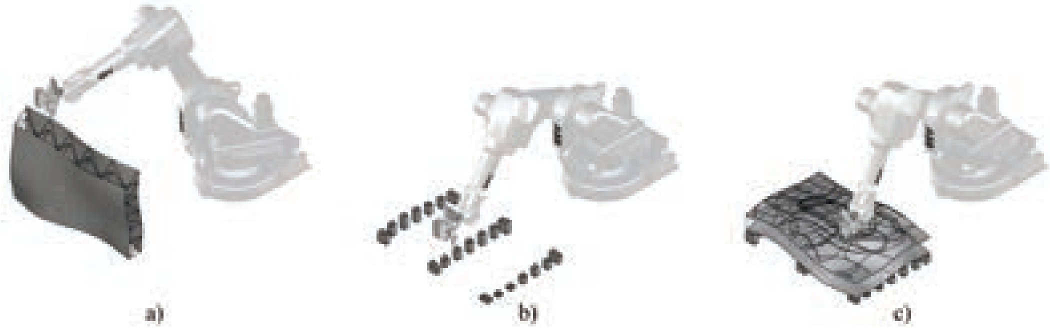
The approach is implemented in two applications, the beam and double-shell sandwich components, to explore design potentials. Specific areas of focus are identified for each full-scale demonstrator:

- *Beam.* This experiment focuses on investigating material gradation of plastic; as a possible option of integrating FFF fabrication processes—FDM, spatial extrusion, and add-on—fabrication steps follow 1) spatial extrusion, 2) deposition onto the spatial structure, and 3) add-on of CFRP (fig. 2).
- *Sandwich panel.* This experiment focuses on the design and fabrication of an efficient CFRP layout, allowing accurate placement of the CFRP in a structurally-informed manner; as a second possible option of integrating the FFF fabrication processes, fabrication steps are as follows: a) simultaneous 3DP of spatial structure and surfaces, b) FDM 3DP of temporary support rests, and c) manual repositioning (90° rotation) of the initially 3D-printed base structure onto the support rests for local reinforcement with add-on CFRP 3DP.

With two prototypes, this research develops path generation methods of integrating spatial extrusion, deposition, and add-on, with special consideration to avoid the geometrical limitations of each of the FFF methods and to allow wide applicability to various shapes and architectural components.

Figure 2: Fabrication steps of the beam component.

Figure 3: Fabrication steps of the sandwich component.



RESULTS

The research demonstrates the approach above through the 3DP of two full-scale building elements: the beam (1.8 m x 0.35 m x 0.15 m; ~30 hours; ø 4 mm nozzle) and sandwich panel (0.9 m x 0.6 m x 0.25 m; ~15 hours; ø 2.5 mm nozzle).

Beam

Spatially extruded structures were sandwiched vertically between a pair of surfaces, allowing the fabrication of the plastic object to be conducted by first 3DP the lower flat surface, then the spatial extrusion, and lastly the upper freeform surface. Consequently, the CFRP material could be directly added onto the top surface of the beam in an uninterrupted manner (fig. 4).

By demonstrating the 3DP of spatial structures with varying density based on the FEA (fig. 5, left), it was observed that the lightweight beam (~15 kg) could be self-supporting and bear approximately 60 kg of the center load (fig. 5, right).

However, the plastic deposition of the upper surface onto the spatially extruded structure reduces the quality of the surface, critically leading to the add-on CFRP being difficult. Immediately following the top surface deposition, these local errors influence the following step of CFRP add-on (fig. 6).

Consequently, precision represents one of the largest challenges, since any significant deviation between the precisely designed base surface and the fabricated one can interrupt the continuity of the add-on paths and affect the functionality of the CFRP.

Sandwich Panel

A pair of outer surface shells was 3D-printed with multi-directional, spatially extruded, minimal infill structures in between (fig. 8, top). Subsequently, the CFRP material was added onto the prefabricated outer surfaces of the panel after manually repositioning the panel on temporary support rests. By demonstrating the CFRP add-on along the calculated stress lines, the minimal carbon fiber materials could effectively reinforce the structure. It was observed that the bonding strength of the 3D-printed plastic was improved, allowing the creation of a self-supporting, double-curvature sandwich-panel element (fig. 7).

Moreover, the double-shell sandwich panel was proven to be fabricated in a single, uninterrupted

Figure 4: The 3DP sequence of the beam (left to right): deposition of the lower flat surface; spatial extrusion of inner structures; deposition of the upper surface; and CFRP add-on.

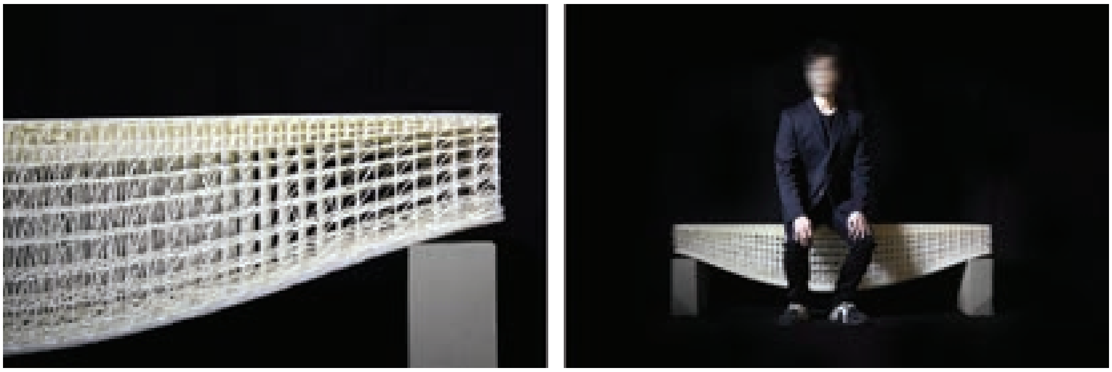


Figure 5: (Left) Graded material density of the spatially extruded structures; (right) sitting experiment on the beam.

fabrication process (fig. 8, top). The simultaneous fabrication of deposition and spatial extrusion enable a high surface quality without substantial deviation, allowing add-on processes (fig. 8, bottom).

However, uneven material shrinkage during the manufacturing process can lead to additive errors on the panel object, which requires the use of distance measuring and add-on path revision processes (Kwon et al. 2018). In addition to this challenge, manual repositioning also causes imprecision resulting in the inaccurate placement of the specific structurally informed CFRP layout.

Furthermore, the current hardware setup limits the thickness of the double-shell structure to no less than 10 cm due to the physical dimension of the custom extruder used. Also, manufacturable complex shapes are limited because of the current setup of nozzle position that is always fixed to the z-axis, while the CFRP add-on was realized multi-directionally, perpendicular to the freeform base surfaces.

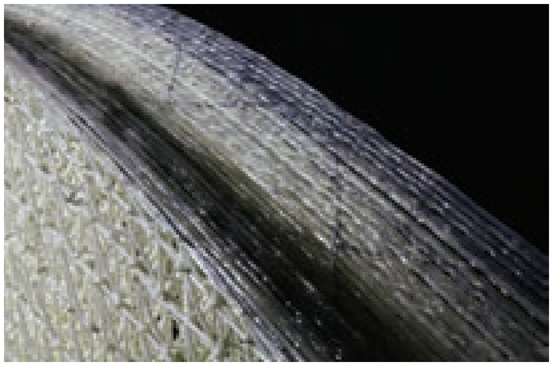


Figure 6: The uneven quality of the upper freeform surface, causing complications of CFRP add-on.

DISCUSSION AND OUTLOOK

From an architectural point of view, the proposed app-roach can be applied to several cases of building components where lightness and geometric- or material-based differentiation with reasonable fabrication speed is required. In order to further broaden architectural applicability, larger-scale applications should be tested.

Whereas thick extrusion methods decrease the fabrication time, they contribute to the loss of precision in geometrically complex artifacts. This dilemma of inverse proportional benefits remains one of the largest challenges. To address this, using multiple diameters of nozzles in a single 3DP process is considered in order to create surface shells with a high-resolution of extrusion (smallest feature 0.1 mm) and infill structures with a thick extrusion. The fundamental limitation of low bonding strength from FFF 3DP appears to be improved by the local CFRP add-on 3DP. Future research will quantify the structural benefits of CFRP through structural assessment methods such as three-point bending and compression tests. Moreover, taking into account the limitations observed from the results, one can consider further investigating:

- *Extrusion tool-head.* The design of the extruder should consider dimensional flexibility in order to minimally interrupt the fabrication process, resulting in building component designs that can achieve higher geometric freedom.
- *Multi-axis deposition and spatial extrusion.* Due to the fixed z-axis of the nozzle during the plastic 3DP, possible geometric features are limited. The ability to freely rotate the extrusion head, which is a unique benefit of using the six-axis robotic arm, can enable the realization of building components with unprecedented geometric freedom and support-free FFF 3DP.
- *Automated vertical repositioning.* Automation for the repositioning of prefabricated plastic structures is considered not only to improve the precision of the add-on process but also to further save the plastic material, which is currently used for the temporary support rests.

CONCLUSION

This paper describes a method of integrating three FFF 3DP strategies—deposition, spatial extrusion, and add-on—to materialize lightweight freeform building components. The presented

Figure 7: 3D-printed sandwich panel with stress line based CFRP add-on.

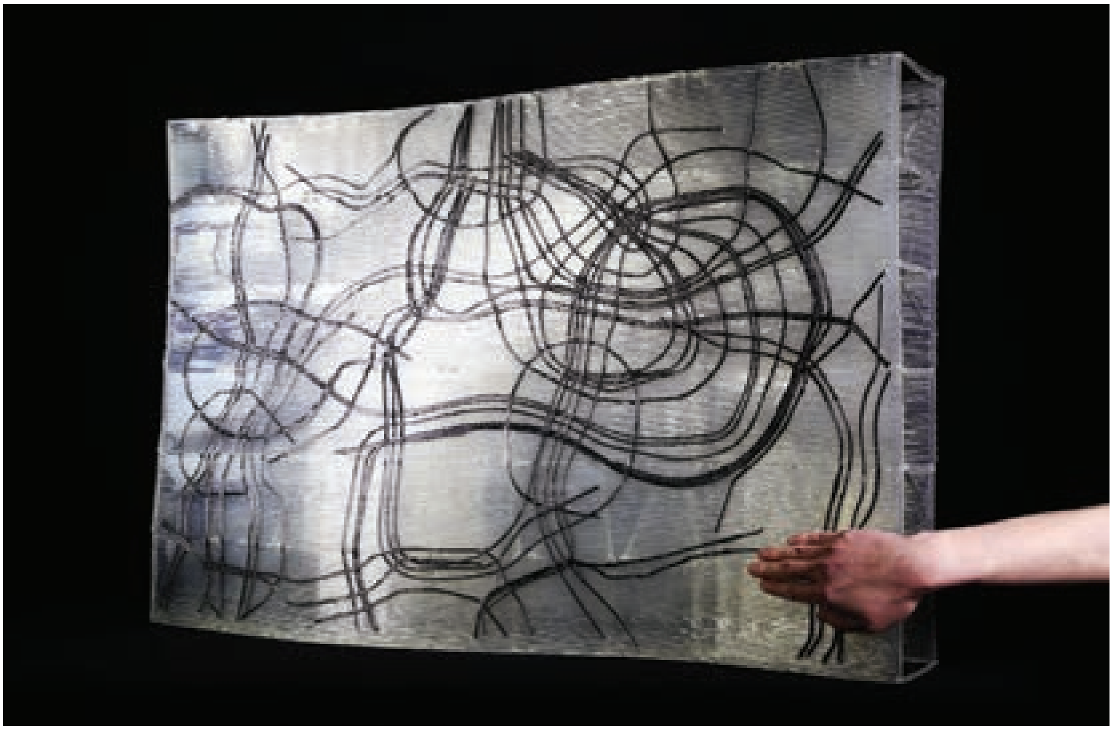
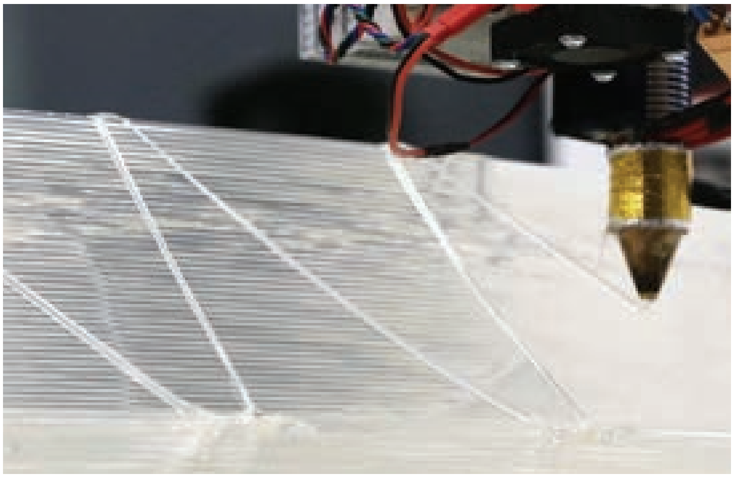
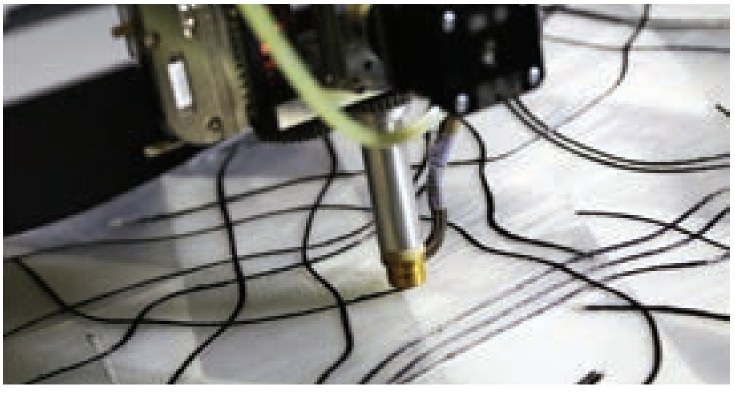


Figure 8: (right) Spatial extrusion processing; (below) CFRP add-on processing.





experiments, the beam and the sandwich panel, have shown the possibility of fabricating complex geometries combining surface and porous structures with features of efficient material gradation and structural multi-material use.

With further improvement of the fabrication process and assessment of structural capacity, the proposed strategy could be used for the prefabrication of double-shell building components, promising a more efficient and sustainable construction process through achieving the lightness of structures, elimination of waste material, and greater design freedom.

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IMAGE CREDITS

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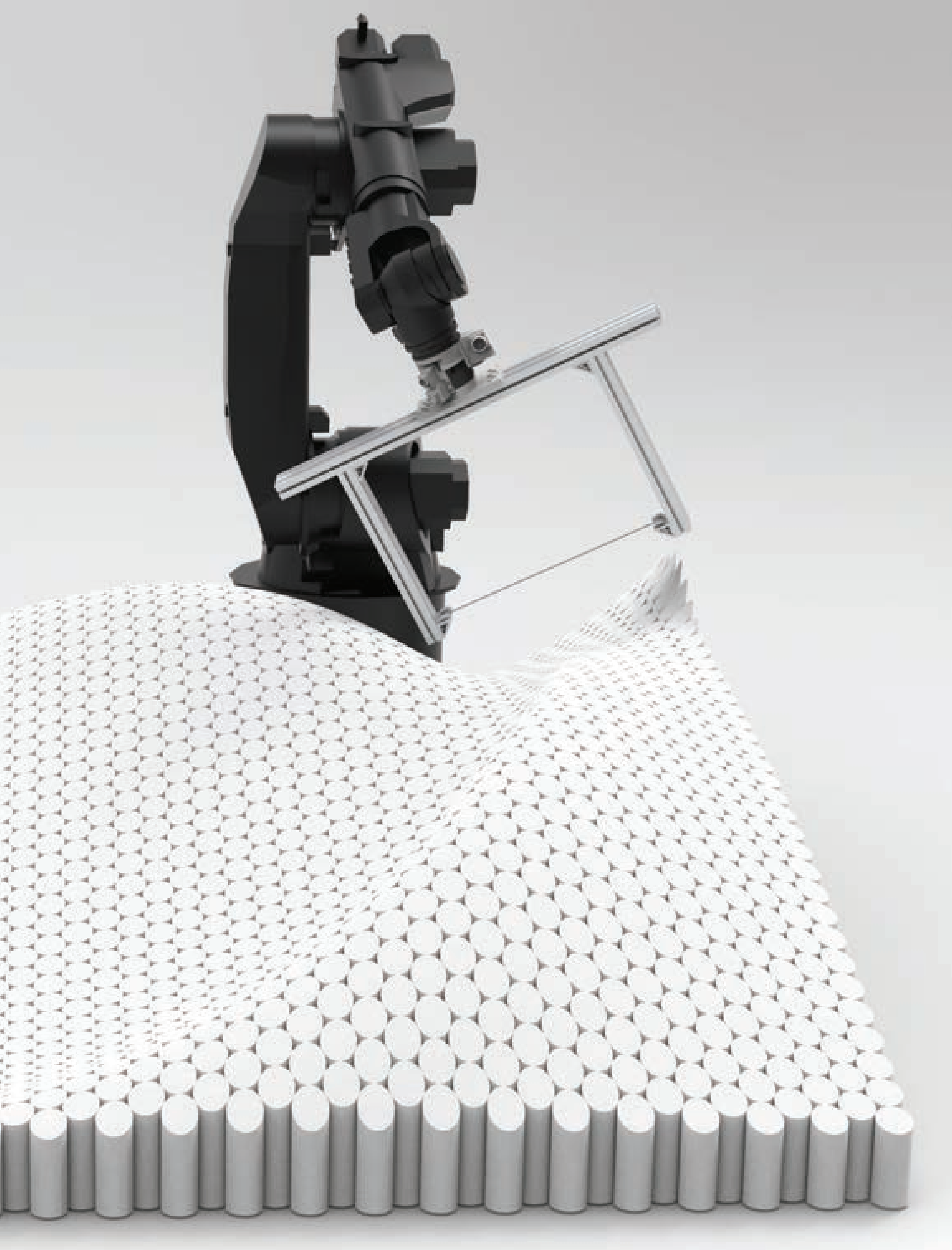

The Guiding Hand: Architectural Authorship in the Age of Robotics

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INTRODUCTION

Architectural authorship is not a singular act but rather a series of reciprocal exchanges between a designer, their selected tools, the mediums they engage, and the context in which their work is created. The guiding hand of the architect and the control it wields fluctuates during the realization of a design intent. The following will deconstruct the notion and definition of architectural authorship through a critical review of the history of craft and architecture. A series of case studies explored the role and latent tendencies of tools and mediums to participate in the design process beyond mere facilitators of a predetermined conclusion. Authorial exchanges between user, mediums, and technology—a KUKA industrial robotic arm—were documented from the formulation of the design intention up through its realization as a physical condition. The goal of the research is to encourage the machine, the robotic arm, to emancipate itself, at least partially, from the commands and instructions of the designer.[1]

AUTHORSHIP AND CRAFT

In Denis Diderot's *The Encyclopedia,* craft is "the name given to any profession that requires the use of the hands, and is limited to a certain number of mechanical operations to produce the same piece of work, made over and over again."[2] Prior to the machine age, creating a series of identical objects through handcrafted production was extremely difficult, if not impossible, due to the unique variables of the designer, their tools, their chosen materials, and the context in which the production was formalized. This process of making illustrates that, although the design idea may begin with the human, the outcome is the result of input from a variety of interpreters and there is value in the variations present within each iteration. Individually, each of these variables and constraints have limitations, but collectively they contribute a number of unique aspects toward a final product. Under these conditions, authorship cannot be credited to a single user but rather as a series of authorial exchanges between all mechanical participants of the making process.

By the 19th century, industrialization and machine technology shifted focus away from handcraft and human skill and toward standardized, efficient, assembly-line production.[3] It was the requirements of a growing society, conflicts between nations, and the "uniquely American penchant for scale and speedthat ultimately created the mass-consumption economy."[4] In order to rise to the demands of the 19th-century industrialized society, emphasis was placed on maximizing the output and efficiency of factory machines rather than the efforts or abilities of the factory worker.[5] It was not that the human hand was no longer required for production, but that the role of the hand was reassigned to that of designer and engineer in an environment where mechanical prowess overshadowed traditional handcrafts. The burgeoning consumer market expected uniformity in product construction, believing that any two items made by the same manufacturer and purchased for the same price were required to be, if not identical, comparable in quality, function, and appearance. This expectation set a prevailing tone across many industries which sought to quickly and efficiently provide product solutions to the consumer through the use of tireless mechanical workers. Mechanical production did not fully eliminate the possibility of errors or variation during manufacturing, but it did significantly increase the likelihood of identical output.

The expectation that mechanical technologies will improve the quality of a constructed object or simplify the design-to-object trajectory prevails today. Although an operator engages technology with a desired result in mind, idiosyncrasies within the machine and perceived mechanical errors or glitches highlight the question of who or what authors the final result. Authorship within this context cannot be reduced to an autocratic condition, but rather it is a sequence of informal exchanges of information and control between the designer and the mediums informing the realization of a design intention. This raises the question of how we, as makers, perceive tools. Lars Spuybroek states in *The Sympathy of Things: Ruskin and the Ecology of Design*: "The oldest forms of technology are tools, like the hammer and the sword; they are operated by hand, and interwoven with complete ecologies of action, with a much wider network of activities than simple use. Tools have persistently been misrepresented through the notion of use, which defines action as fixed purpose."[6] If the fixed purpose of a tool is reconsidered, can tools participate in the design process as instigators and contributors to the development of a design intention instead of only being perceived as mere facilitators of a task?

A classic example of how craft and authorial exchange interrelate during the production process is evident in the creation of abstract paintings by the artist Jackson Pollock. Paintings such as *Lucifer* from 1947 were not preplanned compositions but rather the result of the consequential effects of Pollock's procedural process of painting.[7] With the canvas on the floor, Pollock would distribute various colors of paint via dripping, splattering, and pouring. Working iteratively and post-rationalizing the effects after each step, compositional order and varying degrees of difference in the pattern would emerge over time. Pollock's tools and mediums are equal contributors to the painting's overall legibility and aesthetic. The material behavior of the paint, the brushes chosen to distribute the paint, how the brushes are held, the proximity of the canvas to the paint brush, and the manner in which paint is dripped, poured, and splattered are all contributing factors to the overall characteristics of the painting.

For Pollock, the primary tools of choice for generating paintings were a number of different-sized brushes. However, he did not use the brushes in a familiar or expected manner. Pollock did not directly engage the canvas with the brush. The brush served as an intermediary between the hand, the paint, and the resultant effect on the surface of the canvas. Pollock's engagement and use of his brushes challenges the notion that he is simply wielding a tool at his own discretion. Rather, the brushes are actively participating in the painting's compositional language by acting as a vehicle for emerging and accumulative effects. The stiffness, flexibility, density, and location of each bristle informs the quantity of paint delivered with each gesture. The material agency of each individual bristle, and the bristles as a whole, actively contribute to the figural result on the canvas.

A tool is something that is actively guided by a human, with an expected level of performance, for the purposes of executing and completing a particular task with a desired outcome. A tool facilitates the end goal of the designer by adhering to the commands of the user. Alternatively, mediums operate as negotiators between the designer and their tools. Mediums possess inherent tendencies and behaviors that are initially unknown to the user until the medium is engaged and explored. Once revealed, mediums can challenge early assumptions about the procedural operations, design methods, and preconceived outcomes of the design. Like a misunderstood tool, mediums have the potential to reveal design opportunities and possibilities through latent characteristics.

It is natural for consumers to identify tools simply by their perceived functions, which inherently renders them useless until an author activates them. In his book, *Tool-Being,* Graham Harman describes tools as operating in an inconspicuous usefulness where the user does not even notice or recognize the tool is actively at work.[8] The unassuming tool remains anonymous in the design process until a specific deviation or mechanical failure brings the tool into the forefront as an antagonist, working against the designer. Perhaps this hierarchical scenario can be reinterpreted to grant the tool agency as an active author in the design process.

Figure 1: Illustration of the KUKA KR 60 industrial robotic arm, highlighting the arm's individual axes and locations.

Figure 2: Illustration of the KUKA KR 60 industrial robotic arm's range of gestural motions.

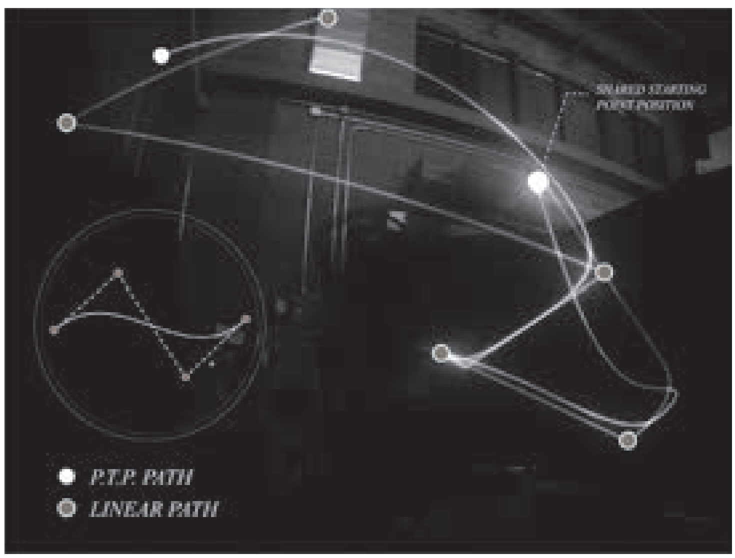


Figure 3: Time-lapse photography light drawing comparing the linear versus point-to-point motion paths with the KUKA robot.

AUTHORSHIP AND TRANSCRIPTION IN ARCHITECTURE

Mario Carpo's book *The Alphabet and the Algorithm* highlights the historical importance of architectural authorship through the influence of Leon Battista Alberti's intellectual authorship, and Filippo Brunelleschi's artisanal authorship. Brunelleschi's design and construction of the dome for the cathedral of Santa Maria del Fiore in Florence, Italy is an example of traditional design-build architecture of the Italian Renaissance. As designer and builder, Brunelleschi actively participated as the guiding hand of fabrication during the realization of his original designs, rather than transcribing the design for builders to construct independently. Brunelleschi personally oversaw the translation of his design concept into the scale of the building. In place of construction drawings, the dome was constructed using a fabrication logic and methodology realized by the innovative lifting machines designed by Brunelleschi. For Alberti, his role as designer ended with the transcription of the architectural design idea into a set of drawings. Architectural authorship was seen as an intellectual endeavor that materialized as a representation on paper that would be constructed later by builders. The final structure was merely a copy of the drawings realized in physical form, to scale.[9] Unlike Brunelleschi, Alberti would not be present on site to revise his original design or ensure the building was rendered correctly from the initial plan, and so the buildings designed by Alberti were highly vulnerable to interpretation by those charged with their construction.

This is still the case in contemporary architectural practice. Interrogation and interpretation of architectural drawings by the builders, unforeseen site conditions, and material indeterminacy can alter what Mario Carpo calls "the relation of identicality between the original and its reproduction."[10] The transcriptive method developed by Alberti and the dictatorial methods of Brunelleschi both rely on control within a human-centric vision of authorship. Contemporary practice has moved toward using technology in a similar way to Alberti, where the digital design is allowed to act as an overarching plan, and the subsequent mechanical output, like 3D printing, is viewed only as a tool that responds to input.

CONTEXT

The exploration of tool latency and design authorship is evident across a wide range of design and visual media disciplines. The mechanical devices created by American artist Roxy Paine as part of his *SCUMAK (1998)* series generate painterly objects through the incremental heating, melting, and depositing of colored polyethylene on a surface, slowly over time. The successive layering of melted material gives rise to unique, non-repeatable compositions. Paine says the art of the objects resides "in the displace contradiction that the origin of those natural forms comes from mechanistic processes. It's in the dialog between what is carefully prescribed and what is naturally happening, and it's in the translation of geologic forces into the form of physical paintings."[11] The hand of the artist, in this instance, resides in the construction of a machine which completes a task in a particular context (the art gallery), and the result of that creative process is the "potential" of an uncontrolled product.[12]

Another example of mechanized creative practice can be seen in the cement printing by British sculptor Anish Kapoor. Kapoor embraces the indeterminacy and expressive capabilities of a material unconstrained by a constructed formwork or expected formal outcome. In his series *Between Shit and Architecture (2011),* Kapoor examines both the construction process and the material qualities of concrete by asking viewers to consider the extrusion process, both a natural phenomenon and an architectural technique, as a generative method for production. The visceral concrete columns made from spiraling concrete strings questions whether the recognizable form (a column), the material (concrete), the machine (a mechanical extruder), or the artist defines the object as a piece of art.[13]

Similarly, Gramazio Kohler at ETH in Zurich interrogates the architectural production process through research projects implementing industrial robotics as an integral component to the generation and realization of a design concept. Their introduction and use of robotics within architecture aims to unify design and production in order to expand the possibilities of architectural materialization.[14] Whether by catapulting clay with the assistance of machines to form aggregate structures over time, or as in *The Foam* project, where continuous streams of polyurethane foam are extruded with an industrial robotic arm, material morphologies and nondeterministic investigations reveal that authorship can be shared or handed over to other sources besides the human.[15]

To extend the dialog perpetuated by Kohler and reinforced by Kapoor and Paine, this paper explores the latent potential of the KUKA robotic arm as an agent or author in the architectural design process. To this end, a series of investigations were conducted at Ball State University to explore the extrusion process. The goal of each study was to search for the hidden aptitude within the machine to participate and contribute to a design's development without the explicit instruction of the user. The project questioned in what manner and at what point might an exchange of authorship occur between the human and their selected tools and mediums.

TOOL AUTOPSY

As industrial robotic arms become more integrated and ubiquitous within the architectural discourse, it is common to see designers focus on the function and

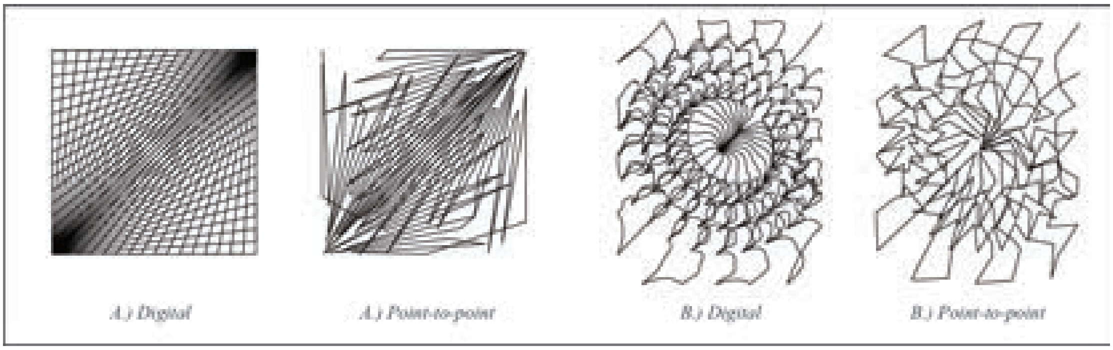


Figure 4: Two examples comparing the difference between patterns generated digitally versus the same patterns transcribed by the KUKA robot using point-to-point motion paths.

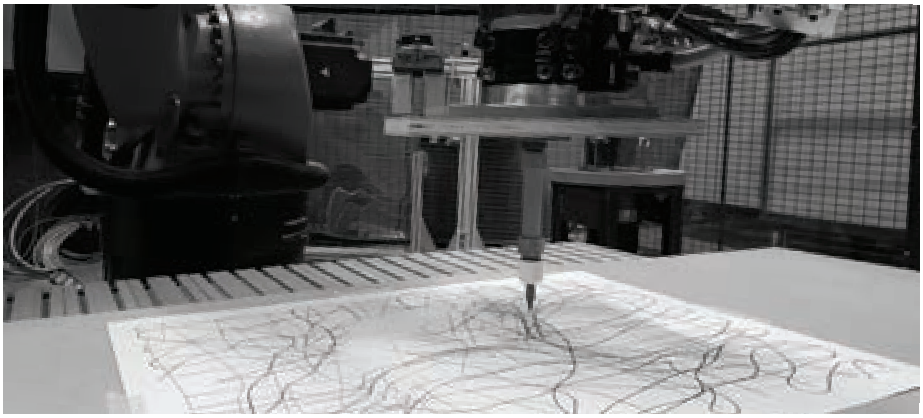


Figure 5: Drawing being transcribed by the robotic arm using point-to-point motion paths.

capabilities of the end of the arm, or the sixth axis. It's similar to a pitcher in baseball: the effectiveness of a pitch may begin with how the ball is gripped in the hand; however, it is the entire motion of the arm, as well as the movement of the body with the pitching arm, that contributes to the ball's trajectory in equal measure. By ignoring the entire series of possible motions lurking within the robotic arm, the functionality of the arm is underdeveloped and ripe for investigation. With this in mind, preliminary applications were explored using a KUKA KR 60 industrial robotic arm in order to identify latent conditions within the arm's gestural movements (fig. 1).

The tool autopsy is a critical exploration into the robot's constituent parts and the operational logic that explicitly and implicitly informs the arm's movements. The KUKA KR 60 robot has the ability to perform three basic motion paths: circular, linear, and point-to-point. Linear and circular motion are prescriptive paths of travel defined by the user. Point-to-point, or PTP, motion is an unpredictable, gestural movement informed by the capabilities of the arm's axes to move at certain speeds (fig. 2). In a PTP motion path, the designer indicates the locations of points in Cartesian space for the robot to travel toward and reach. The arm interpolates the most efficient path of travel based on the arm's initial positioning, the location of the points it must travel to, and the arm's slowest axis. These constraints collectively contribute to a series of impromptu movements. In order to illustrate the range of difference between a linear motion path and a PTP motion path comprised of the same points, a time-lapse photography light drawing was produced (fig. 3). The light drawing highlights the differences between the two paths based on moments where the curves overlap and the degree of separation that occurs when the arm is free to author its own trajectory via PTP motion.

A second series of studies explored the authorial opportunities hidden within the robotic arm through the translation of digital patterns into robotically transcribed physical drawings. The setup to execute the drawings with the robot included the 3D modelling software Rhino, the KUKA|prc plug-in for Grasshopper, a custom spring-loaded marker holder as the end effector, and a drawing surface with Bristol paper. The robotic arm, using point-to-point motion paths, transcribed patterns generated in Rhino. The results were drawings that deviated significantly from the original, digital transcriptions (fig. 4). Many contributing factors determined the transition of authorship from the digital file to the robotic arm—factors such as the digital translation of the user designed pattern to a source code language that would allow the robot to run, the PTP motion path discerned by the arm, the marker within the holder end effector, the paper, and the surface beneath the paper (fig. 5). All of these participants contributed to the final drawing. The process highlighted the futility of producing identical final drawings, even though identical digital source material and a

Figure 6: Completed drawing generated by the robotic arm using point-to-point motion paths.

precise mechanical instrument were used as tools for the study. Each independent attribute that contributed to the drawing exhibited inherent and latent characteristics which informed the final outcome (fig. 6). The irregularities evident in the attempted duplication of the drawings echoed back to the conditions and emergent patterns within Pollock's paintings. Upon assessing the results of these studies, it was determined that further exploration of the potential for machine agency and research into authorial exchange using the robotic arm would be conducted through three-dimensional, additive fabrication techniques.

Figure 7: Additive fabrication setup for initial applied research studies.

ROBOTIC CRAFT

The intention behind exploring additive fabrication with point-to-point motion paths via the KUKA robotic arm was to explore the possibility of tools operating as mediums and acting as real-time authors of a formal construct. The setup for material extrusion included sourcing the original digital data from the animation software Autodesk Maya, the KUKA|prc plug-in for Grasshopper in Rhino, the robotic arm, a custom end effector consisting of a pneumatic caulking gun with an airline connection, an air pressure gauge, high-strength construction adhesive, and an aluminum build platform (fig. 7).

The process began by sourcing the digital data from Maya to translate into the KUKA source code. If authorial exchange was going to occur generatively and thoroughly throughout the production process, the digital blueprint files needed to participate in the exchange as well. Autodesk Maya has the capacity to simulate physics in a digitally dynamic environment. For this study, a network of curves assigned dynamic properties which could, over the course of time and throughout a number of simulations, begin to imply the geometric profile of a cone. Extruding material consistently in the Z-axis informed the rationale behind the conical geometry. During the simulations in Maya, the dynamic curves possessed inherent tendencies and agency analogous to physical materials. For instance, the curves possessed an elasticity due to the structural logic and subdivision of each curve; a static cling or attraction variable

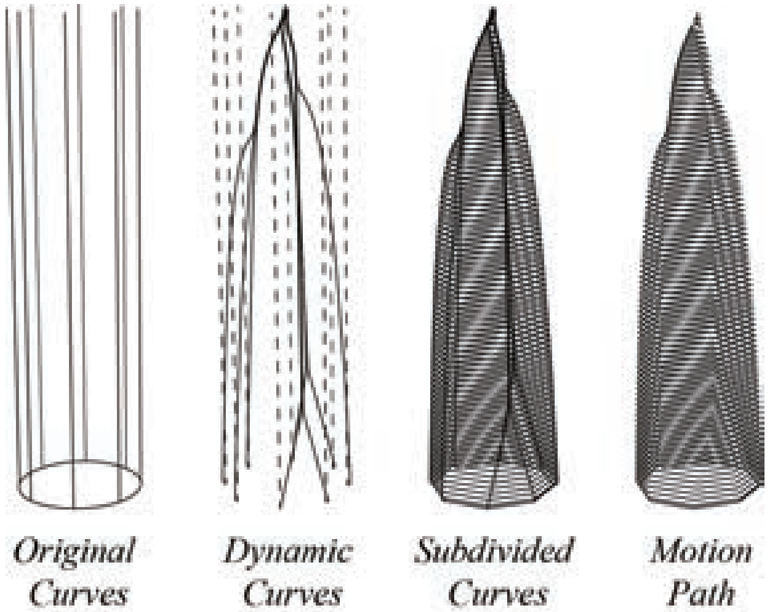


Figure 8: Step-by-step development of a motion path provided to the robot.

prompting adjacent curves to interact and stick to one another; and a density or mass capable of responding to gravity, or additional external forces such as turbulence. Therefore, the curve networks could author their own final arrangement using these properties without the explicit instruction of the user.

The translation and rationalization of four select configurations of curves sourced from Maya was completed in KUKA|prc. Prior to the generation of the source code for the robot to run, the four sets of curves were subdivided into a series of points informing a motion path (fig. 8). Alterations to the subdivision logic provided a number of PTP motion paths which would be explored for each set of curves. Approximately 45 overall extruded studies were completed for all four sets of curves (fig. 9).

During production runs, it became evident that the speed of the robot's gestural movements during material extrusion had to be adjusted, as the material, a high-strength construction adhesive, had the tendency to build up over time and settle (fig. 10). The material agency of the adhesive was the final interpreter and author during production, which was evident by the material slumping, drooping, and curling. These material characteristics could not be contained or predicted by the user (fig. 11). The material's latent tendencies were revealed at different moments throughout deposition or during the curing timeframe. The pattern and trajectory of extrusion, dictated by the point-to-point motion path, influenced the quantity and location of material deposited. The ornamental and structural integrity of successive material extrusion became highly informed by previous layers of adhesive. Formal qualities and language transitioned from redundant surface effects to irregular rustication and with slumping overlaps.

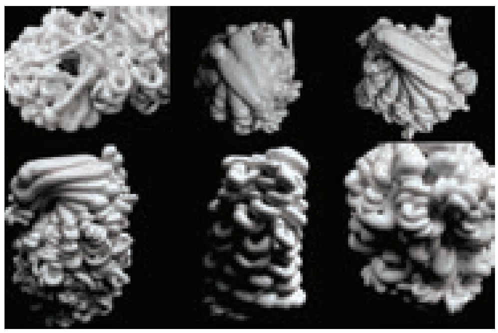


Figure 9: Nine examples of extruded studies generated from the four sets of curves.

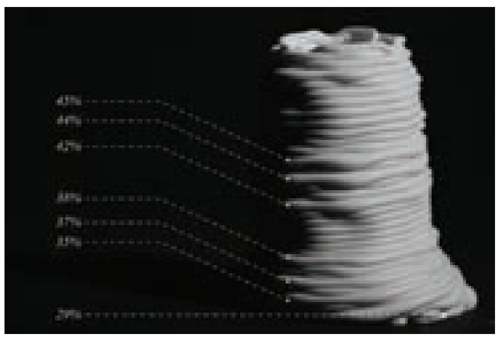


Figure 10: Locations indicating a change in the robot's speed and pace during extrusion. The settings were altered manually during production in response to material behavior.

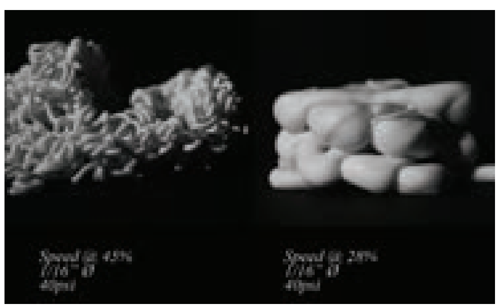


Figure 11: Comparison of material's effects when production runs are executed at higher and lower speeds utilizing the same source digital files.

The point-to-point motion path produced multiple uniquely authored iterations working with the same source content—one set of curves but altering their subdivision logic (fig. 12). The resultant range of ornamental effects and build configurations warranted additional vetting (fig. 13). How would a change of scale influence additional material behaviors with the adhesive? What scenarios would allow structural forces to merge with ornamental effects? Increasing the surface area of the extrusion and continuing to modify the motion paths began to imply potential architectural applications at an increased scale.

TECTONIC GRADIENTS

Keeping with the same workflow parameters, a new set of dynamic curves were generated in Maya to increase the surface area for the material extrusion. The fabrication materials used and the preliminary setup were also consistent with the previous round of fabrication studies (fig. 14). In addition to the scale of the build, conditions and parameters that prompted the extruder nozzle to reengage with previously deposited layers of material were encouraged. These conditions tended to occur at points of intersection along the path of extrusion within the original digital blueprint.

The extruded pattern, seen in top view in Figure 15, consisted of varying amounts of concentrated material along the perimeter with a more regular and redundant striated interior structure (fig. 15). The largest amount of ornamental rustication, which developed during the deposition process, was located along the outside of the pattern. Over time, the legibility and composition of the plan evolved and changed with the introduction of new material. As was the case in the extrusion of the conical geometry, the PTP motion path of the robot and the material behavior of the construction material were very influential in authoring the formal and tectonic language of the final form.

The tectonic aesthetic of the constructed object was at times blurred. Throughout the composition, there are moments where the layer-by-layer extrusion process is explicitly legible and moments where the construction logic is not visible due in large part to the absence of additional formwork or scaffolding (fig. 16). Most contemporary examples of tectonic aesthetics found in additive construction, such as cast-in-place concrete, highlight the methods in which the assembly was created. Tie holes in exposed surfaces and joint lines left over from the formwork not only illustrate the methods used to create construction material, but also indicate the limitations of the human laborer who will be doing the construction work. The common spacing of the formwork joint lines corresponds to an eight-ft-long sheet of plywood, which an installer can handle without mechanical assistance. When visible, these characteristics are routinely accepted or expected as a natural result of the construction process. One of the takeaways from assessing the objects created during the research studies was that the emerging aesthetics reminiscent of the extrusion process would expand the possibilities for what is expected or accepted in the final building. Similar to the work of Kapoor, the extrusion process can be the predominant method for the creation of structural and material forms where patterns emerge as part of that process and embody the ornamental and functional aspects of the building.

APPLIED PRACTICE

Future development of the studies described above will follow two parallel research tracks. The first will continue to increase the build scale and modularity of the extruded material objects to be used for constructing a small-scale pavilion. The second track will explore additive manufacturing and authorial exchange with the KUKA industrial

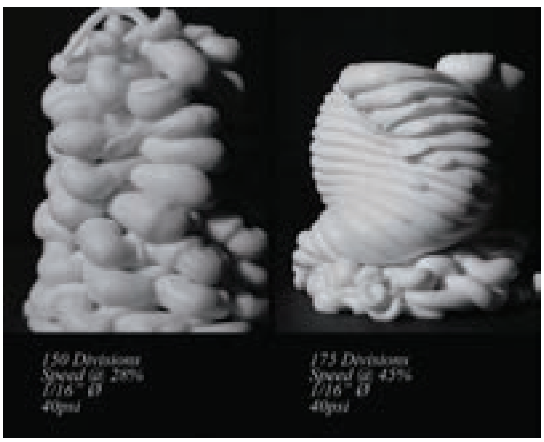


Figure 12: Range of material's effects and prototypes produced, along with corresponding parameters.

Figure 13: Range of ornamental effects: build formations and structural tendencies that emerged during the research trials.

Figure 14: Additive fabrication setup for second round of applied research studies.

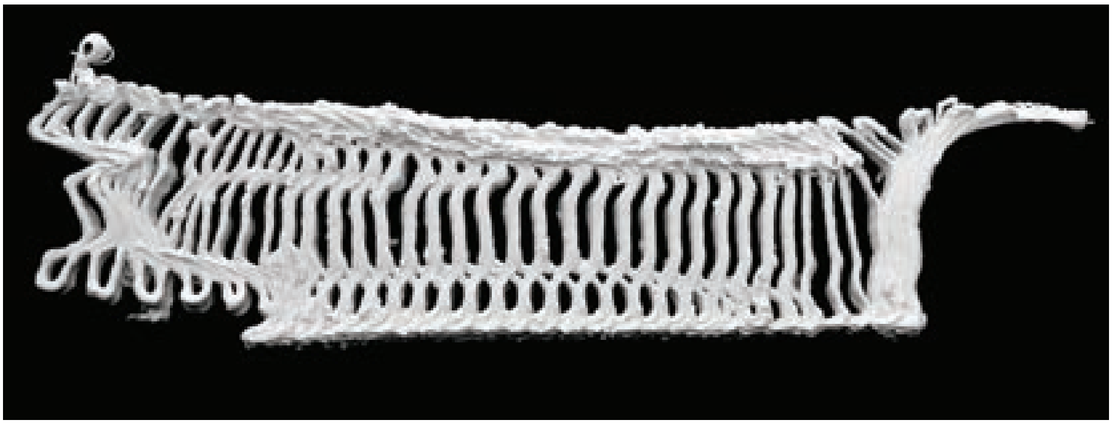


Figure 15: Top view of overall extruded object from second round of applied research studies.

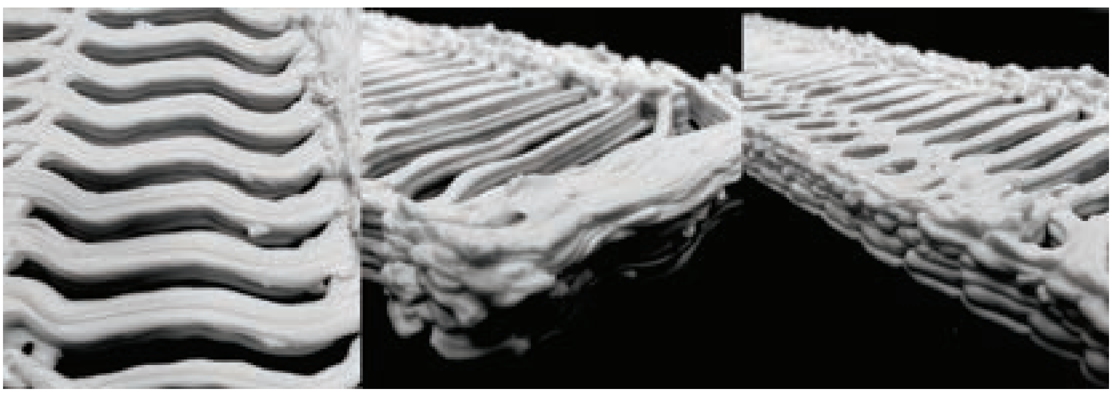
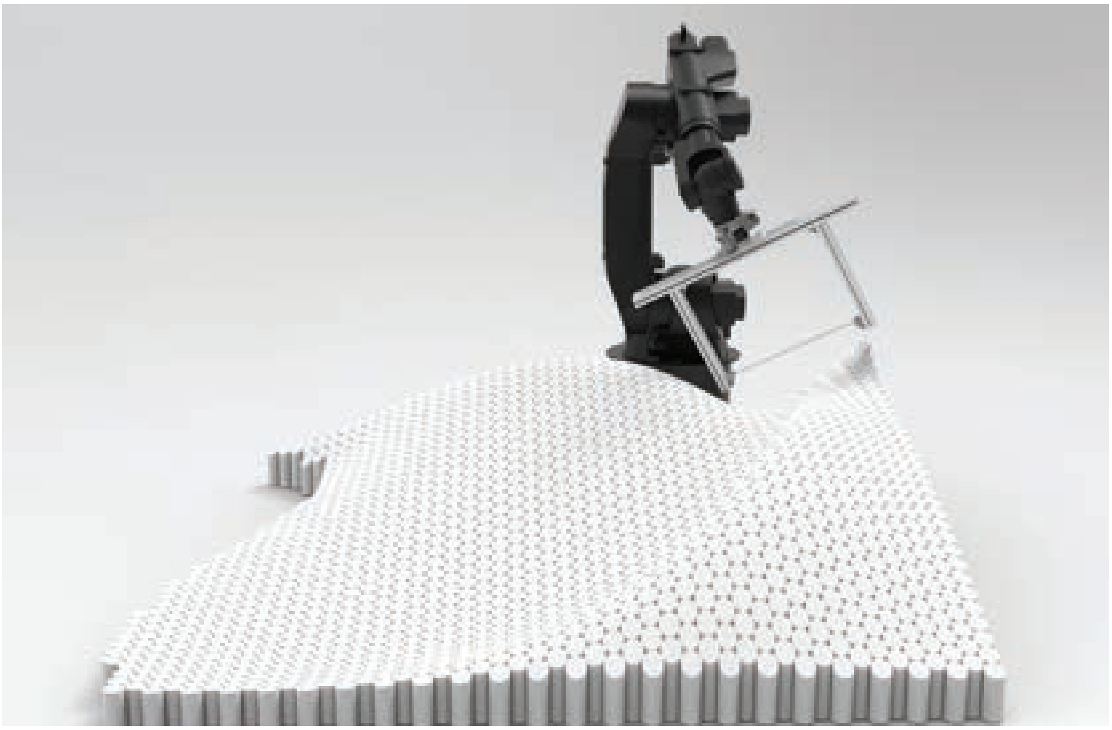


Figure 16: Detailed views indicating the locations of emerging rustication and ornamental effects.

Figure 17: Fabrication setup for future round of applied research studies. Extruder replaced with a hotwire foam cutting end effector.



arm by using a hotwire foam cutting end effector. In this project, the point-to-point motion paths will inform the cutting of closed-cell polyethylene foam rods into a soft topography for public interaction. The setup and translation process will be similar to the previous studies, with the exception that the material being engaged will be solid and the cutting process will be subtractive instead of additive (fig. 17). Also, the points of the motion path will be informed and sourced from the built environment and reconstituted in digital space. The final installation will ultimately be located in a small city in Indiana.

As was the case in the other research studies, the soft topography project will encourage authorial exchanges throughout the design and fabrication process. The interpretation and activation of the topography will continue with public interaction in the installation space. Since it is impossible to fully predict how the public will utilize and engage with the surface, the active installation will further blur the lines between typology and expectation. The topography will blend the existing exterior wall with the horizontal surface of a walkway situated immediately adjacent to a public building. It will be difficult to distinguish where the wall begins and the sidewalk ends, promoting a new reading of the built environment. The potential for this kind of reading lends itself to the manner in which the extruded objects began to blur the legibility of a part-to-whole relationship within a tectonic assembly. Lessons learned from this public installation will be integrated back into the development of the pavilion consisting of extruded components.

CONCLUSION

Point-to-point motion allows the robot to activate its joints in a manner that enables expression from the robot. It still achieves the goal of position, but the path in which it travels to get there is without human direction. As industrial robots become more engrained in the production of architectural components, or even work collaboratively with laborers on building sites, the relationship between human and technological medium becomes even more important. When viewed as more than an assistant within production processes, tools possess the capabilities to unveil potentials and avenues of exploration previously unseen. Novel new methods for form finding, material testing, and tectonic assemblies will emerge when harnessing the knowledge gained from feedback between the designer and the production process.

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IMAGE CREDITS

All images by the authors, except:

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Discrete Cellular Growth

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ABSTRACT
The use of time-based computational simulations in architectural design has led to highly complex geometries; however, those often are difficult to construct. In order to generate more easily buildable structures, we therefore attempted the integration of the placement of identical discrete components into a time-based growth simulation. We present a research project focusing on computational cellular growth which simulates the development of organisms as accumulations of cells, discretization of the resulting surfaces, and their construction through prefabricated components. Different intercellular behaviors as well as external forces acting onto the cells were explored during the design process. One of the outcomes was constructed physically as a 1:1 large-scale prototype and compared to a free-form structure that was generated by a similar growth simulation. The placement of the components results in geometries that still share many of the qualities of the previous free-form growth structures, but which at the same time exhibit distinct geometric behaviors of their own.

1 INTRODUCTION

Architectural designers have used various time-based computational simulations to generate highly complex geometries (Stuart-Smith 2016, Snooks 2013, Andrasek 2012). However, the results often pose the difficulty of a feasible construction. The generated geometries are often free-form without any repetition of elements or curvature, often combined with a high degree of intricacy. Architects have therefore often not been able to realize designs that have been generated with time-based simulations, or have done so only at a smaller scale with methods such as 3D printing or a tessellation of complex geometry into simpler surfaces.

In order to generate more easily buildable structures, we attempted the integration of the placement of identical discrete components into a time-based growth simulation. We present a research project focusing on computational cellular growth which simulates the development of organisms as accumulations of cells, discretization of the resulting surfaces, and their construction through prefabricated components. One

Figure 1: Bryx Front View

of the successful outcomes was constructed physically as a 1:1 large-scale prototype (fig. 1). We compare this prototype with a previous project that was based on the same generative growth algorithm, but that was translated into free-form tessellated surfaces for construction (Klemmt and Sugihara 2018). Different intercellular behaviors as well as external forces acting onto the cells were explored during the design process of both projects.

The placement of the components results in geometries that still share many of the qualities of the previous free-form growth structures, but which at the same time exhibit distinct geometric behaviors of their own.

2 RELATED WORK

Since the introduction of computational tools in architectural design, many architects and designers have been interested in the simulation of time-based processes via iterative algorithms. Those include mathematically abstracted systems such as cellular automata (Wolfram 1983) but, more commonly, systems that aim to simulate behaviors and processes that occur in the natural world. Often those are based on the movement, division, or other behaviors of programmed particles or agents. Swarm simulations, which can recreate the movement patterns of social animals, have been used by various architectural designers to create arrangements in space or by tracing the movement paths of the individual agents (Snooks 2013; Stuart-Smith 2016; Andrasek 2012). Differential growth is based on the division and proliferation of particles that maintain specified relations towards their neighbors and has been used to computationally "grow" complex geometries (Louis-Rosenberg 2015; Bader et al. 2016). Recursive subdivision is based around the repositioning and insertion of new vertices into an initially simple mesh geometry in order to refine its shape (Hansmeyer 2010; Hansmeyer and Dillenburger 2013).

Different methodologies have been utilized for the construction of the complex geometries at the installation or building scale resulting from those or related generative processes. While there are many

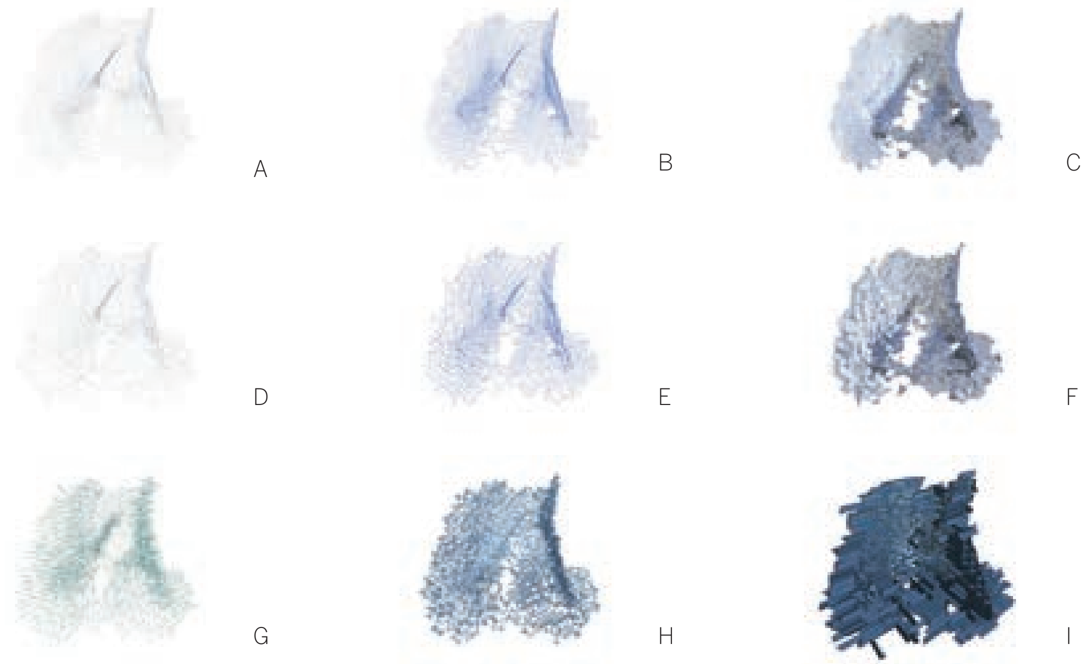


Figure 2: Cellular Growth: A) Cell Accumulation. B) Range of Influence. C) Cell Neighborhood. D) Cell Connections. E) Division Triggers. F) Voxel Grid. G) Occupied Voxels. H) Component Placement. I) Components.

possibilities, some of the commonly used methods are 3D printing, CNC cutting, or a tessellation into smaller components. 3D printing has so far mostly been applied at a smaller scale. Large-scale examples include (Ruffray et al. 2017; Yu 2017; Chiusoli 2018). 3D CNC cutting of components has been used for the Armadillo Vault by ETH Zurich's Block Research Group (Block et al. 2017). The tessellation of a complex geometry into smaller, possibly only flat or single-curved segments, has been used at various scales. Or1 by Orproject was the first single surface constructed in this way (Fairs 2008), a method that has since been used by various architects (Fornes 2015; Thiemann 2011). At the large scale, several of Zaha Hadid's double curved building facades are broken down into mostly flat or single curved panels (Ceccato 2012). In all of those cases, the final overall form will still be a double curved freeform geometry.

On the contrary, the other possibility is to work with discretized or voxelized geometries. In this case, either the overall form is built up of repetitive identical components, or a complex geometry may be rationalized into the repetitive units. In a voxelized geometry, it is possible to base the discretization on an underlying spatial 3D grid so that every component fills a 3D grid cell or voxel. Those could be cubes, but other spatial grids can also be used (Retsin 2016). Alternatively, a component could have any shape, but with specific connection points toward its neighbors that define how multiple components can be arranged (Sanchez 2016).

For this paper, our interest lies in the comparison of the freeform and the voxelized construction methods, specifically in the use of the tessellation of a complex geometry versus a construction of a voxelized form, both generated through closely related growth algorithms.

3 GROWTH SIMULATIONS

Cellular growth simulations attempt to computationally simulate the growth processes of entities that are made up of multiple individual cells (Lomas 2014; Bader et al. 2016; Louis-Rosenberg 2015). The simulations start with a small amount of initial cells. The growth and the development of the form are based on cell proliferation, cell differentiation, and morphogenesis. Programmed as point clouds, the cells are subdividing and taking on specific functions within the larger accumulation. During the growth, the cells react highly emergently according to intercellular behaviors toward their neighbors, as well as to global location-dependent forces. Those behaviors and forces then shape the resulting geometry (Klemmt 2019).

Algorithmically, the cells are calculated by X, Y and Z coordinates in 3D space. In every iteration, first the cell neighborhood is recalculated: Every cell defines which other cells it regards as its neighbors according to their proximity and according to a maximum number of neighbors. Cells can therefore start or cease to be neighbors from one iteration to the next if they move within or past the maximum range. A cell's neighbors will then influence its movement and division behavior (fig. 2).

Figure 3: Gaizoshoku Side View.

Figure 4: Gaizoshoku Detail

3.1 Cell Movement

Different forces are controlling the movement of the cells and are added up as vectors as the cell's acceleration. The previous velocity of the cell is reduced by a drag factor, then the acceleration is added to it. The velocity is then added to the previous position of the cell in order to define its new position.

The cells represent units with an approximately spherical volume. The center points of the cells therefore need to stay at a distance close to the intended diameter of the cells. In order to achieve this, a neighbor force is acting between adjacent cells. This force pushes cells further apart if their distance is closer than the defined target distance, and it pulls cells together if their distance is larger. The further two cells are positioned from each other, the smaller the influence of this force.

A planarity force causes the cells to locally arrange within surfaces, rather than to form volumetric clusters. This force functions by identifying the local plane of the cell, the plane that passes through the three closest neighbors of the cell. The cell is then pulled onto this plane along the plane's normal vector.

Other forces that have been explored include a strata force, which causes cells to arrange along parallel surfaces. An orthogonal force causes cells to arrange along orthogonal planes. Gravity pulls the cells downwards. Attractor forces cause cells to move toward or away from a point depending on their proximity to it. Object forces cause cells to move toward or away from imported mesh geometries. Constraints or obstacle objects prevent cells from moving into restricted areas in space.

3.2 Cell Division

Various triggers can cause cell division; however, for both of the presented case studies, the aim was to identify cells on the margins of the accumulation for division so as to grow the structure outwards. The marginal cells were identified by the distance to their closest neighbors: A centrally positioned cell will have neighbors all around it and therefore a smaller average distance towards its neighbors than a cell on the edge.

Upon being identified for division, a new cell is inserted into the model adjacent to the dividing cell. Additional rules for the direction and velocity of the parent and child cells after division will have an influence on the edge conditions of the accumulation.

4 GEOMETRY RATIONALIZATION BY SURFACE TESSELLATION

4.1 Gaizoshoku

The main difficulty of the construction of the resulting, highly complex geometries at an architectural scale is the economic feasibility of the geometries. The previously completed project *Gaizoshoku*, developed by Orproject in collaboration with Satoru Sugihara, was

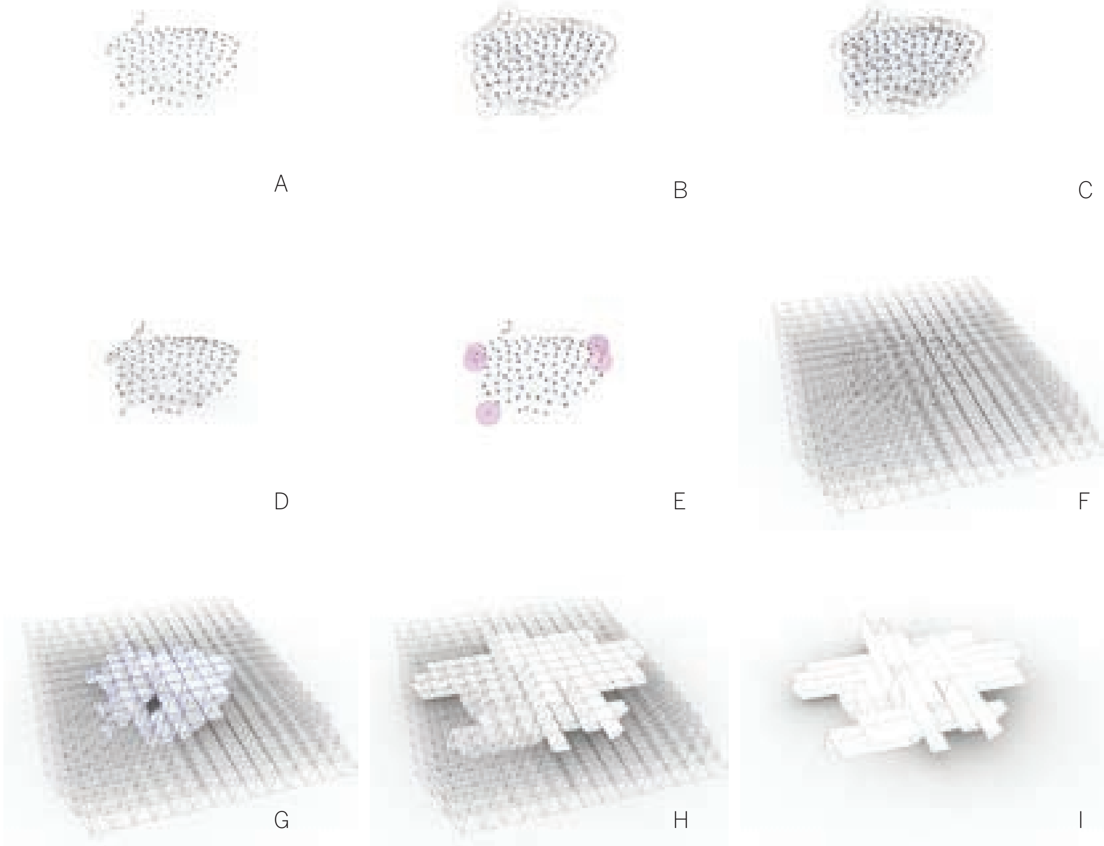


Figure 5: Discrete Growth: A) Cell Accumulation. B) Range of Influence. C) Cell Neighborhood. D) Cell Connections. E) Division Triggers. F) Voxel Grid. G) Occupied Voxels. H) Component Placement. I) Components.

constructed for an office interior in Beijing in 2015. The project utilizes the same growth simulation for the development of its geometry as the below presented project *Bryx*, but without voxelizing the individual cell locations. Instead, the cell locations remain in their freeform position in space, and the translation of cell centers to material happens via their triangulation into mesh surfaces (Klemmt and Sugihara 2018) (fig. 3).

The planarization force that is integrated into the algorithm causes the arrangement of neighboring cells into planar surfaces and in the process assigns each cell a normal vector. Based on those normal, it is now possible to connect neighboring cells into mesh triangles, with the cell positions forming their nodes. For *Gaizoshoku*, those base triangles were further deformed parametrically in order to create a varying opacity of the overall structure. Connections between adjacent panels were placed centrally on the edges of the base triangles so that two panels always meet at one joint, fastened by a set of two bolts (fig. 4).

4.2 Construction

The installation, excluding the reception desk below, was constructed from 2,521 different pieces. Each piece was marked with four numbers: the identifier of the piece in the center and the identifiers of the three adjoining pieces at the corresponding edges. The structure has an area in plan of about 18 m^2, with a height of about 1.3 m. The construction took about two weeks for a team of six workers, with a cost for construction of only about $10,000.

5 GEOMETRY RATIONALIZATION BY VOXELIZATION

5.1 Bryx

Following the discrete paradigm, we used identical components in order to construct a larger assembly of the cells while avoiding techniques, such as panelization or the slicing of surfaces, which would lead to a large number of custom components as in *Gaizoshoku*. This happened through the implementation of a space discretization in the growth simulations so that the resulting geometries can be feasibly constructed from identical components (fig. 5).

The voxelized grid used in the design process is a triangular pyramid grid, which uses alternating pyramid and tetrahedron voxels. The components are an elongated assembly of eight voxels—four pyramids and

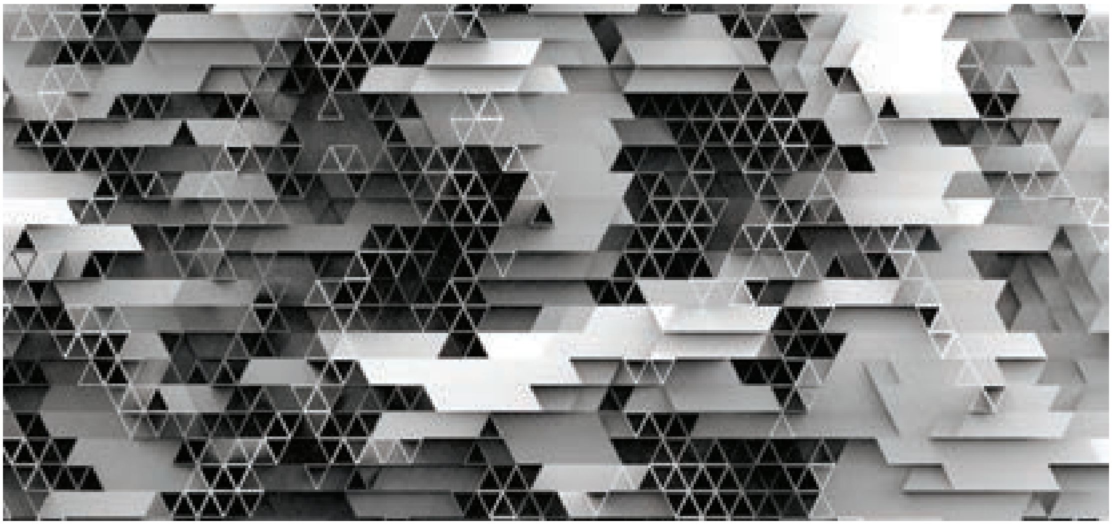


Figure 6: Voxelized Assembly

Figure 7: Voxelized Assembly

four tetrahedrons—that together form a triangular tube. Those components are then placed in every iteration of the simulation through the voxels that a cell occupies, with options to vary the component's orientation. All aspects of the algorithmic process—cellular growth, voxelization, and placement/orientation of components—are in mutual feedback, affecting each other throughout the duration of this iterative process (figs. 6 and 7).

5.2 Full-Scale Prototype Fabrication

The prototype was constructed from 450 identical prefabricated components cut out of straight triangular aluminium extrusions that were custom manufactured for this project. The geometry of each component then corresponds to the eight voxels that it occupies in the growth simulation. The use of such discrete elements allowed for economic feasibility and a straightforward assembly process. As all components are identical, there was no need for labelling logistics.

For this project, the components were connected with epoxy glue, although other means of assembly, such as bolts, rivets, or high-strength double-sided tape, could be explored. The assembly process proved to be very efficient, and all 450 components were assembled in less than 12 hours (figs. 8–10).

6 EVALUATION

In order to evaluate these two different methods for materializing surfaces generated on the principles of discrete cellular growth, the prototypes are compared on the qualities of resulting geometries and their differences, as well as the viability of the construction method, including its time, cost, and ease of assembly.

Both installations can be understood as a part or prototype of a larger architectural system. The cellular growth simulation itself produces articulated spatial arrangements with varying degrees of complexity and porosity. The *Gaizoshoku* installation truthfully translates the generated geometries into physical output, with minimal differences between the node positions of the two. This has, however, required a large number of unique pieces, allowing for little tolerance and interchangeability in the construction process, increasing the construction time and complexity. Likewise, the scalability of the material system beyond an installation or a furniture piece can be questioned.

Bryx, on the other hand, compensates the loss of resolution with speed and ease of the construction, thanks to the use of the self-similar and interchangeable discrete elements. The repetition of the components not only simplified their assembly, in which two components always connect in repetitive arrangements, but it especially pertained to the fabrication of the identical components. This could be outsourced to a regular aluminium manufacturer that did not require advanced digital skills. Instead of a need for digital cutting templates, as in *Gaizoshoku*, the simple top, front, side elevations were sufficient to describe the single component type to the factory.

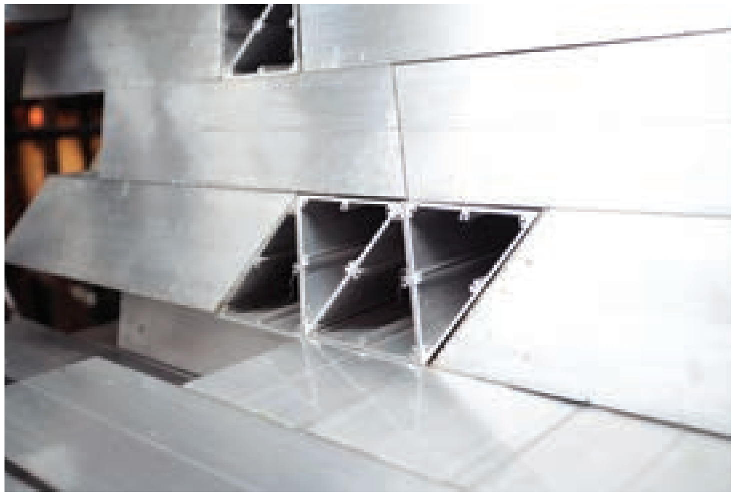
Likewise, materializing the surface through discretization allowed for a more heterogeneous treatment of the surface itself, through change in the porosity, layering, or orientation of the discrete elements along the underlying surface—suggesting that additional spatial qualities, absent from literal translation of the surface topology, could be achieved on an architectural scale. This results in the generation of legible architectural elements of varying porosity, on top of enclosures derived from cellular growth. The resulting formations can, to a certain degree, depart from the underlying surface, as the qualities of generated enclosures are not directly bound to the topology of the surface, but are rather the consequence of local and global patterns formed through the distribution of the discrete components.

The output of the underlying growth algorithm in both cases is a point cloud. It could be argued that in *Gaizoshoku*, this point cloud is interpreted as a surface that can curve to enclose space and form volume and structure, whereas in *Bryx*, the point cloud is interpreted as volume, which is already structural and can be used to form larger structural assemblies and surfaces, and likewise enclose space.

Figure 8: Bryx Side View

Figure 9: Bryx Back View

Figure 10:
Bryx Details



7 CONCLUSIONS

Both *Gaizoshoku* and *Bryx* can be regarded as successful projects in terms of their ability to create a physical construction within a defined budget and time frame. Both were based on the same underlying generative algorithm; however, the means of rationalization for their physical construction were very different, with *Gaizoshoku* using a surface tessellation vs. the discretization used for *Bryx*. Those yielded clear differences on various levels, ranging from aesthetics to ease of construction, and the resulting geometric and spatial qualities. The discrete construction methodology used for *Bryx* appears to be significantly simpler and more economical, and also possibly more easily scalable for building construction. However, for any design task there will be different requirements as well as design intentions from the architect that define how a complex freeform geometry can best be translated into its physical reality.

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LIMB: Inventory-Constrained Design Method for Application of Natural Tree Bifurcations as Heavy Timber Joinery

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ABSTRACT
LIMB is a project recently started at Taubman College at the University of Michigan to explore the potential use of natural tree bifurcations as a new joinery method in heavy timber construction.

This research studied the natural occurrence of branch bifurcations in different wood species to develop practical concepts for design and fabrication of timber joinery in a single bifurcated wood form which would replace traditional mortise and tenon or steel connections.

Through the design and fabrication of a full-scale reticulated dome, this research showed how organic variations in tree limb bifurcation bring about valuable and sustainable opportunities for generative architectural design of heavy timber construction.

Toward this goal, a hybrid physical/computational workflow was developed to study the application of these organic elements through the integration of computational design modelling and 5-axis digital fabrication. The computational workflow used the inventory of harvested tree crotches to inform the geometry of the dome to reduce material use and routing time; moreover, the workflow evaluated the structural performance of the dome geometry using finite element analysis under self-weight and environmental loads and provided performance and fabrication feedbacks which informed the design process.

This computational workflow was then integrated in a genetic-based form exploration process where variations in design parameters were studied through visual and quantified fabrication and structural feedback, and the final geometry was chosen based on visual aesthetics and fabrication constraints.

This fabrication and inventory-aware process was a proof of concept for practical application of tree branch bifurcation for full-scale construction. Beyond the reduction of waste and added value, this research explored opportunities for more organic and sustainable design and construction of heavy timber joinery in the industry.

1 INTRODUCTION
Historic precedents for the use of tree crotches in wood structures can be found in both 17th-century framing for naval vessels, as well as joinery in timber barn construction.[1] Presumably, this technique

Figure 1: Bent and bifurcated elements taken from natural tree sections, from l'Encyclopédie méthodique Marin.[1]

offered angular joints without complex mortise and tenon details. Additionally, this could achieve a degree of moment resistance that exceeded other joining techniques. These are demonstrated in Figure 1, which shows examples of the described use of natural tree bifurcations. In these cases, the wood grain naturally follows the shape of the piece.

More recently, Claus Mattheck at the Karlsruhe Institute of Technology carried out extensive physical testing of the behavior and strength of natural forked tree sections.[2] In his work, he also provided guidelines for the selection and defect detection in these pieces in nature. More extensive research was carried out on structural and fracture capacity of tree bifurcations in hazel (Corylus avellane) by Seray Özden et al.[3] This research studied the toughening mechanism of the tree forks through destructive fracture tests to study the fracture capacity of the interlocking wood grain that produces the critical join between branches at the apex of a hazel fork. Gareth Buckley et al.[4] studied the effect of the angle of inclination on the morphology and strength of bifurcations in hazel trees. The bifurcations were subjected to rupture tests until they failed, and the results show that, as the angle of inclination increased from 0 to 90 degrees, the rising branches became more elliptical in the vertical plane, theoretically increasing the bifurcation's bending strength in this plane. The diameter ratio was also found to be a significant factor in determining bifurcation yield strength in the samples tested.

This research studies the potentials of using tree bifurcations to take advantage of structural benefits of a joint with a single piece of wood that purposely grew under natural forces for bifurcation in nature. The structural connection is moved away from where the vertical and horizontal members come together to develop a more strongly constructed joint. Beyond the reduction of waste and added value, this project has the following architectural opportunities:

- Overall architectural effect relates to the natural occurrence of branch bifurcations and their formal implications in exposed structures such as roof trusses.
- A reusable system made from locally sourced materials that is environmentally conscious in its life cycle and transportable for future uses.
- The development of new ways of connecting linear timber elements beyond the "crotch" where universal scarf connections are revisited using digital fabrication.
- A structural system that is scalable to utilize many parts of a tree, from major tree bifurcations at the base suitable for large pavilions, to smaller bifurcations adaptable to furniture.

Recent researchers and designers have tried to use locally sourced trees directly in fabrication without the need for extensive processing. This included unprocessed tree bifurcations as truss elements or round timber as columns and structural elements.[5]

This research was developed based on a syntactical approach to design. The interest was not in unique form generation based on unique parts, something that is very well explored in the realm of digital fabrication, but rather constructing a reusable language of bifurcated joinery. This research elaborates on the natural occurrence of tree bifurcation as a tectonic element using contemporary digital practices to propose new timber construction systems.

We designed a digital fabrication workflow that extracted standardized milled parts from an inventory of salvaged material. The cataloging of recurring angles and other physical properties inherent to different species of trees allowed for further development of the structural possibilities of this system, which can be applied to nearly any type of tree bifurcation. This then allows for various combinations within the language of bifurcated timber joinery seen in Figure 2. Some of these combinations include:

1. Spatially optimized parametric branching nested structure for occupiable space.
2. Spatially optimized parametric hexagonal organic dome with multi angular facets.
3. Three-way triangulated columnar structure.
4. Two-way triangulated frame reminiscent of the traditional timber framing.

The goal of the work presented here was to make use of these naturally forked tree sections as joining elements in architectural structural systems. In this effort, we focus on the design and fabrication of a reticulated dome structure. The raw tree crotches were cut to size and milled to final form and dimensions in a 5-axis CNC router. The design intent was to produce standardized nodal elements that can be joined easily to connective strut elements. By using the CNC router, exact final angular and linear dimensions can be precisely attained.

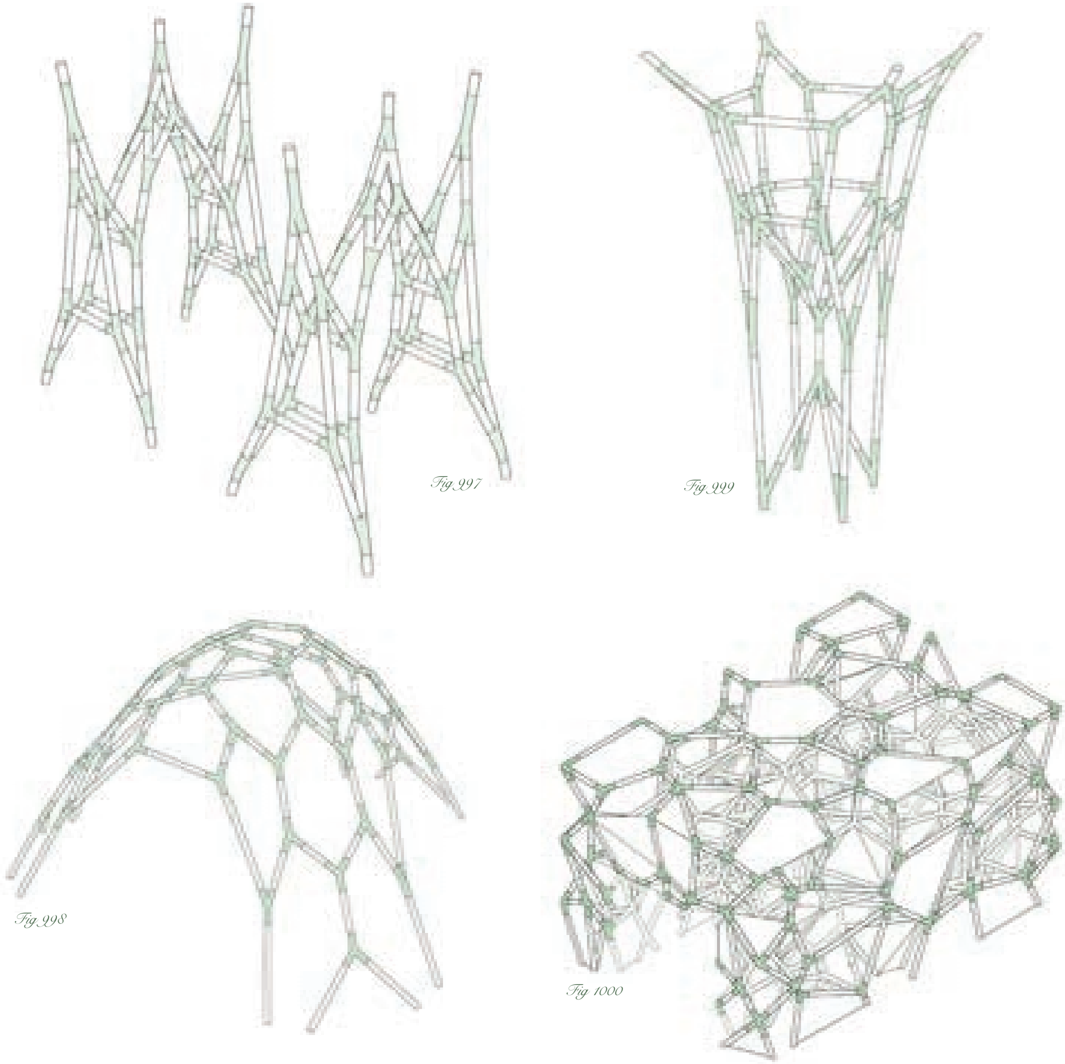


Figure 2: Different structural typologies proposed using tree bifurcation joinery.

2 DESIGN PROCESS

Natural forces in trees develop adaptive growth through the process of thigmomorphogenesis, which develops organic variations in size, shape, and fiber composition of tree bifurcations. This organic variation in tree crotches requires a specific design process that accommodates the uniqueness and variation of bifurcation geometry while also imposing a certain level of standardization for production.

Toward this goal, a computational workflow was developed to study the application of these organic elements through integration of computational design modelling and 5-axis digital fabrication. Through physical studies of the crotch geometries, key descriptive parameters of these limbs (e.g., dimensions and angular measures) were extracted as a data inventory which was then used in a computational process to determine the best fit of these crotches as structural joints.

The placement was determined through a novel two-step dynamic inventory-constrained form-finding process. This process imposed the available crotch geometries into the design geometry though iterative variation of local geometry to minimize the geometric discrepancies. As a fabrication aware process in this method, global geometry responded to organic crotch geometries in a bottom-up process that first informs the location of appropriate tree crotch in the design geometry and then iteratively minimizes the discrepancies of each crotch and its corresponding joint in the design geometry, leading to reduction in routing time and material use. This process transformed the design geometry into an organic shape which responds best to the available inventory of crotches. This method was implemented in Python, used dynamic relaxation formulation for minimization of discrepancies, and is compatible with different visual programming software. The process is scalable and adaptable for different design and structural typologies.

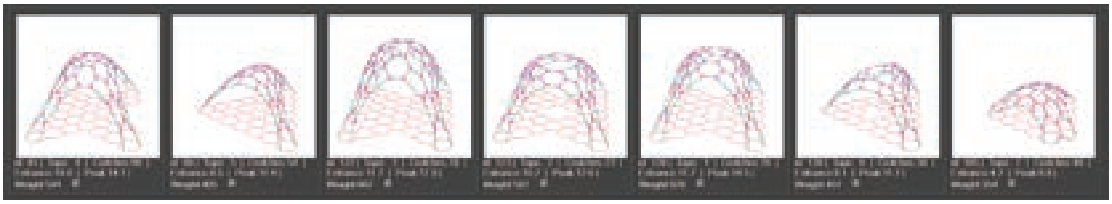


Figure 3: Different dome typologies the parametric model can explore.

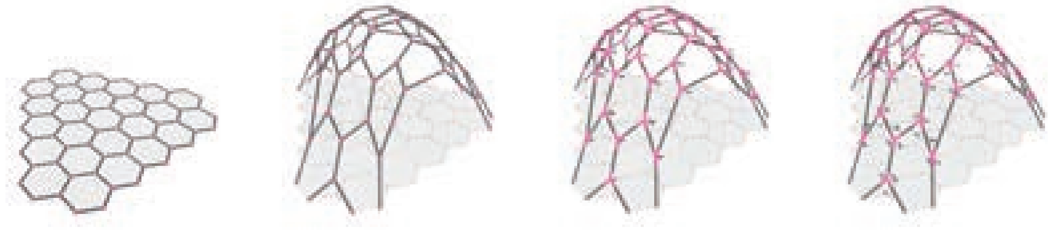


Figure 4: Catenary-based form-finding process.

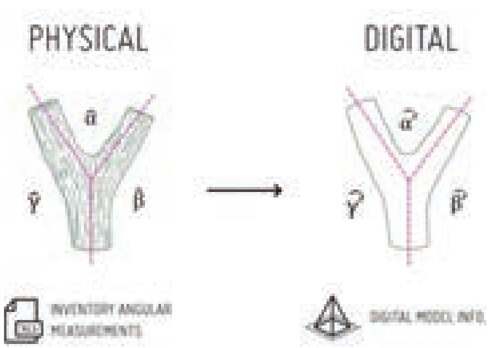


Figure 5: Physical/digital measurements.

3 RETICULATED SHELL

Reticulated shell was the first full-scale prototype designed using the proposed method. The design process of the reticulated shell executes the following steps in the generation of the design solution:

1. Selection of a base topology grid.
2. Relaxation of the grid to find an optimal compression shell geometry.
3. Assignment of the crotches from the inventory to the shell joints.
4. Minimization of the difference between the assigned crotch angles and the corresponding dome joint geometry.
5. Analysis of the shell under gravity and snow loading.
6. Genetic-based form exploration process to find the final design solution.
7. Export of performance metrics, fabrication information, and images.

3.1 Selection of a Base Topology Grid

Because tree crotches generally join three members, a hexagonal grid was chosen for the shell mesh. Also, for this initial study, it was desirable to limit the total number of joints and members to reduce fabrication time. With this specification, the grid topologies were limited in overall size and complexity. A parametric model can develop different grid topologies which control the number of joints, and some contain a central oculus that further reduces the number of joints and members. Figure 3 shows the seven topologies included in the form-finding process.

3.2 Catenary-Based Form-Finding of the Compression-Only Dome

The next step was to use the Grasshopper plugin Kangaroo[6] to apply an upward force to find a compression-controlled shell and solve the equilibrium state using dynamic relaxation. The force level (rest/length ratio) which drives the height extension is taken as a variable, and spring tensions are set over three ranges of the surface: the supporting legs, the edges, and the central portion. This will influence the final curvature in the different regions. The examples in Figure 4 show the form-fining process.

3.3 Assignment of the Crotches and Sorting the Inventory Data

Once the idealistic compression-only dome geometry was generated, the digital crotches are generated at every joint of the dome and the three angles between the limbs of each crotch are measured (fig. 5). In order to assign a crotch from the inventory to the closest joint in the digital model, we first had to sort the inventory data based on the angular measures. A natural way to sort the inventory was to define the controlling angles based on the morphology of each crotch. For the sake of clarity, we set up series of naming rules that determined that in each tree crotch, the biggest limb would be called the trunk, and the two other limbs were called branches. Three angles and diameter of each limb defined the overall geometry of the crotch. The angle between branches was the smallest of the three angles and called the bifurcation angle. We sorted the inventory data based on the bifurcation angle, and we set up the digital crotches vertically on their trunk limb. Then we assigned inventory items to the joints in the dome geometry based on the smallest sum of the difference between three angles as formulated as square root of sum of square as below:

Calculating Angle Differences to Determine the Closest Joint for Each Crotch in the Inventory

$$\sqrt{d_{ij}=(\alpha-\alpha')^2+(\beta-\beta')^2+(\delta-\delta')^2}$$

$$\forall\, i \in \{1\ldots n\}$$
$$\forall\, j \in \{1\ldots m\}$$

d_{ij} = SRSS of angles' difference of inventory crotch number i and digital dome joint number j
n = number of inventory elements
m = number of joint elements in the digital model

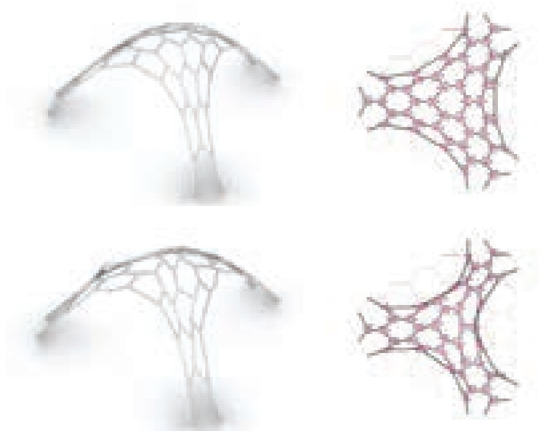


Figure 6: Iterative process of minimizing angular differences.

3.4 Minimization of Angular Differences

Once all of the joints in the digital model were assigned the corresponding crotch from the inventory, we formulated the minimization process to iteratively and simultaneously minimize the discrepancies between all of the tree angles of each joint and its assigned crotch. This process was developed based on defining angular constraints between each of the two limbs of the digital joints and constraining them within a given angular tolerance from the corresponding angle of the assigned crotch. Based on this method, the theoretical model had a number of constraints equal to three times the number of joints in the model. To solve this constrained model, we had to systematically and simultaneously change the joints angles in the digital model to minimize the discrepancies. This was done using the dynamic relaxation method to find the overall equilibrium of the geometry by solving the coupled constrained model iteratively. This process minimally changed the local geometry of the idealistic compression-only dome to incorporate the inventory data in the model and minimize the discrepancy of the digital node and the assigned crotch geometry for each joint in the model. In effect, this process ultimately reduces the milling time and material use and evolves the optimal compression-only geometry to a more organic shape which responds to the inventory (fig. 6).

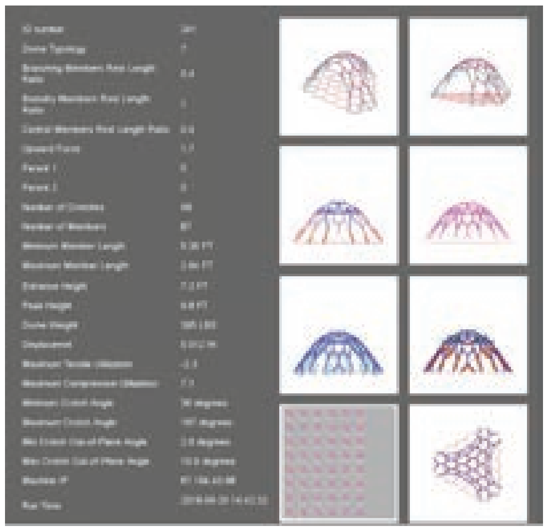


Figure 7: Generated data for each design solution.

3.5 Analysis of the Shell Under Gravity and Snow Load

Once the final geometry of the dome was defined, this geometry was analyzed to evaluate the structural performance of the dome under self-weight and snow load. Two basic categories of data were collected for the shell: geometric parameters and structural parameters. The main geometric values included: clear height of the side arches, center maximum height, number of joints and members, longest and shortest members, defining crotch angles, and base topology type. Since the member sections and wood density were preset, the overall weight was also calculated.

The shell was considered homogeneous, and the connections of members were considered fixed connections. Hardwood material properties were assigned to the members, and the dome was supported using pinned supports. The dome was analyzed under self-weight and 30 psf projected snow load using linear first order structural analysis using Karamba (structural analysis plugin for Grasshopper).[7] Values recorded from the analysis included maximum axial force, moment, and deflection, as well as utilization factors of members under axial and bi-flexural forces (fig. 7).

3.6 Form Exploration Process Using ParaGen

In order to find the best dome geometry based on multiple design requirements, we used a form exploration process to study and explore the design space generated by the computational model. The generation of the solution space, along with the exploration to find the best solutions, was accomplished using ParaGen,[8] a design aid developed at the University of Michigan. Basically, the system couples some parametric form generation with simulation and analysis tools to generate and evaluate the entire design solution. The results are uploaded to a SQL server and can then be sorted and analyzed using SQL queries. Through visual and quantitative analysis of design solutions, the design space is narrowed down to find the best design solution based on visual aesthetics, performance metrics, and fabrication requirements (fig. 8). Then, all of the data on the final design solution is exported for the fabrication process.[9]

3.7 Export of Performance Metrics, Fabrication Information, and Images

The computational model provided a smooth data transfer for performance metrics and fabrication data. The performance metrics and geometric information

Figure 8: The ParaGen cycle showing the steps used to generate a range of solutions.

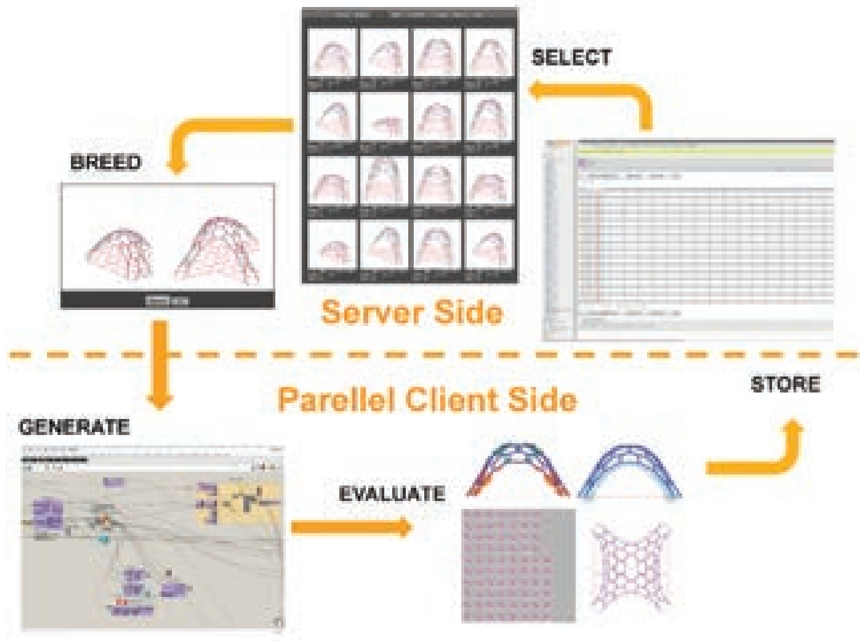
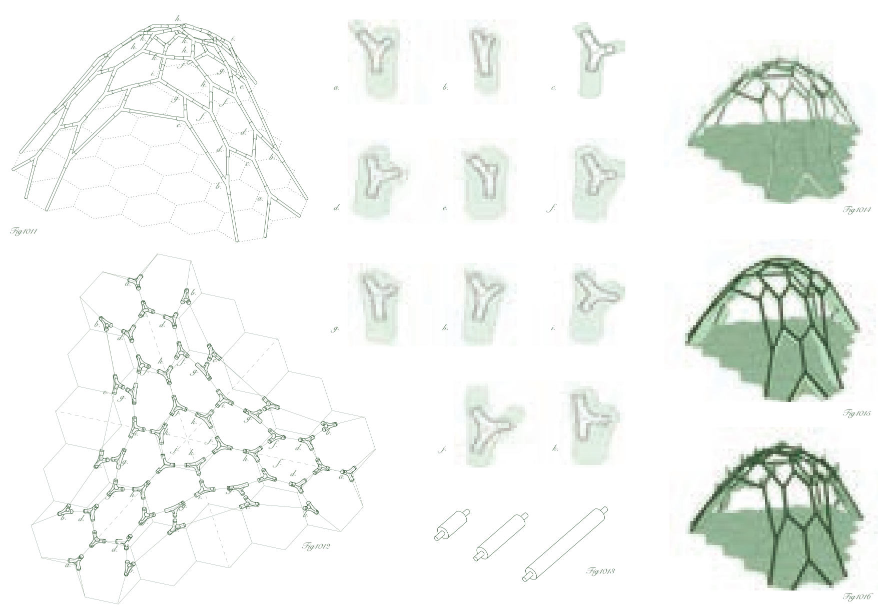


Figure 9: Exported fabrication and analysis data for the final design solution.



were exported into data tables and DXF files. Additionally, the final joint geometry layout was exported to then be used in the development of fabrication data, including nesting and tool pathing (fig. 9).

4 FABRICATION PROCESS

Through numerous scaled fabrication tests, different fabrication requirements and issues of working with organic tree crotches were resolved, and a fabrication workflow was developed to process the tree crotches into their final finished form. The developed workflow included: tree crotch acquisition; pre-processing, scanning tree crotches, and inventory generation; milling process, physical test, and post processing; straight member piece fabrication; pegged connection; and erection. These steps are further described below.

4.1 Tree Crotch Acquisition

Because of their size and disruptive grain pattern, tree crotches are oftentimes not harvested commercially, cannot be turned into mulch, and frequently end up being landfilled. Our ongoing workflow utilized discarded urban tree bifurcations from the City of Ann Arbor, Michigan. The team acquired 72 tree crotches from different wood yards near Ann Arbor.

4.2 Pre-Processing, Scanning Tree Crotches, and Inventory Generation

The crotches were visually inspected for defects and labeled. Then, their physical dimensions were measured. The length and diameter of each limb, as well as the angle between each limb of the crotch, were measured and tabulated in an inventory. This inventory was then used in a computational process to optimize the crotch assignment to dome joints (fig. 10). Then, each crotch was scanned using photogrammetry to generate a digital model of the crotch geometry for milling purposes.

Figure 10: Inventory measurements and data.

4.3 Milling Process, Physical Test, and Post Processing

Multiple 5-axis milling tests were conducted to develop an efficient fabrication process for this project. The desired finished geometry of each joinery was fit inside the corresponding scanned raw crotch geometry using 3D modeling and transformation in Rhinoceros 3D software (developed by Robert McNeel & Associates). Using Mastercam software (developed by CNC Software), milling toolpaths were generated for each piece and tested for the milling process (fig. 11).

All of the pieces were milled and sealed using a sealant to delay drying and cracking. The end of each limb of the crotch was milled to accommodate a peg connection to the linear connection member. Milled pieces were stored for assembly. Figure 12 shows a piece mounted in the milling jig at the conclusion of the 3D routing operation. Every piece went through this process, which took about two hours for each.

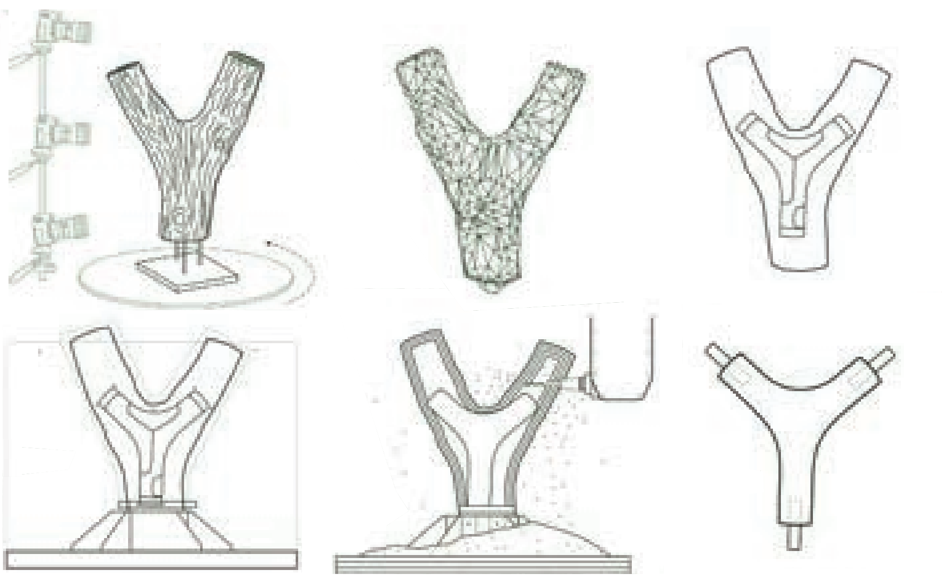


Figure 11: Scanning and milling process.

Figure 12: 5-axis milling process.

4.4 Straight Member Piece Fabrication

The straight strut elements between nodes were fabricated using 70 mm (2-3/4 inch) diameter billets. For these, rough turning maple blanks (commonly used to produce baseball bats) were used. These are knot-free pieces and should have a strength comparable to select mixed maple (NDS allowable compressive stress of 6000 kPa [875 psi]).

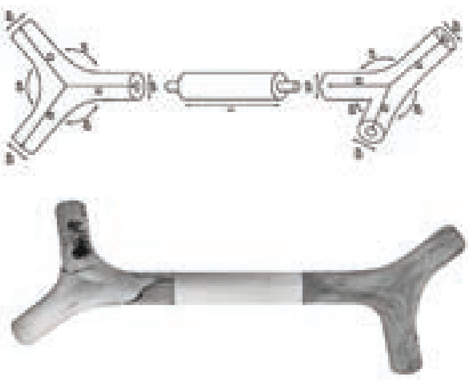


Figure 13: Pegged connection design.

4.5 Pegged Connections

The connecting element between the crotch node wand the straight struts was a simple 25 mm (1 inch) wood dowel used as a peg. In the original design, the intention was to glue the peg in place with casein (wood) glue (fig. 13).

The joint was tested in this form in flexure and was found to develop the full tensile strength of the dowel, which was 276 Nm (204 ft-lbs). However, because the prototype needed to be disassembled, the pegs were fixed in place with screws rather than glue, which reduced the flexure capacity to about 100 Nm (73 ft-lbs). The allowable compressive capacity would still be based on the net section and was about 20 kN (4500 lbs).

4.6 Erection Process

The erection process was easily accomplished with temporary bracing of the nodes. Due to a time limit to

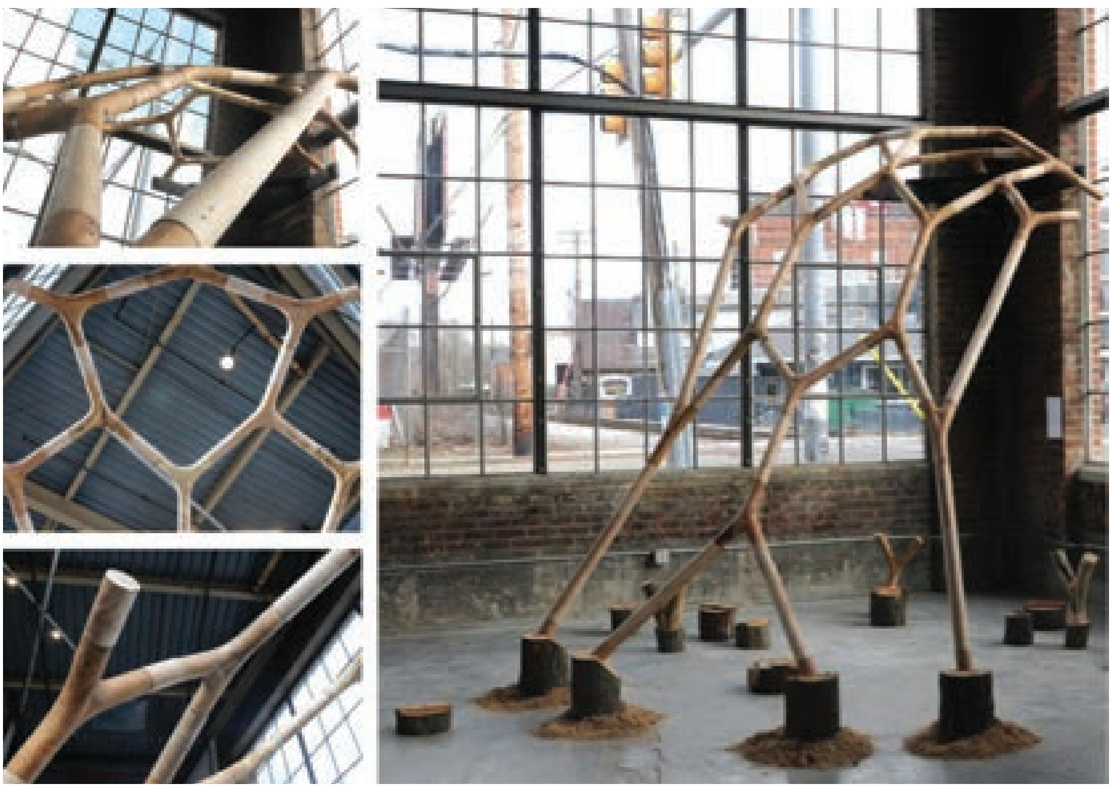


Figure 14: Details of the dome assembly.

produce the prototype, only one-third of the designed dome was fabricated and erected. Although the erection of the shell took less than one day, the production of the joints through the process described above proceeded at a rate of about two per day. In the prototype, because disassembly was necessary, the pegged joints were screwed and not glued, which compromised the strength. This resulted is some joint slippage during erection (fig. 14).

5 CONCLUSION AND FUTURE WORK

The concept of repurposing the waste product of tree crotches did succeed, and a section of a dome was fabricated. The computational workflow proposed in this research effectively addressed the issues in form finding and inventory assignment, while also providing performance feedback and necessary fabrication data, which is directly used for the fabrication process; this workflow can be easily adapted to respond to different structural typologies. The design exploration process with ParaGen helped the team to study and analyze the design space toward choosing the most desirable solution based on aesthetics, performance metrics, budget, and fabrication requirements.

The full-scale prototype erection process was successfully done in a day. Problems encountered include the time required to scan and mill each piece. Also, the grading of the wood was a concern. One approach would be to pre-shape pieces with a band saw, thus exposing potential defects in the wood, reducing milling time, and expediting drying. After a few weeks standing in the dry indoor environment, some cracking of the crotch pieces was also observed. As a means of crack prevention, tests are currently being run using polyethylene glycol (PEG) injection under pressure. Also, kiln drying techniques using controlled pressure, temperature, and humidity to dry the lumber without cracking are being pursued.

Figure 15: The constructed prototype of one-third of the full dome.

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