Material Resistance / Procedural Resistance

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> "Resistances, those facts that stand in the way of the will" – Richard Senet

In 1505 Michelangelo was summoned to Rome to design the Tomb of Pope Julius II. Originally intended for Saint Peter's Basilica and consisting of nearly 40 freestanding figures, the version completed in 1547 was a ghost of the original proposal. Following Julius' death in 1513, numerous funding reductions and competing demands of Michelangelo's time led him to permanently stop work in 1523 on what were to be a series of enslaved figures that would form the base of the tomb. As a result, six slave figures were left unfinished and stand as a physical record of Michelangelo's process. [figure 1] While the sculptures provide insight to the techniques of the day, perhaps more striking, is the resulting imagery. It is one in which the slaves struggle to break free from not only their torments, but also the very stones from which they are formed. The juxtaposition between identifiable human forms and rough hewn stone animate the figures in such a way to suggest the slaves coming into a state of existence out of the stone. Michelangelo speaks to this as he describes his process as one that does not sculpt figures into stone but rather liberates them.

Sculpting natural materials is an inherently precarious proposition. The material characteristics that enrich the object under formation are the very things that present challenges to those working the material. In the case of Michelangelo's enslaved figures, one must have the skill to read and navigate the veins and pockets within the stone to ensure material integrity is preserved and vision achieved. In his seminal book, The Nature and Art of Workmanship, David Pye refers to this negotiation as a workmanship of risk. In contrast to a workmanship of certainty, in which "the result is predetermined and unalterable once production has begun" [1] risk relies upon acquired knowledge to address problems as they are uncovered. The stone quite literally, presents resistance to the act of chiseling. The skill of the individual working the material is directly related to their ability to work through the material resistance. This is not the result of shear will, but rather an opportunistic response to those things uncovered. It is a form of enlightened improvisation. While, in the case of the enslaved figures, the risk is tethered to materiality, risk can also manifest through the tools and techniques employed. In essence, Pye's distinctions between certainty and risk speak to the very relationship between design and realization. This is inherently a negotiation between will and feasibility.

In the sphere of architecture, this relationship has, by necessity, typically been top down with design largely determined prior to fabrication or construction. This is understandable, as the act of building is often a unique, complex assembly of a multitude of components and materials. [2] In light of the inherent costs, those with a vested financial interest in the process must mitigate risks and keep surprises to a minimum. As a result, there is an implicit bias towards resolution prior to fabrication and often, reliance upon low risk conventions.

Increasingly advanced design, simulation and management tools such as a building information model-

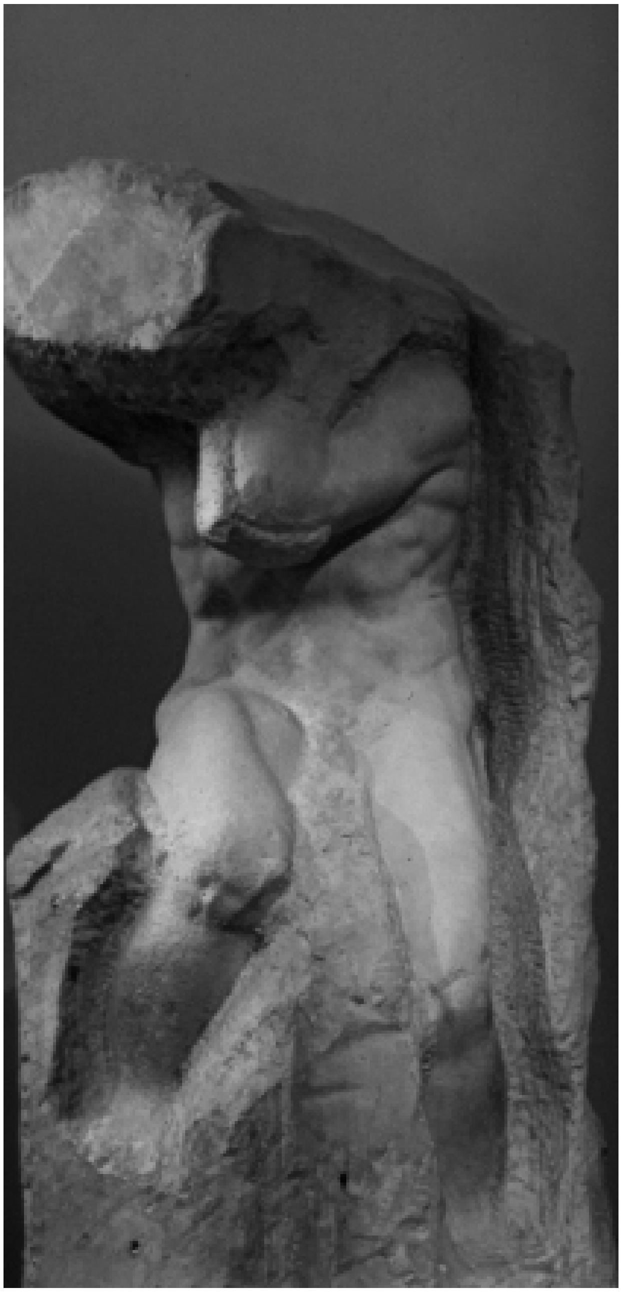


figure 1: Michelangelo Slave

ing software promise an even greater degree of design resolution and efficiency before the commencement of construction. In the context of practice, the benefits of such tools have been made clear.[3] Streamlined information sharing and the ability to "see" every piece of the building are changing the ways architects collaborate and the extent to which a building is understood prior to construction. While this process remains novel in the construction industry, it has been utilized for quite some time in the aerospace industry as an attempt to remove all uncertainties prior to the costly endeavor of fabrication. [4] While an airplane and a larger building may share complexity, most buildings are typically one off custom constructions with unique material conditions. As a result, the design processes are implicitly distinct. While the data may facilitate a streamlined process, and in the case of the airplane, lead to highly optimized engineering, it alone does not ensure a great or even good building by standards beyond measure. Ideally, in the case of architecture, the data of the virtual model is parsed through the expertise of the architect and a growing list of specialists. Here, the distance between virtual design data and material reality is compressed through an architect's material sensibility, borne out of observation and engagement of material conditions and their associated limits. A classic example is that of precision. While the 1:1 modeling environment of design software affords absolute dimensional precision, only the architect versed in material reality will transpose intrinsic material characteristics such as dimensional variability or material movement to the virtual simulation. As such, the virtual design data is most useful when understood in relationship to the physical conditions it represents. Otherwise the data is relegated to a graphic, devoid of any intelligence.

Digital fabrication technologies are increasingly utilized to realize novel form and to achieve greater efficiency within the construction process. They have been heralded as processes that redefine traditional systems of communication while empowering those with access to the virtual building information.[5] Herein lies the paradox of contemporary design and construction. While use of software in the design process may in the past have distanced the designer from the messiness of physical reality, emerging connections between software and hardware tools are increasingly extending the hand and intent of the designer deeper into the process of fabrication. Digital design and material processing have reinvigorated a material discourse and currently offer potent connections to architecture's physical presence. Within the academy, the promise of such processes is a material awakening or, as Richard Sennett refers to, a material consciousness [6] whereby one develops an interest in physical things one can change. This active engagement of materiality prompts a reassessment of virtual design data that, for the young architect, are often devoid of material characteristics. The result is a materiality infused with the characteristics of its digital processing. [7] Here the presence of the digital is evident through geometric complexity, control and fidelity rather than a singular formal or aesthetic representation of digitally derived form.

Since its inception, the architectural design process has relied upon various forms of representations, simulations or proxies.[8] The sheer size and complexity of buildings does not allow the degree of full-scale studies common in other design disciplines. The design of a product, such as a chair typically affords a degree of immediacy and direct material investigation not found in architecture. The evolution of the Eames shell chairs, beginning with plywood, evolving into sheet metal and culminating with fiberglass speak to the feedback loop afforded through direct material engagement and testing.

While mockups or material studies may be executed prior to construction, they generally have served as a test of prototypical conditions or occasionally a limited palette of options. Their execution is necessary to the process of construction but typically has not served as the catalyst for design advancement. As abstractions, material proxies may represent a limited range of material characteristics, but they often serve as a rendering of form rather than a tool to elicit fundamental material properties. As is the case with virtual design data, their utilization relies upon ones ability to project materiality into an otherwise inert form. This again, relies upon a sophisticated design process that is conscious of materiality.

Over the past decade, digital fabrication tools have grown exponentially in presence throughout the academy. The result has been a veritable arms race amongst institutions intent on projecting themselves as cutting edge. The transformative potential of these tools is clear and the opportunities to explore complex physical form have been well documented, however the material focus of such processes is very much emerging. The focus of our investigations resides in the pedagogical impact of the process, specifically the value of a student's understanding that materials and processes present resistance and limits that inform the design process. It is in this space between intent and actualization that the student discovers they must reconcile their will with what they can achieve. Limits are discovered rather than predefined within the software.

Digital fabrication tools can be generally understood as task centric and loosely categorized as either subtractive or additive processes. Contrary to this condition, the industrial robot is not designed or biased toward a specific task or method of fabrication. Industrial robots are found in food processing, material handling and heavy manufacturing. They have a long history and significant presence in mass production settings such as automotive assembly lines and have typically been implemented as a measure to streamline production, increase productivity and improve safety. In this context, the robot has been principally utilized for highly repetitive tasks. Historically, the time and associated cost to program the robot was outweighed by the productivity gains once the machine was operating. Other than occasional maintenance, the robot could predictably cycle the predefined task into the foreseeable future. The articulating arm industrial robot differs from most other digital fabrication tools in that it, in and of itself, does not bias a particular method of fabrication. The tool on the end of robot dictates what the machine can or can't do. While industrial robots have grown in manufacturing sectors over the past 30 years, their use in the construction industry has been marginalized due to high implementation costs, operational complexity and labor concerns. While current utilization has been primarily limited to the academy, decreasing equipment costs and significant developments in human machine interaction suggest an untapped potential for industrial robots within the construction industry.

An ABB IRB 4400 industrial robot was acquired by the digital fabrication lab [dFAB] in the School of Architecture at Carnegie Mellon University as a supplement to existing task specific digital fabrication tools. The IRB 4400 is a six-axis articulating arm with a reach of approximately 2 meters and an end-of-arm load rating of 40kg [figure 2]. The robot work-cell was further outfitted with a rotary table that acts as a seventh axis, providing additional flexibility and reach for the robot. The first, of what will be a series of courses taught to undergraduate architecture students, focused on the utilization of industrial robots in the field of architecture. The intent being that each course will be structured around a specific type of fabrication and architectural condition. A guiding principle for the research is a focus on the material and tectonic potential through the process. Subtractive processes, specifically multi-axis milling served as the

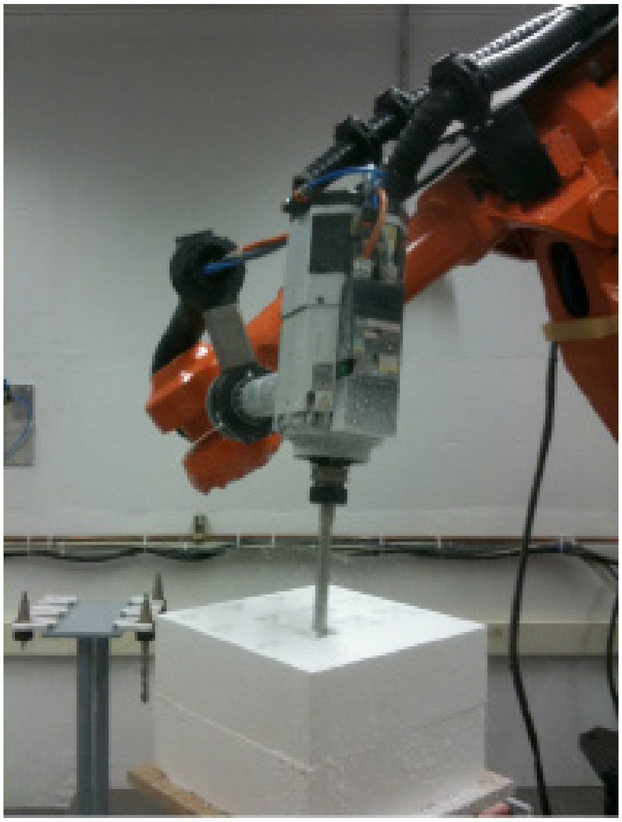


figure 2: industrial robot with milling tool

mechanical process, while the architectural screen served as the condition. To this end, the robot was configured as a multi-axis subtractive tool with a high-speed cutting spindle mounted on the end of the robot arm, allowing for the cutting of foams, plastics and woods.

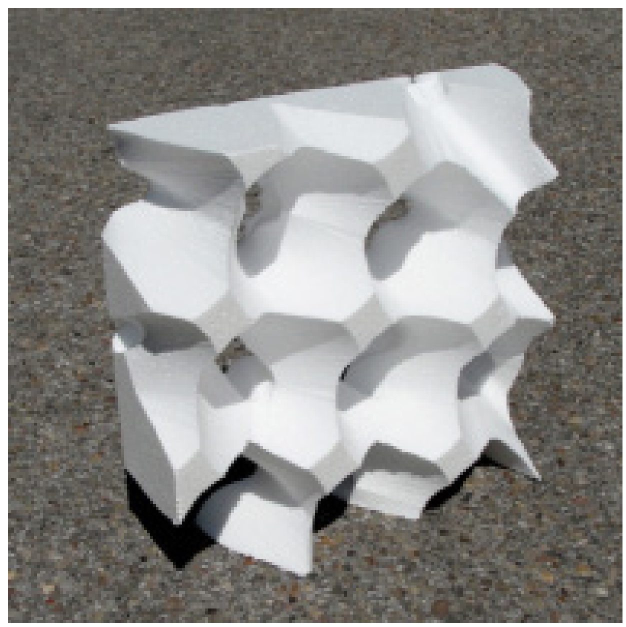
Significant differences exist between a milling robot, such as the IRB 4400 and traditional subtractive CNC equipment. Whereas most subtractive CNC equipment operates about three axis and tends to limit milling to one surface at a time, the industrial robot allows a substantially greater degree of carving options such as undercutting, where the axis angle of the cutting tool varies from what is traditionally fixed at ninety degrees on three-axis CNC equipment. While industrial robots offer a significant degree of task and motion flexibility, they do not have the same degree of stiffness found with traditional subtractive CNC equipment such as milling machines or routers. As a result, the palette of potential robot carved materials tends to be limited to softer materials such as foams and woods. While this limited material palette could be used to focus the material component of the initial experiments, the seemingly limitless milling flexibility found with the robot could easily become unproductive and an excuse for a lack of critical engagement with the process. As is the case with most educational pursuits and studio projects, increasing options does not ensure greater pedagogical effectiveness or project complexity. To the contrary, constraints are enabling devices that can serve as catalysts for the design process. The distinctions between opportunity and distraction are subtle, contextual and often challenging for undergraduate students to assess. Therefore, the methods and range of robot motion was focused to ensure a depth of engagement on the student's behalf.

figure 3: material / process study

The architectural screen both separates and connects the spaces and individuals on either side. As a surface, wall or object, the screen is defined by the relationships between material and void, across the screen and through its thickness. Here, one's attention vacillates between the screen, its implicit boundary and the resulting effects. Screening can be achieved through a permeable surface or object, or can be the result of a spatially loose assembly of components that leads to porosity at the joint. These distinctions speak to a geometric and tectonic logic that is potentially reliant upon subtractive or additive methods. The porous nature of the screen implies a degree of correlation between its two faces. This can be reciprocal or the resultant intersection between two distinct surface conditions and geometric systems. Initial investigations probed these conditions through the development of complimentary, yet non-intersecting geometric systems and surfaces. The translucent properties of Corian were exploited to reveal a superimposition of the two systems. [figure 3] While the surface denied a literal visual connection, the relationship between surface geometry and tool trace were revealed when backlit. Slight variations in the sheet thickness resulted in a broad range of translucency throughout the ½" sheet thickness and spoken to the latent potential within a relatively thin piece of material.

As the investigation proceeded, the influence of materiality shifted in light of the necessity to work with distinctly different materials on the robot. The maximization of thinness, associated with the use of Corian shifted to the maximization of thickness offered through the use of foams. Furthermore, the affordability and speed with which the robot mills foam promoted an iterative design process. The additional thickness found with foam, allowed for the development of spatial transformations through the thickness of the material. A focus on surfaces that were previously reciprocal yet non-intersecting evolved into a focus on the relationship between surfaces and perforation.

While the industrial robot offers a higher degree of milling flexibility, the considerations for how the machine will remove the material are far greater than found with traditional three-axis machines. Industrial robots, such as the IRB4400 typically have more than one robot arm orientation for any given point in space. Robot orientation can be resolved by the robot controller software in real-time or planned in conjunction with the generation of robot instructions. If, robot orientation is resolved by the controller, unpredictable robot motion may occur, leading to collisions between the robot and the milled material or any supporting fixtures or jigs. In light of these added levels of planning, initial use of the robot began as relatively simple operations and grew in complexity to match the learning curve. This was manifest through subtractive studies based on distinct collections of points, lines and surfaces and began with drilling and ended with mult-aixs milling. [figure 4] In milling operations,



figures 4 and 5: multi-axis milling

material is typically carved through a progressive engagement of the bit tip with material. The added freedom of the robot offers alternative methods for subtractive milling. As robot milling progressed, attention focused on use of the length and edge of the bit as the cutting surface. This type of milling, referred to as swarfing, utilized the ability of the robot to tilt the bit about the z-axis and subsequently allowed for a substantial degree of geometric transformation along the z-axis. [figure 5]

figure 6: multi-axis milling detail

The axis of the bit acted as a rule line and could be traced through the material to develop a ruled surface. This method of material subtraction served as the framework for all subsequent student investigations. The thickened perforations of the surface were developed as lofted surfaces that consisted of two loft curves, ensuring a ruled surface. The relationship between bit tilt (about the z-axis) and resulting maximum achievable milling depth operated as a parameter to guide the development of surface geometry. Closed boundary curve geometry was created at minimum and maximum levels along the z-axis, corresponding to the thickness of foam stock. Tool-paths were calculated as straight lines between an equal number of points along both curves. Robot motion was calculated through each of the rule lines, resulting in a smooth surface. The geometry and resulting voids achieved through this method of milling could be transformative, allowing for spatially distinct or intertwined voids. [figure 6] While use of expanded styrene foam [EPS] in these investigations allowed for quick, rather inexpensive iterations of a thick material, it offered few compelling material properties beyond its insulation capacity and extreme light weight. Ironically, the closest form of resistance levied through the use of EPS was manifest through its fragility and relatively low resolution. Foam, in and of itself, was not sufficient as the final implemented material.

As work proceeded, there was a shared sense that materiality and the methods for processing material be explicitly addressed and expressed. This ambition moved the conversation of materiality beyond that of a proxy or simulation in which the immediacy of material characteristics may be sacrificed, into the realm of specific material properties and limitations. The pedagogical potential of the project lie in the ability to serve as a counterpoint to design studios in which the proxy is an abstraction device. In the context of this project, a meaningful process must provide students with the immediacy of material engagement, stripped bare of the proxy. The understanding of material and process transformed from a single step subtractive workflow in which foam served as the proxy, into a multi-step process in which foam was utilized as a negative mold for subsequent casting. [figure 7] The distinctions between casting and carving, particularly in the context of Pye's negotiation of risk are significant. The 'unknown' variables embedded deep within Michelangelo's marble block are displaced in casting processes. When executed properly, the material is

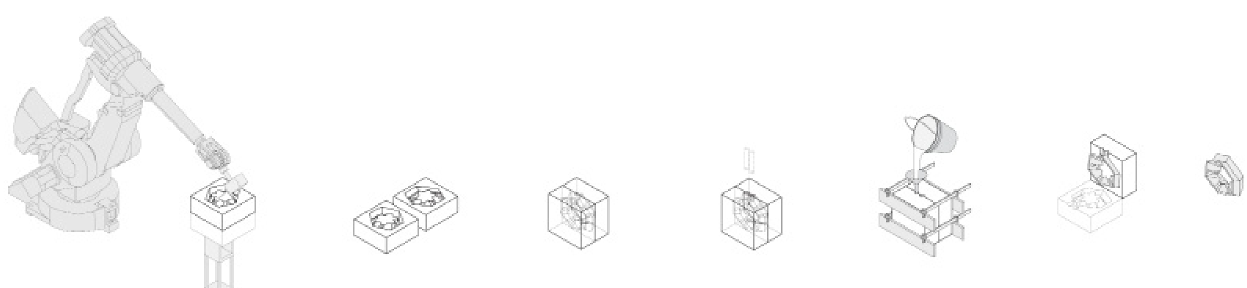


figure 7: robot milling / casting workflow

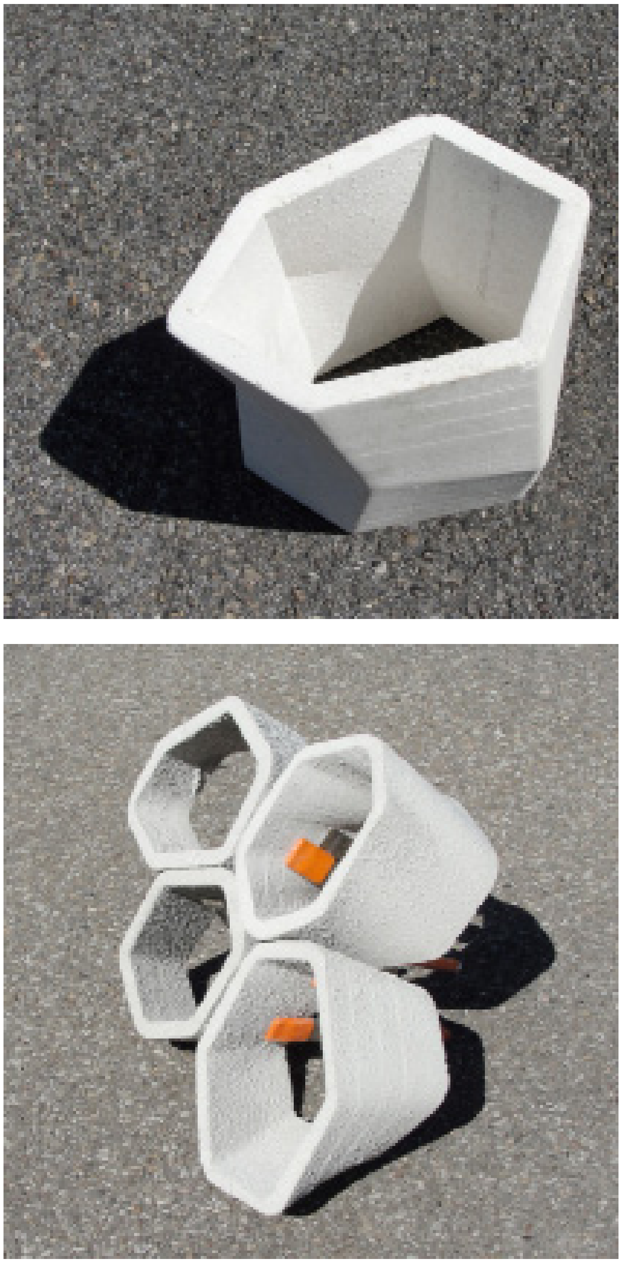


figure 8 and 9: cast components

quite consistent, even with the use of aggregates. Resistance is manifest first and foremost through the constraints found within the process.

The potential for a thick, spatially varied screen was retained while the completed screen could be manifest through a range of cast materials. Casting materials were limited to those that were readily available and cost effective. High strength cement and fast setting plaster were deemed most appro-

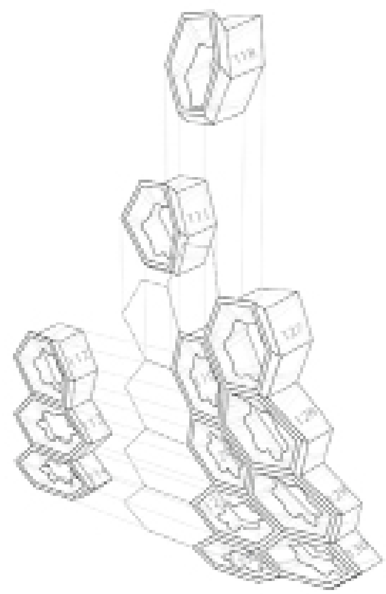


figure 10: nested components detail

priate for casting plasticity and structural viability. Initial, tube-like castings relied upon simple one-part molds and consisted of a ¾" thick ruled surface as the spatial envelope and structural component wall. The trace of the bit was inverted and now as solid, was manifest through the cast component wall. Each casting contained a single void that was an offset of a perimeter hexagon and could be nested as a cellular system of components. [figure 8 and 9] While the physical strength of the initial castings was promising, they were deemed unsatisfactory due to the fact reliable stacking and nesting could not be achieved without the use of an adhesive or mechanical fastener. Ideally, the sys-

figure 11: nested components

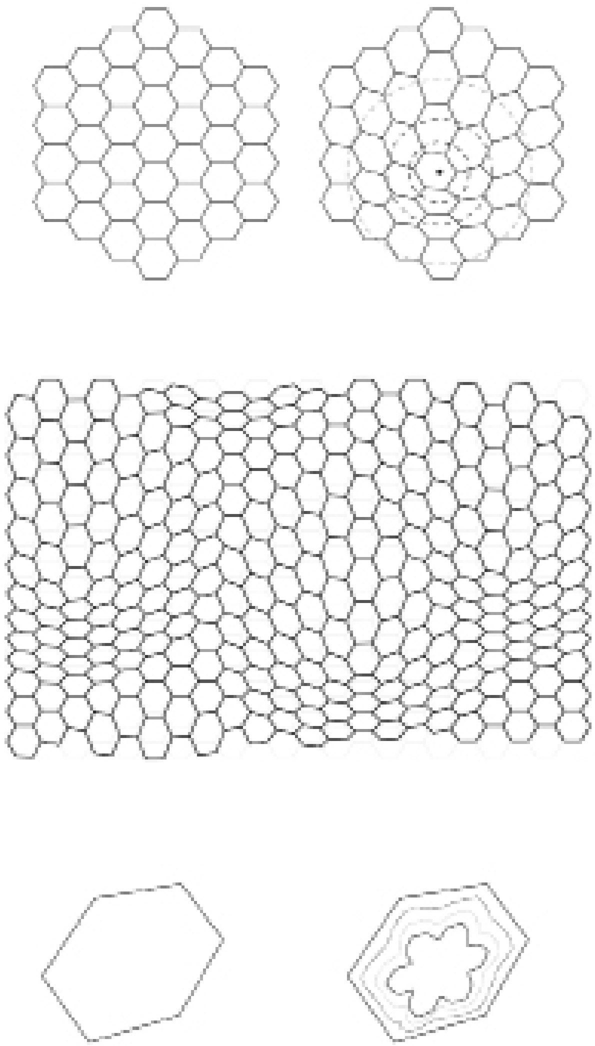


figure 12: geometric principles

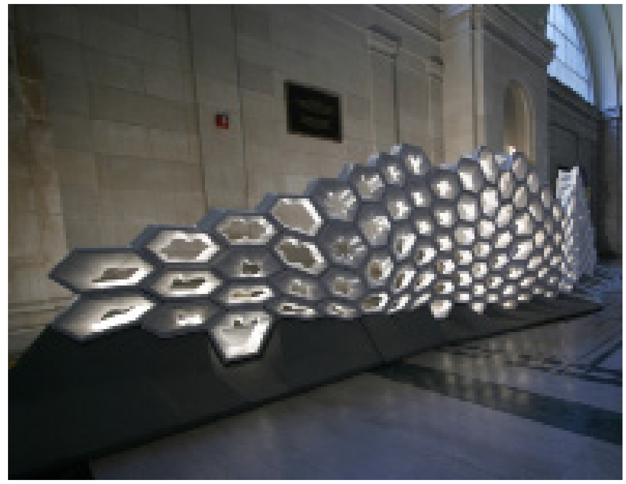


figure 13: completed component wall

tem of components should be dry stackable, yet capable of producing a broad array of internal voids in response to particular performance criteria such as light transmission and airflow. By addressing exterior and interior surface geometry independently, rather than as offsets of the same surface, component nesting (exterior surface) and performative potential (interior surface) could be refined simultaneously under distinct criteria. A system of "ridges" and "valleys" along the outer surface allowed components to reliably stack and nest without a secondary means of attachment, [figure 10] Furthermore, two-part molds allowed a greater degree of geometric transformation and facilitated a significantly thicker screen. An extruded hexagonal tiling system acted as the geometric basis for screen geometry and provided a substantial degree of rigidity through the packed nature of the pattern. [figure 11] Transformation points were subsequently placed across both sides of the surface and served as the basis for algorithmic transformations between outer and inner surfaces. [figure 12] As these transformations diffused across the tiled geometry, size, shape and directionality of openings adjusted in conjunction with a change in distance from the transformation points. The result is a dynamic range of spatial conditions that shift as one moves along the wall. [figure 13]

The physical manifestation of the screen resists simple associations and stands in contrast to typical perforated conditions. The screen is at once materially substantial and rigid yet highly porous. The pattern of openings abides by a strict set of interrelated geometric transformations but is comprised of over 150 unique components. While the geometries are controlled and speak to their digital origins, the surfaces are decidedly textured and evocative of the multiple processes undertaken. The smoothness and seamlessness of digitally generated and fabricated surfaces is subverted, resulting in a material logic that evokes both the machine and the hand. As such, materiality is a manifestation of both analog and digital processes. The resistance presented by processes and materials necessitated recalibrations of intent and resulted in a complex set of translations between geometric systems, digital and analog processes and material characteristics. The resulting construction offers a material and tectonic language that is both reliant upon and evocative of emerging fabrication processes, while also referencing longstanding methods of material use and construction.

ENDNOTES

1. David Pye, *The Nature and Art of Workmanship*, (Cambridge University Press, 1988), 4-8.
2. Stephen Kieran and James Timberlake, *Refabricating Architecture*, (McGraw-Hill, 2004).
3. Ibid., 25-27.
4. Ibid., 79-84.
5. Branko Kolarevic, *Architecture in the Digital Age: Design and Manufacturing*, (Spon Press, 2003), 29-54.
6. Richard Sennet, *The Craftsman*, (New York: Yale University Press), 119-146.
7. Gramazio and Kohler, *Digital Materiality in Architecture*, (C Baden: Lars Muller Publishers 2008), 7-11.
8. James Ackerman and Wolfgang Jung, *Conventions of Architectural Drawing: Representation and Misrepresentation,* (Harvard University GSD, 2001), 8-36.