# FABRIC-FORMED ROBOTIC FACADES

## The robotic positioning of fabric formwork


**Joseph Sarafian**
**Perkins + Will**
**josephsarafian@gmail.com**

**Ron Culver**
**Culver Architects**
**ron@culverarchitects.com**



### ABSTRACT

The method proposed is derived from a parametric workflow that employs the precision of 6-axis robots and the flexibility of fabric to rapidly create a fabric formwork. Complex geometries can be cost-effectively executed in a precise digital to physical workflow.

Conventional concrete casting techniques are labor-intensive, material-intensive and inaccurate, making them unsustainable and inefficient for facades with variable, organic geometries. As a result, parametric design must be rationalized and reduced to meet the requirements of conventional construction techniques.

After consideration of some historical and commercial antecedents as well as current applications, a six-axis system is delineated using identical flexible fabric sleeves. Custom built end effectors are positioned by a pair of programmed six-axis industrial robots to capture and stretch the sleeves into positions based on locations extracted from a 3D model. An intricate series of unique objects are composed as dictated by the design. Custom, large-scale assemblies are proposed for manufacture to meet the specific project needs of load-bearing facades and glazing modules.



### KEYWORDS

Robotics, precast facade, parametric workflows, fabric – textiles, design optimization


### INTRODUCTION

The innovations of mid-century modernism are giving way to a technological paradigm shift in design. Values of restraint are being replaced by the geometric exuberance of Parametricism. Variations in building form and in product design are leading to the emergence of mass customization.

Nevertheless, while architects are increasingly designing complex geometry in building facades, those designs are typically unrealized due to technological and economic constraints. Traditional rigid formwork has distinct disadvantages for casting complex forms from concrete. Likewise, time-intensive computer numerically controlled milling and subsequent form assembly fail to adequately produce the compound shapes and undercuts required of complex geometries. Moreover, the casting of multiple parts with even slight variation is typically cost-prohibitive.

The system portrayed below facilitates realization of complex parametric geometry from unique cast masonry components. Robotically controlled, flexible fabric formwork becomes the means of rapid, replicable and economical production where geometrically complex concrete objects can be accurately fabricated with practically infinite organic variation and texture.

## BACKGROUND

### *"MASS CUSTOMIZATION" REPLACES MASS PRODUCTION*

Just as Fordism facilitated mass production, rapid prototyping has lead to a second industrial revolution: mass customization. The ability to create repetition through the engineered efficiencies of scientific management propelled Henry Ford's production line for automobile manufacturing and has provided a model for all other subsequent assembly line manufacturing processes. Standardization and efficiency were inherent in this cost model as the entire process was calibrated to the production of one singular design. (McLeod, 1983) However, with the emergence of CAD/CAM (computer aided design & computer aided manufacturing), such batch production is no longer the only means of creating a cost-efficient product. Digital designs are translated to physical product by means of tool-path commands, rather than schematic drawings that require human interpretation. Each unique command (g-code) is written such that the CNC (computer numerical control) mill, laser cutter, 3D printer, or robot arm can instantly position itself to the necessary coordinates for fabrication. Thus, the need for an elaborate production and assembly line is eliminated, facilitating the fabrication of unique parts. With the proper front-end user interface, individuals can have their products custom-built without redesigning an entire production line. Many companies are already reaping the benefits of exploiting mass customization through rapid prototyping. The following examples highlight the advantages of mass customization and rapid prototyping and are precedents for the work presented in this paper.

Nervous System is a jewelry and clothing design studio that uses generative algorithms to create products based on design principles inherent in nature. Founders Jessica Rosenkrantz and Jesse Louis-Rosenberg also created a user interface that turns shoppers into designers by allowing them to modify Nervous System's parametric geometry products through various controls and sliders. Customers see their modifications rendered in real-time 3D visualizations (Fig. 1). Once a purchase is made, a wax negative is then 3D printed, followed by a cast metal poured into the form, and the jewelry thus produced is shipped. (Rosenkrantz et. al., 2016)

ShopFloor®, by Zahner is a web-based app that enables users to create unique steel designs using three pre-set rapid prototyping processes. "Cloudwall", "Imagewall", and "Aluminum Bench" are three design families with editable parameters such as size, perforation, and material type that allows users to toggle their preferences for customizable metal walls or furniture assemblies that are manufactured and shipped to their location. (Fig. 2) (Zahner, 2016)

Neither of the aforementioned companies allow for unlimited design freedom, rather they leverage their designs by allowing users to control selections of discrete variables. The robot-controlled casting system proposed in this paper is yet another paradigm to facilitate variability within constraints using a new kind of rapid prototyping. The robot, however, is more than the next 3D printer as it has more than one output technique. As a tool it is more similar to the hammer, making possible a myriad of uses without preference to a single construction methodology. Forming concrete is but one output in the field of possibilities, including milling, extruding, carving, and welding, among others.


*Figure 1: The user interface featuring customizable jewelry by Nervous System*

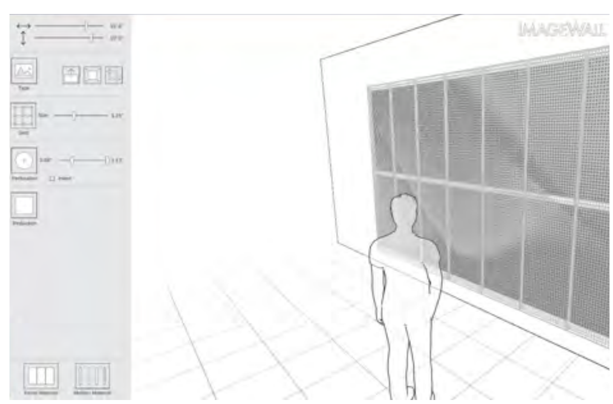


*Figure 2: The user interface for "Shop Floor" by Zahner*

### *THE BROAD MUSEUM VS. THE AMERICAN CEMENT BUILDING*

Two Los Angeles structures are emblematic of how the implicit variations of parametric design are transforming the simple repetitive forms of modernism. The repetition of braced concrete in the American Cement Building is one of the purest expressions of the 20th century where form and function combined in tectonic synchrony, while the Broad Museum by Diller Scofidio + Renfro provides a 21st century equivalent demonstrating variable parametric forms.

The thirteen story American Cement Corporation's building on Wilshire Boulevard was designed by DMJM in 1964. DMJM showcased the various expressions of concrete, from the cantilevered entry overhang, to the sculptural twisting columns in the parking lot, to the facade itself, where precast concrete X-braces form a lattice of support structure (Fig. 3). This bracing eliminates the need for interior columns, creating unimpeded spaces with monumental views of the city. Yet human scale was carefully considered in each 11' tall precast module. Each weighs two tons and features a curvaceous subtraction, precisely where a person's line of sight occurs, allowing for increased angles of vision. Each element of the building provides both a functional (often structural) purpose and an aesthetic one.

Despite its structural attributes, the cast components of the American Cement Building are repetitive. While demonstrating variations in dimension of similar form, the Broad Museum panels were value engineered down to a handful of sizes so the economy of scale of 2500 panels fabricated and installed reduced cost. With the American Cement Building as a possible precedent to The Broad Museum early designs even featured a structurally loadbearing exoskeleton (Fig. 4). Unfortunately, once the costs of fabricating a structural facade that still permitted an opening at ground level were calculated, that exoskeleton concept was scrapped. Instead, the Broad's essentially decorative facade of Glass Fiber Reinforced Concrete (GFRC) by Germany's Seele conceals a completely unrelated structure underneath. (Hawthorne, 2015)

The Broad Museum's significant departure from the American Cement Building marks a snapshot of the current state of architecture. The once dominant modernist synergy of structure and aesthetics has devolved into an architecture of segregation with the increasingly divergent design and construction industries. Previous desires for structural feats are no longer on the agenda for architects and engineers; separation of expertise has created divisions of labor, preventing the desire for and delivery of such feats. The adoption of expense-reducing robotic fabric formwork proposed by this paper into the fabrication process could initiate greater exploration of geometric variation.

*Figure 3: The American Cement Building by DMJM*

*Figure 4: The Broad Museum by Diller Scofidio+ Renfro*

### *PARAMETRICISM VS. MODERNISM*

As the modernist values of reduction and simplicity are replaced by the hyper-saturated information era, new ideals and techniques are emerging. Patrik Schumacher coined Parametricism as a term in 2008 to represent a trend toward parametric design tools happening within architecture. Parameters are selected as the impetus for an encoded chain reaction of modeled outcomes. For example, a network of load path calculations can drive the size of structural members, performing millions of calculations in order to optimize a unique solution. This new design methodology represents a correlation of subsystems that react, recalculate, and redesign in real-time. Rather than being a sequential series of design decisions that result in an inevitable conclusion and built form, parametric design allows for a feedback loop of digital and physical parameters to influence each other. Historically, design and fabrication have always been separate endeavors. (Schumacher, 2009)

Traditional fabrication techniques have yet to adapt to the fluid manipulation required by Parametricism without incurring great costs and greater erosion of design intent. Facade design demonstrates this pattern of parametric innovation followed by massive compromise upon construction in the built environment. Attempts to rationalize compound deformed geometries with existing commercial facade technologies limits the realization of complex designs, increases reliance on secondary structural and envelope systems, dampens thermal and ventilation capabilities, and is hampered by expensive and time-consuming construction methodologies.

### *ROBOTIC CONSTRUCTION: THE FULFILLMENT OF PARAMETRICISM*

As discussed above, the 6-Axis robotic fabrication process dramatically increases realization of parametric forms once thought of as merely digital experiments by limiting their cost and increasing their accuracy. Robots in architecture will transform not just the forms themselves but also the process of constructing buildings, potentially limiting the cost of erroneous human interpretation in the construction process. With a robotic fabrication, digital commands translate the design, avoiding traditional information loss.

Architecture as a profession is increasingly eliminating contractor interpretation and sending information directly from the computer to the field. This trend creates savings in the reduction of setup time and errors with their inherent delays that consistently plague projects. Traditional formwork is derived as the negative of the desired mass, requiring wood or other static formwork production. The most relevant antecedent to fabric formwork is CNC milled EPS foam. Once the desired shape is modeled digitally, the negative form is created then subdivided such that it can be milled using a 5-axis CNC mill. After a rough cut and final cut, the milled foam must be assembled and reinforced. This process is time consuming and error prone in each of the steps. Alternatively, casting with fabric only requires 3D modeling the desired shape, sewing the desired shape out of fabric, positioning it with robots, and then casting. It creates a repeatable system of automation from which many different shapes can be derived from a single fabric form.

Many companies and professionals are already demonstrating these robotic fabrication advances worldwide. Among them are Branch Technology and the University of Stuttgart. Branch Technology has created new techniques to 3D print carbon-fiber reinforced plastic with a robot, creating lattices of wall structures inspired by nature’s reduction of material (Fig. 5) to form the core of its proprietary wall system. When insulation foam is sprayed within the matrix to prevent buckling, a 1.7 lb block of their lattice supports 6,000 lbs without failure.

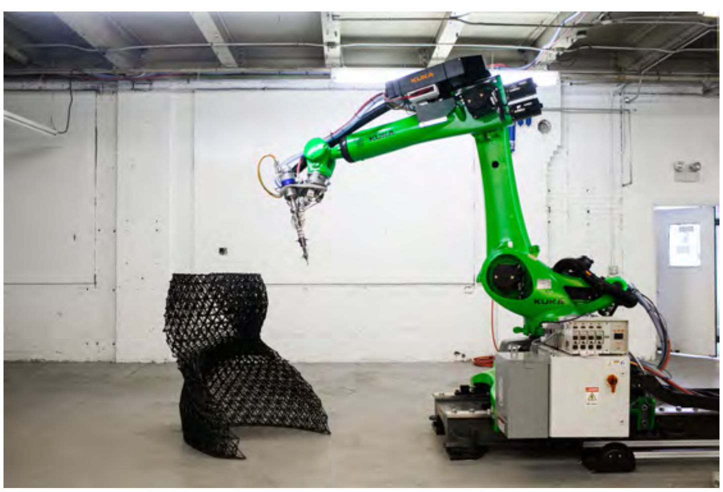

*Figure 5: 3D Printed Carbon Fiber-infused plastic from Branch Technology*

Achim Menges of the University of Stuttgart in Germany has built a number of pavilions using robots in ways foreign to building construction, but reminiscent of construction found in nature. His design of the ICD/ITKE Research Pavilion 2014-15 takes inspiration how a water spider uses an air bubble to construct its habitat around itself. The pavilion concept starts with inflating a pneumatic pillow. A robot placed in the center then lays and hardens strands of carbon fiber and resin along the inside, creating a hardened shell when the pillow is deflated. The pavilion size and shape are therefore a resultant of the robot's work area, demonstrating the new forms emerging out of robotic construction. This design was not simply a translation from 3D to the built world, it required a constant feedback loop, measuring its environment to accommodate for deflections in the pillow due to air pressure that were unanticipated in the digital file. (Menges, Achim 2014-15)

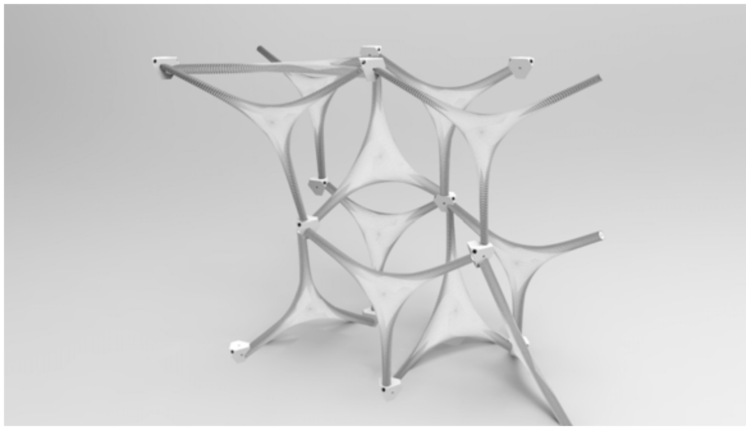

*Figure 6: Digital rendering of composition prior to casting*

## METHOD

### *PROTOTYPE*

The first prototype, Fabric Forms, (Fig. 6) exhibits the robotic casting process delineated below. This built proof of concept for a self-supporting structure consists of 13 individual pieces of 1:12 scale and stands 32" (81.3 cm) tall (Fig. 7). Constrained to three controlled endpoints, each Y-shaped component is derived from two robots and a stationary fill point positioning each arm of the sleeve (Fig. 8). Additional robots and/or customized, project-specific robotic assemblies can enable any theoretical shape.

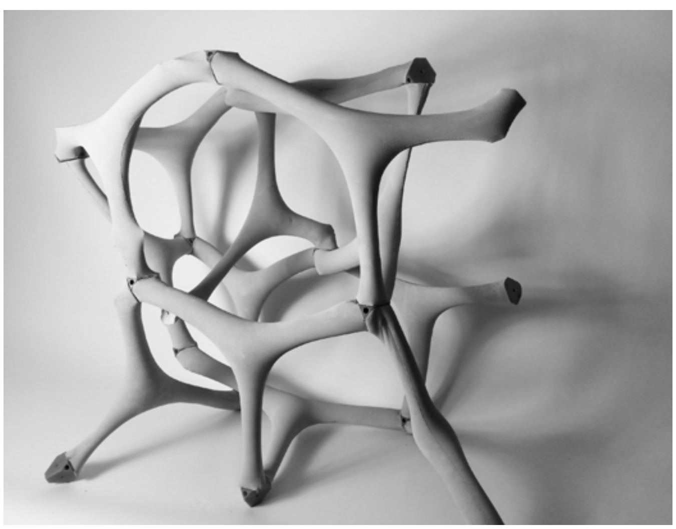

*Figure 7: Fabric Forms composition proof of concept*

*Figure 8: Fabric Forms Concrete casting with Kuka robots at UCLA Suprastudio*

### *DIGITAL WORKFLOW*

A feedback loop is achieved through the Finite Element Method (FEM), which "uses subdivision of a whole problem domain into simpler parts, called finite elements" [Reddy, 2005]. By calculating the characteristics of the smaller elements, comprehension of the whole can be achieved. FEM starts with a 3D composition and analyzes the loads on discrete elements. Each element is then analyzed for structural stability to understand the performance of the whole. Using Karamba for Grasshopper3D, gravitational load paths that act on each member in the system are calculated to understand their behavior prior to fabrication. A load model is then generated which can output cross section sizes for members, a displacement simulation, and axial stress values for each unique Y-shaped element (Fig. 9). Elements can be regenerated to achieve higher or lower network density, refined to meet the structural and performance criteria and re-generated again. Once the components are analyzed, their endpoints are determined and optimized. These coordinates are sent to the robotic arms, which translate the Euclidean coordinates into physical space.

### *ROBOTIC ASSEMBLY*

An armature capable of anchoring one cast object is installed between two 6-axis robotic arms. One fabric limb is affixed to each robotic arm and the remaining limb is affixed to the top of the armature (Fig. 10). This top limb is attached so that it can also serve as the cement filling point with a retaining cutout that constrains the end to the shape of the nodal connector. After filling, the open end is capped with an acrylic form with inserted nut attached for bolting (Fig. 11).

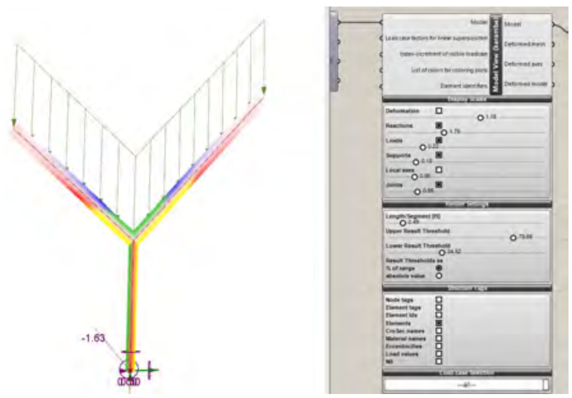

*Figure 9: Structural analysis using Karamba3D*

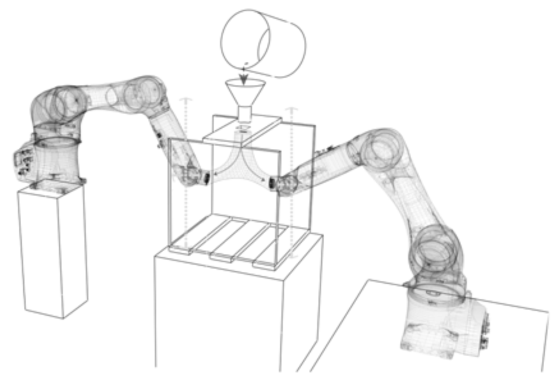

*Figure 10: Typical robotic casting arrangement*

Each of the side limbs similarly has an end-arm tool in the shape of the matrix connector. It includes an insert nut attached that allows the fabric to be tensioned prior to pouring the cement mixture. The tools allow secure and rapid attachment/removal from the robotic arms for more consistent casting.

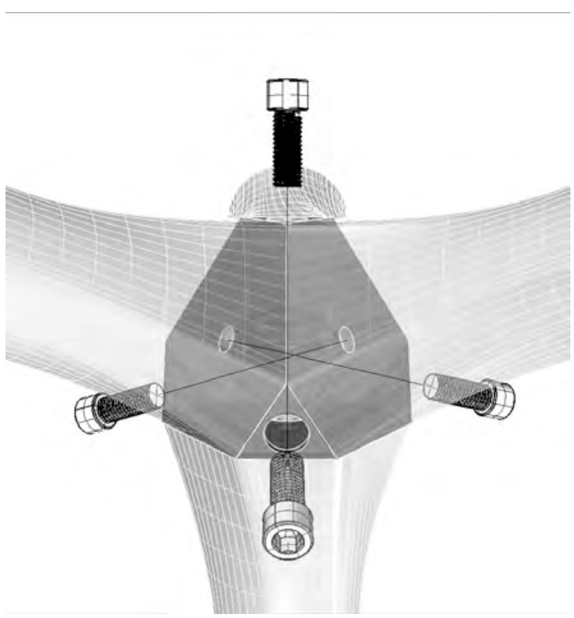

*Figure 11: Fabric Forms Coupler bolting method*

## PROJECT DATA

### *FLEXIBLE FABRIC*

This project relies on Lycra, a type of flexible fabric similar to Spandex. The original patent held by Joseph Shivers on segmented copolyetherester elastomers (otherwise known as Spandex) indicates a potential 325% elasticity (Shivers 1962) and spandex yarn has 650% ± 30% elongation (Senthilkumar et al. 2012). However, it is invariably blended up to 80% with other natural and man-made fabrics in order to make it more practical in the manufacture of garments (Reisch 1999). In field tests for this project, elongation of 217.5% was achieved prior to fibrous failure. The lycra employed in the prototype project achieved an optimal tension suitable for casting the volume of concrete used when stretched between 130% and 200%. At maximum tension flexible with zigzag stitching of polyester thread, the form filled with casting material naturally and with sufficient volume to produce usable results.

### *ROBOTIC FABRIC FORMWORK VS. OTHER FABRIC CASTING METHODS*

While other fabric casting methods seek to constrain the fabric to specific shapes without undue deviation, or tailor the fabric specifically to the cast object (West and Araya 2010), the Lycra used in this project specifically enables the radical manipulation of the fabric formwork. This allows an almost infinite number of potential cast concrete geometries with a singular fabric starting profile. The use of fabric as a formwork also plays a role in the compressive strength of the member. Because Lycra allows moisture to wick through its fabric while retaining the cement, a high-strength concrete is produced with minimal air pockets entrained in the object (Orr et al. 2011).

### *STRUCTURAL COMPOSITION*

Ready-mixed 9,000 psi construction grout yields fast cure times of 3,000 psi within one hour, enabling removal from the robotic arms with an initial set time of 30 min. Despite the high ultimate compressive strength, unreinforced test castings are highly susceptible to fracturing at finite edges and breakage from sudden impact. Introduction of 1⁄2” nylon monofilament fiber at the rate of 0.032 oz per pound of cement dramatically improves the tensile strength and edge definition without compromising surface appearance.

Further tensile reinforcement of 16.5 gauge tie-wires in each leg of the Y-shaped fabric acts as a scaled facsimile of conventional steel reinforcing bar.

### *ROBOTIC FABRIC FORMWORK VS. CONVENTIONAL FORMWORK*

While planar and repetitive elements will continue to be championed by conventional rigid formwork, the benefits of robotic fabric formwork are evident when fabricating elements of variable organic geometry. CNC milled EPS formwork revolutionized the industry in recent decades and facilitated work such as Frank Gehry’s Der Neue Zollhof, which required multiple unique formwork elements in its execution. However, the sacrificial nature of the formwork, the milling time to fabricate the double curved formwork and the resultant waste make this an expensive proposition (Janssen 2011). Moreover, the amount of 2lbs/pcf EPS required to mill formwork for a similarly sized 20lb concrete object using flexible fabric supported by robots is approximately 20lbs (10cuft) which represents 31,900 grams $CO_2e$ (carbon dioxide equivalent) vs. .25 lbs of fabric which embodies just over 2 grams of $CO_2e$ carbon emissions (Ruuska 2013, Fabrics International 2016). Using the same metrics, the cost of EPS is $100 to a comparable fabric cost of $5, the CNC milling/ finishing time is 6 hours vs. manual sewing/assembly time of 6 minutes, etc. In all, the material and labor cost advantages are tremendous for flexible fabric robotic forms, given the appropriate geometric applications.

The ability to introduce incremental or dramatic variation between pieces constitutes a significant design advantage, as does the resultant form-found geometry with gravitational and volumetric differentiations. The natural curvature between the endpoints effectively reduce structurally vulnerable sharp turns and provide additional mass where it is needed at the connectors with bone-like structural efficiency.

| FORMWORK TYPE: | WOOD | EPS | FLEXIBLE FABRIC |
|---|---|---|---|
| **ATTRIBUTES:** | | | |
| Linear Formwork Shapes | yes | yes | no |
| Double Curved Shapes | no | yes | yes |
| Variable Organic Shapes | no | no[1] | yes |
| Form-Found Geometry | no | no | yes |
| Automated process capable | no | no[2] | yes |
| Reusable Formwork | yes | no[3] | no |
| Recyclable | yes | yes | no |
| Form cost per 20lb casting[4] | $20 | $100 | $5 |
| Time to build / mill / sew formwork | 1 hour | 6 hours | 6 minutes |
| Carbon Footprint CO2e in grams | 1,625[5] | 31,900[6] | 2[7] |

NOTES:

1 Possible but not efficient
2 Not at time of this writing
3 Usually sacrificial
4 Estimated
5 reThink Wood, 2015
6 Ruuska, 2013
7 Fabrics International 2016

*Figure 12: Comparison of wood, EPS and fabric formwork*

## FUTURE RESEARCH

Methods to use this system within facade design can take two paths. One explores the use of small-scale components aggregated into a 3D lattice on a building substructure. This approach is reminiscent of Erwin Hauer's modernist screen walls and the facade of the Broad Museum but with organic variation. Such a design could feature Y-shaped pieces bolted into an hexagonal lattice grid (Fig. 13). A second hexagonal grid offset from the first creates depth and is bolted to the substructure at the steel "coupler" elements. Depending on the orientation of each robot combination, gravity forces will cause the center of mass to sag at a variable rate based on fabric elasticity. This can be controlled by proportionally increasing the fabric stiffness in the engineering of the formwork, with smaller formwork volume and/or greater stiffness toward the bottom of the object in the orientation in which it is cast.

An alternative approach is designing a true structural facade system similar to the American Cement Building but consisting of gradual variation a 2D distorted grid. Larger structural pieces spanning entire building floors with glazing interspersed typifies this method. With a load-bearing application, facade and structural performance can be achieved with a singular, coherent design language.

Forthcoming research will be conducted at Orange Coast College using the Architectural Technology facility with Steven Fuchs. Other collaborations will include Evan Atherton and David Thomasson from Autodesk's Pier 9 research facility in San Francisco. An upcoming large-scale installation is proposed for an event to be held in Palm Springs in 2017.

Achieving building-scale components will require changes to the fabric formwork, reinforcing and the robotic arrays employed. Form stiffness must increase proportional to the increase in concrete volume so that gravity is controlled and unwanted distortion is minimized. Fabric with less elasticity, such as cotton knit or 8% spandex knit (45% and 95% elongation respectively) (Easter, 2006) and engineered combinations of fabrics in distortion-prone locations of the cast object will allow tailored object shapes and sizes. Gravitational deformation can be further alleviated by removing either the center or perimeter mass. Removing mass at the perimeter simplifies the object, the load path and results in the least amount of material per piece.

Building-scale reinforcing will include basalt rebar, a cast fiber material with tensile strength greater than glass fiber. With twice the bending strength of steel, (Gencarelle 2016) woven basalt rebar can be manually draped within the form along with the fabric formwork during casting more readily than steel reinforcing. Basalt also can be woven into a fabric or mesh to replace the lycra fabric form, allowing the casting of larger shapes without the bulging associated with Lycra. Formwork of basalt can then remain on the finished cast piece, acting as external reinforcement. Upcoming experiments will include the introduction of steel cable of various dimensions integrated into the fabric forms during casting. Strength testing of the various reinforcing methods will also reveal the most efficient and cost-effective approaches for different product applications.

The robotic array required for larger-scale fabrications needs to be sized in accordance with the scale of the castings. The 7-lb capacity Agilus robots used in the prototype can be directly exchanged for robots with up to 2850-lb capacity in order to manage the gravitational loads of the cast pieces and handle the concrete pumping equipment for filling. Further, the robots will provide handling of the cast pieces that exceed human lifting abilities, even facilitating job-site fabrication and installation where space and staging permits.

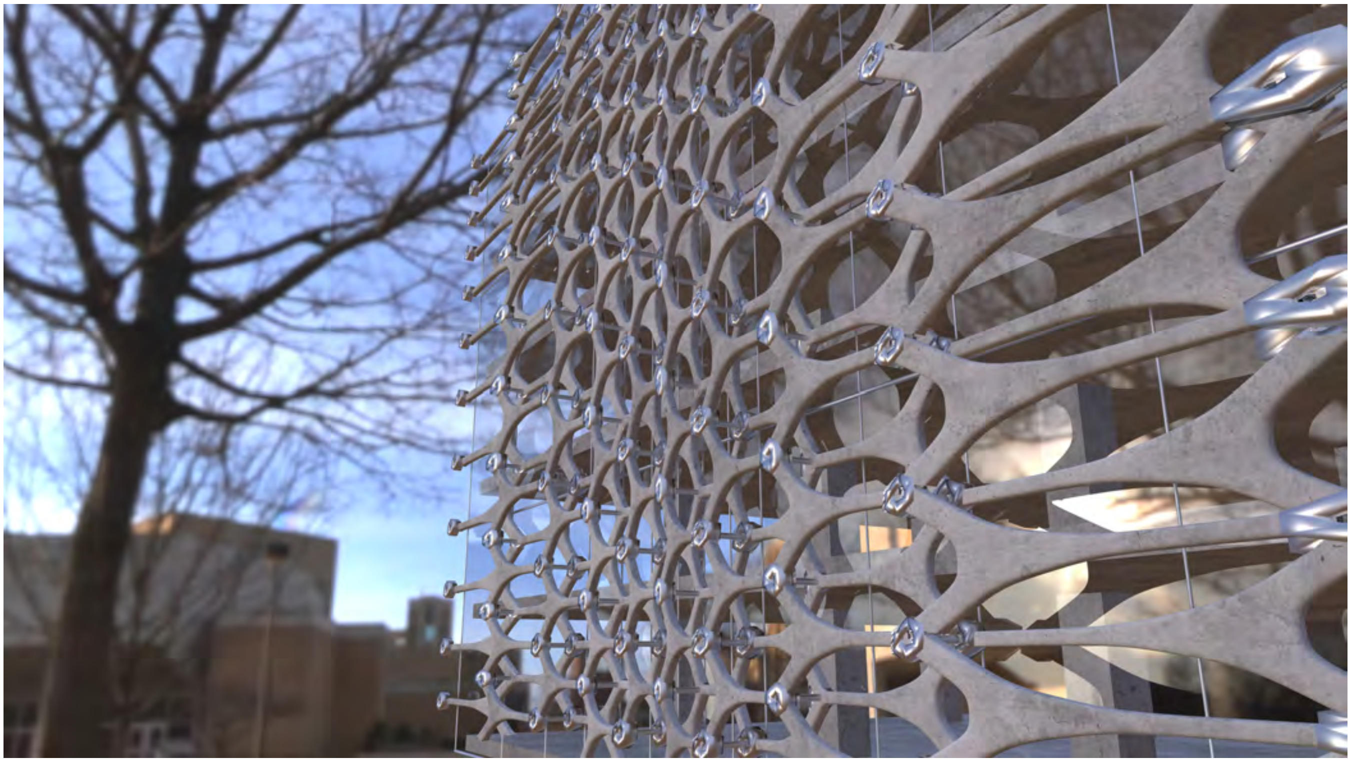

*Figure 13: Robotically cast facade concept by author*

An alternative approach is to design the system as a true structural facade, similar to the American Cement Building but consisting of gradual variation a 2D distorted grid. Larger structural pieces spanning entire building floors with glazing interspersed typifies this method. With a load-bearing application, facade and structural performance can be achieved with a singular, coherent design language. Forthcoming research will be conducted at Orange Coast College using the Architectural Technology facility with Steven Fuchs. Other potential collaborations include Evan Atherton and David Thomasson from Autodesk's Pier 9 research facility in San Francisco.

## CONCLUSION

The dissemination of robotic fabric formwork into the construction industry enables the realization of the next generation of parametric, node-based lattice structures and significantly reduces concrete construction costs for conventional components. Multi-directional pieces can be cast without rigid formwork and their destructive removal.

The robotically controlled system resulting from this research proved its ability to facilitate a rapid and economical digital workflow to realize complex or truncated parametric geometry. Most importantly, this method can help the construction industry adapt to emerging digital fabrication tools and allow for rapid and precise design to production cycles that go beyond rapid prototyping. The effect is a digital-to-physical workflow that is abundantly more flexible in its dimensional freedom and more economical than the industry standard.

Future development of this system would likely include the use of custom-built robots tailored specifically to the configurations of the pieces to be cast, allowing for larger scaled pieces with multiple limbs and/or connection points. Customized robotic work processes could one day replace human labor in many professions including those on the construction site.

## ACKNOWLEDGMENTS

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