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Variable Carving Volume Casting

A Method for Mass-Customized Mold Making

Brandon Clifford, Nazareth Ekmekjian, Patrick Little and Andrew Manto

Abstract The digital era fosters variability and change, though this desire loses traction when applied to methods falsely assumed to be repeatable—casting. This collision has produced a plethora of expensive, wasteful, and time-intensive methods. This chapter presents a method for rapidly carving variable molds to cast unique volumetric elements, without material waste. This method employs a multi-axis robotic arm fitted with a hot-knife to carve foam into mass-customized negatives. In doing so, it re-engages a gothic craft tradition of producing unique volumetric architectural elements. The act of rapidly carving volumetric material mines knowledge from the past in an effort to create novel forms that are not possible in the aggregation of standard building components. This chapter advocates for, prototypes, and analyses this variable, sympathetic, and reciprocal approach that carving once offered the built environment. We found the method to be effective and promising, when informed by limitations and constraints embedded in the process.

Keywords Robotic fabrication · Multi-axis · Formwork · Mass customization · Digital craft · Free-form geometry

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1 Introduction

Architecture has a long history of working with volumetric materials in a variable way. Only recently, as a result of the Industrial Revolution, has the building industry advocated for sheet materials and standardized building components (Clifford 2012). With greater attention paid to robotic fabrication in architecture, there has been a resurgence surrounding the topic of volumetric materials and their capacity to engage computational, algorithmic, free-form, or otherwise complex geometries that are not capable of being described through the Albertian orthographic representations of architectural intent (Carpo 2011).

In recent years, designers have transferred Philibert de L'Orme's method and definition of *art du trait géométrique* (currently known as stereotomy) into the carving of large volumetric positives in expanded polystyrene (EPS) foam (Fallacara 2006; Feringa and Sondergaard 2014; Rippmann and Block 2011). Their projects, though working as an analog for stone construction, argued for the advantages of EPS for its regenerative abilities, lightweight, and machinability (Clifford and McGee 2011). A paper (Stavric and Kaftan 2012) expanded the carving of foam beyond the use of traditional linear cutting geometries into custom profiles. The use of custom profiles is not a new idea either, as it has been used historically for mold profiles in the method of plaster scraping as well as molding shapers for wood moldings and ornamental columns. A project (archolab.com/archives/40) recently applied the use of plaster scraping to robotic processes.

Recently, attention has been paid to the problem of creating complex molds to cast free-form geometries. Many projects have applied subtractive computer numerically controlled (CNC) technology to create custom formwork with high precision. This approach assumes the waste and non-repeatability of the molds in favor of further freedom in geometric creation. Another approach is to approximate subtle curvature through the bending of sheet material against a superstructure (www.designtoproduction.ch/content/view/17/26/). This approach limits the global figure of the geometry to the maximum bending of the material in response to the Gaussian curvature. In a similar method, the use of a variable mold through pneumatics and actuators has been used to articulate a geometry via points across a malleable material in papers such as (Pronk et al. 2009; Raun et al. 2010). Gramazio and Kohler (dfab.arch.ethz.ch/web/e/forschung/164.html) have also demonstrated the advantage of re-usable materials to create serially variable molds. This method is not dissimilar to the use of earthwork as formwork for on-site or tilt-up concrete construction.

This chapter proposes a precise and rapid method for carving negative molds with a custom robotic hot-knife for highly variable free-form geometries without the material waste of typical subtractive machining approaches. It uses the column as an exercise to prototype this method and EPS foam as the carved material.

2 Digital Gothic

This chapter assumes a digital gothic approach as described by Ruskin (1960) in his text '*The Nature of Gothic*'. Ruskin describes the qualities of gothic as being determined by the maker and (his) methods of making. This approach can be conversely opposed to the classic approach of assuming the identical copies of a style that has been pre-determined by one 'thinker'. In establishing this dichotomy, one comprehends the history of division between thinker and maker, as well as the occasional alignment. With the advent of digital technologies in design and fabrication, our profession has found a reciprocal and harmonious relationship between the two. This chapter exercises one development in this reciprocity by generating sympathetic architecture (Carpo 2011; Spuybroek 2011).

3 Fluting and Bundling

The use of fluting or bundling (inversion) has been employed in the creation and subsequent ornamentation of columns for millennia, as demonstrated in Fig. 1. The earliest cataloged column types emerged in Egypt, Assyria, and Minoa 3000 BCE and were made by lashing reeds together at their ends caused them to cinch tightly to one another, and subsequently, bulge outward slightly at their midpoints. Later builders transferred these fluted geometries into stone construction. In his text '*Contrasts*', Pugin (1836) describes the classic period as "white, marbleized ghost of an essentially wooden architecture". Some of the earliest Egyptian stone columns even mimicked the bundled arrangement of reeds through the design of convex flutes. As column orders developed, fluting took on different roles. In the most recognizable column types, Doric, Ionic, and Corinthian, fluting developed by the Greeks as an analog to tool marks left in tree trunks as the bark was stripped away. They had concave, vertical flutes that were carved normal to the stone face. The global form also bulged at their midpoints (a technique known as entasis) referencing the previous reed columns and providing a visual effect that made columns appear more slim and elegant. Gothic builders bundled columns into piers in order to branch ribs above to create vaults. Later builders used fluting increasingly as bundling rhetoric like the twisting Solomonic columns of the baroque period that appear as two columns entwined. While this chapter does not advocate for the simple re-application of fluting as a stylistic choice, it does grapple with these issues due to a method of making constraint (see Sect. 5.1).

Fig. 1 Luxor Temple, Parthenon, Reims Cathedral, Hotel Neuschwanstein

4 Tooling

The scraping of tree trunks presented itself symbolically in ancient Greece via the flutes of columns. In some cases, tool marks were left as a vestige of the means of making. Figure 2 shows a room at *Les Baux-des-Provence* carved away from solid limestone and left with all of the tool marks from its excavation intact. These markings demonstrate a direct relationship between the global geometry, and the direction of the tooling. In other cases, tool marks are made much more deliberately and in an effort to efficiently create surface texture. Surfaces at *Hôtel Carnavalet* are chiseled in an inverted pyramid pattern and exhibit an efficient method of patterning, while the vermiculation carvings at the *Louvre* in Paris demonstrate a space filling patterning irrespective of direction (Clifford 2012). Ultimately, any carved surface bears the history of its tooling, though with rigid materials such as stone and wood, it is possible to further sand, polish, or finish a surface beyond the tooling. These processes are a balance between efficiency and resolution; however, as Pye (1968) argues in his text '*The Nature and Art of Workmanship*', nothing should be taken pride in that can be accomplished with some sandpaper.

In contemporary practice, tool-paths are commonly displaying themselves as the marks left by the machining of objects out of larger pieces of material as result of subtractive machining. In cases such as in *Commonwealth's* 'Lard Series' (http://www.commonwealth.nu/projects/61/lard), the overall form of the surface is quite deliberate. The parallel tool-paths are imprinted ever so slightly on the surface only as a trace of how the bench was made. Skylar Tibbit's 'Path Responsive Surface Milling' (http://sjet.us/phila_path_responsive_surface_milling.html) displays an entirely different attitude to the use of tooling in the production process. In his project, the tool-paths do not merely serve as a trace of production, but rather had a major role in the physical surface definition of the final object. Tool marks don't always have to imply movement over a surface. Rather, contemporary tools allow for the explicit control over tool entry, engage, and withdrawal motions.

Fig. 2 *Les-Baux-des-Provence* Bouches-du-Rhone, France (*left*). *Hôtel Carnavalet* Paris, France (*middle*). *Louvre* Paris, France (*right*)

Avi Forman's work (http://www.flickr.com/photos/69844849@N00/5175767950) at the *Yale School of Architecture* shows an artifact formed through the use of thousands of individual drill points. The resulting surface emerges as a highly stippled combination of holistic form and nuanced individual tool-marking similar to the surface at *Hôtel Carnavalet*.

5 Methodology

The column prototype described in this chapter is fabricated with a robotically controlled hot-knife to carve negative geometries from EPS foam. These mold negatives are then sealed with a vacuum bag and used to cast unique Glass Fiber Reinforced Gypsum (GFRG) positives. This process involves the computing of the tool-paths, the rapid prototyping of potential forms, and the development of fabrication techniques used to make finished artifacts.

5.1 Hot-Knife Tooling and Geometric Constraints

Two hot-knifes were tested in the prototyping of this method. The first mounts an off-the-shelf hot-knife that is originally designed to be used by a human hand. It has a long bent handle that works well for a manual operation, but creates collision obstacles during robotic operations. The second version is a custom mounting that minimizes the handle and accommodates a larger blade. While this development does resolve the collision obstacle, both employed a semi-circular or 'J' blade

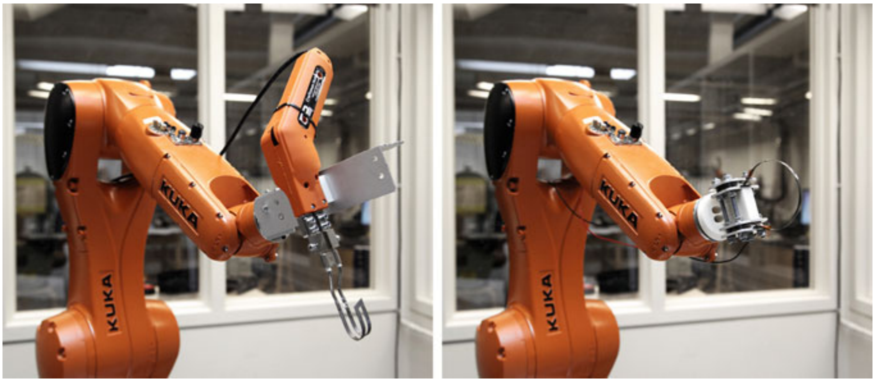


Fig. 3 A comparison of the two prototyped knives. Off-the-shelf craftsman hot-knife with a 1″ diameter ‘J’ blade (*left*). Custom hot-knife mounting with a 3.25″ diameter blade (*right*)

profile. The first is 1 in. in diameter and the second is 3.25 in. in diameter as shown in Fig. 3.

The hot-knife cuts through EPS foam by melting it at high temperature, creating both a minimum and a maximum step-over for the tool-path. Figure 4 demonstrates the maximum step over is a function of tool width; while minimum step over attempts to limit areas of re-melting from previous tool-paths. Typical CNC subtractive (milling) machining assumes there is a maximum, but no minimum. For this reason, milling can either express the tooling and enjoy the benefits of minimum passes, or increase the resolution of the step-over to greater approximate a smooth surface. This approach is dedicated to resolution, allowing the tool path to pass any way they are prescribed by the machinist.

While similarities can exist in appearance between these two methods, it is important to note that not all geometries can be translated from one to the other. Beyond the requirement of a minimum step-over, another major difference between milling and this proposal is that of direction. A milling tool-path has no direction because the blade is spinning. This also means a mill can turn a corner with zero radius, but the proposed method has a blade with a direction and therefore can only turn with a wide sweeping radius. The advantage this method has over milling is the ability to generate non-symmetric custom profiles.

Due to the constraints of the method, the approach demonstrated in this chapter is dedicated to the conscious decision of tooling location. This chapter does not advocate for the universal use of tool-path visibility, though this method of the hot-knife carving requires attention to this issue. Figure 5 shows a few of the tool-path strategies prototyped.

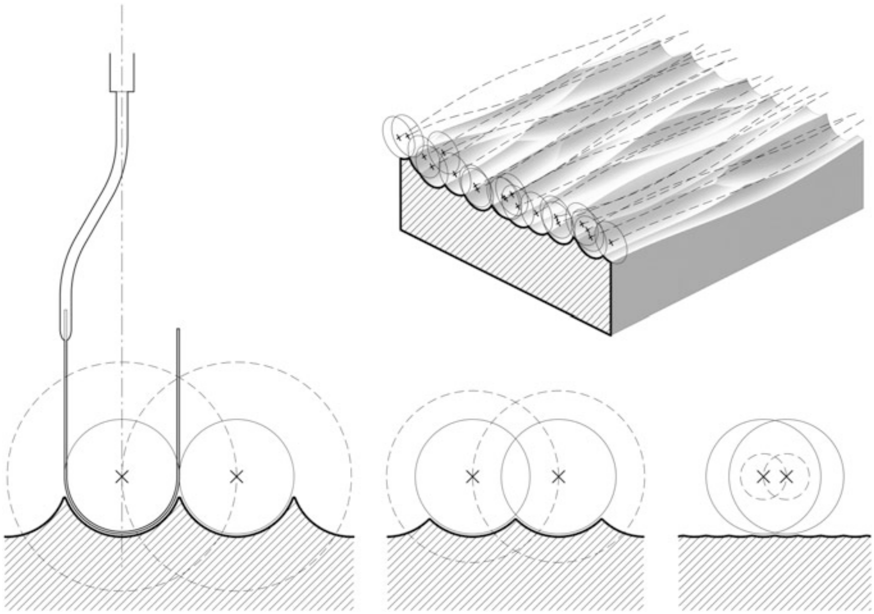


Fig. 4 A diagram describing the range between the minimum and the maximum step-over

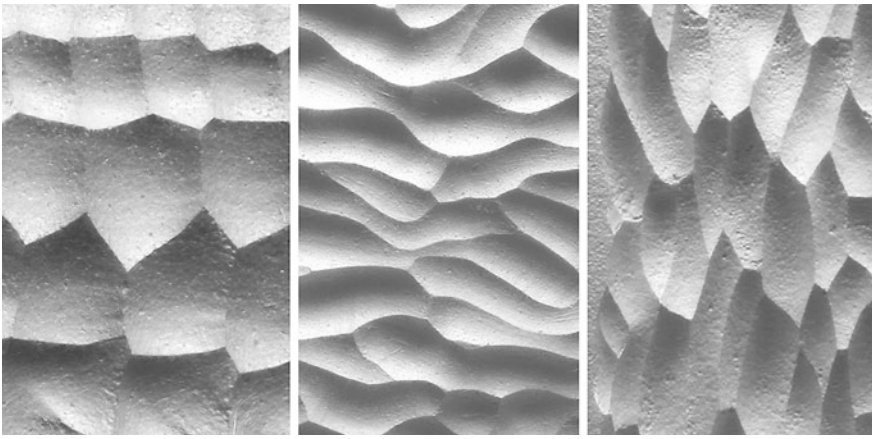


Fig. 5 Multiple tool-path prototypes

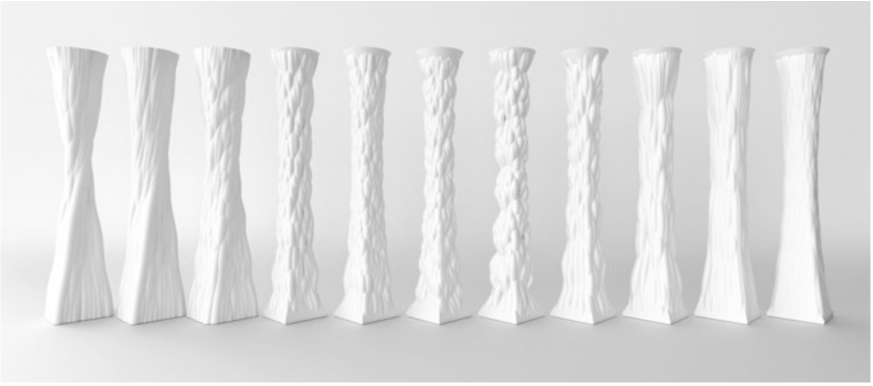


Fig. 6 Quarter sized rapid prototypes of serial variability

5.2 Digital Modeling and Computed Simulation

The column design is developed with a set of constraints such as the height (36 in. tall) and geometric transitions (from 6 in. square base to 6 in. diameter circle top) making this prototype comparatively proportionate to the Doric order. Figure 6 demonstrates a series of rapid prototypes. The forms are generated with curves that modulate normal to the surface of the column to create waves.

5.3 Materials

This prototype uses 2 lb/cu ft density Expanded Polystyrene (EPS) foam for the molds. The Glass Fiber Reinforced Gypsum (GFRG) used to cast into this mold is comprised of Hydrocal, a white gypsum-based cement that has higher strength (up to 5,000 psi) and quicker setting time than typical plaster. It also uses Chopped Strand Glass Fibers (CSGF) as reinforcement to increase mechanical strength of the Hydrocal. 1/4″ long fibers are chosen due to the high degree of surface resolution necessary in the final casting. The two part cast is then filled with Expanding Water Blown Urethane Foam, a two-part castable rigid foam that expands many times its original volume when mixed together.

5.4 Multi-Axis Robotic Carving

Multi-axis robots are a type of programmable machine with multiple rotary joints. The tests undertaken in this chapter are conducted on a KUKA KR6 R700 6 axis robot. The maximum reach of the extended robot arm from its base position is

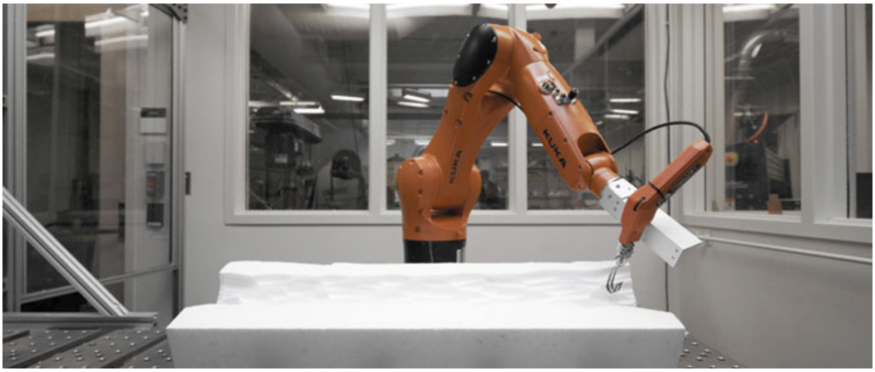


Fig. 7 Robot and hot-knife assembly carving EPS foam

roughly 28 in., but the necessary positioning of the arm for certain geometries often means the reach is less. The 12″ × 36″ block of EPS foam pushes the reach of the machine and necessitates a rotated stock orientation to ensure tool-paths stay within reach. Figure 7 shows the first knife fitted with a semi-circular blade mounted at the end of an aluminum extension holding the knife. Curves are extracted from the digital model and subdivided with 'normal planes', which the robot uses to correctly align and guide the hot-knife through the material.

5.5 Casting/Mold Making

The design of this column requires two mold negatives used to cast two positive column halves that are brought together to form a single column. The required yet added texture of the tool-path geometries in the molds made releasing the casts difficult.

A number of demolding strategies were tested, from a laborious process of applying and sanding joint compound over the surface to mold wax, vegetable oil, and even water based spray release agents. Occasionally poor or uneven application can create difficulty in demolding. When these stubborn areas do not release, solvents are applied to melt the EPS foam away from the GFRG cast.

The preferred method for demolding involves stretching a thin latex sheet over the mold and applying a vacuum, effectively sucking the latex to the face of the mold. This technique creates a sealed surface into which plaster can be cast and serves as an excellent mold release system. The first tests utilize a relatively thick latex sheet (0.07″ thick), which creates an alluringly smooth surface on the casting, but also deformed and rounded the edges of the mold to a degree that was unacceptable. A thinner sheet of latex (0.02″ thick) is used next to achieve a higher resolution finish. An unintended by-product is the change in finish quality from a highly polished and shiny surface to smooth, but textured as seen in Fig. 8.

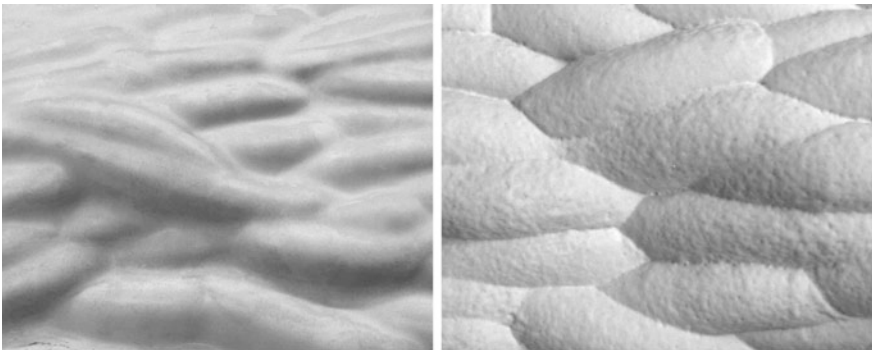


Fig. 8 Comparative resolution between 0.07″ latex sheet (*left*) and 0.02″ latex sheet (*right*)

This method is rapid, efficient, and durable. The resulting surface finish is also highly controllable given the variables of foam density and latex thickness.

5.6 Assembly and Finishing

The two plaster casts are sanded along their common joining faces until they are both planer. The halves are temporarily held together with tape while two-part expandable urethane foam is poured in the hollow cavity. The foam expands and hardens, permanently joined both halves together.

6 Analysis

A number of questions, concerns, and future research goals have been established. The hot-knife proves to be an expedient way of creating complex surface features in EPS foam, but its use is met with certain difficulties. Finding the center point of hot-knife blade and creating proper alignment on the robot is difficult due to the flexible nature of the blade, and its lack of clear registration points. Also, blade temperature fluctuates depending on the depth and time of the cut, which led to an excess of melted foam when too hot, and tear-out of foam when too cool. We found these difficulties easy to overcome and further research will engage a feedback loop with a temperature sensor to speed up or slow down the carving path. We also see value in the creation of custom blade profiles.

This method is not dedicated exclusively to columns. Future work will address the gothic method of branching and bundling as seen in fan vaults and column piers. Gouging has the potential to be re-directed, multiplied, or extended in response to transitions or anomalous conditions in free-form geometries. The 'macro-mark' contains another advantage particularly aligned with robotics. These large gouges are not aligned to resolution, and therefore the possibility of translating large material within the reach of the arm can be accomplished without the requirement of perfect indexing. This strategy is akin to the feathering of hair, where it is not clear where one set of paths start and the others begin.

Though this prototype employed GFRG and expanding urethane foam, there is nothing about this method that is strictly dedicated to these materials. Future work will expand this material pallet with the similar mold creation method.

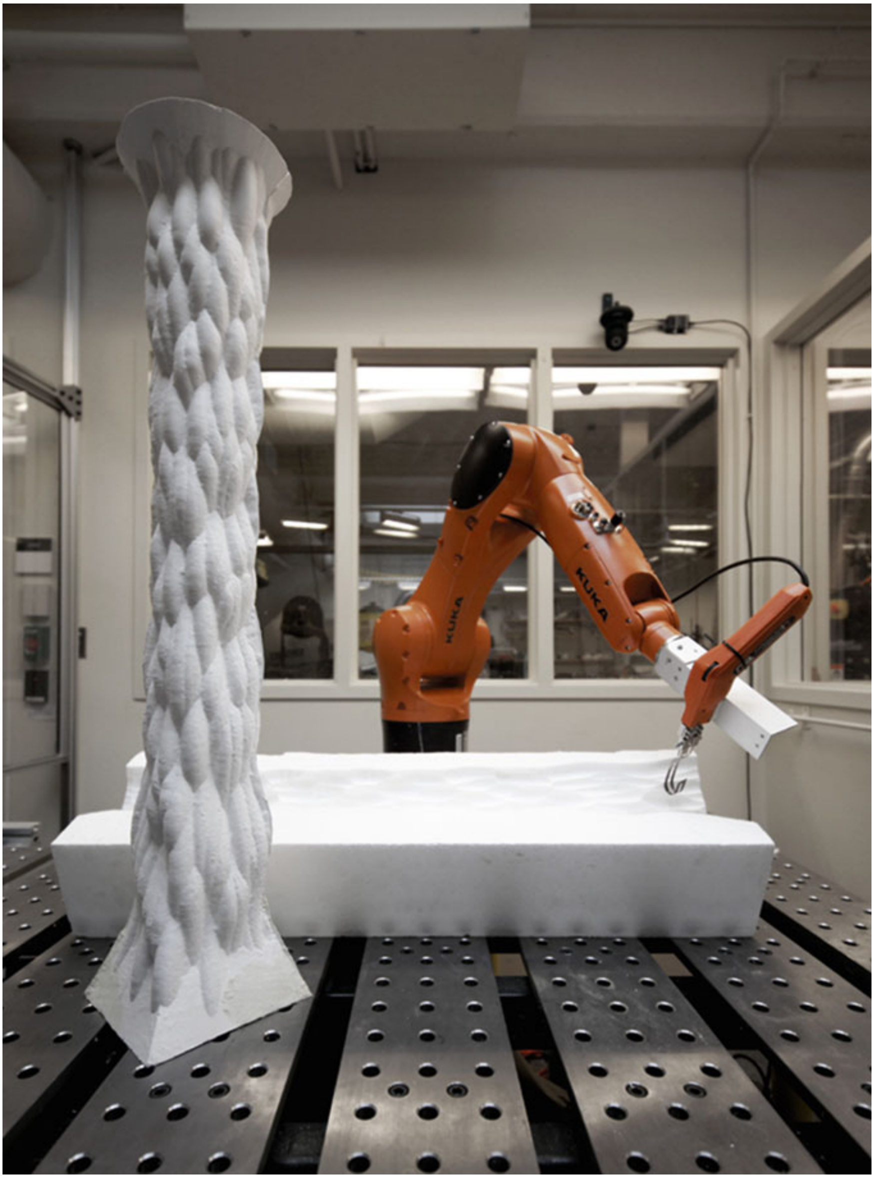
7 Conclusion

This chapter presents a process for producing mass-customizable formwork for free-form geometries without material waste. It successfully demonstrates the practicality and potential by rapidly carving variable molds to cast unique volumetric architectural elements. The foam molds as well as the releasing process used to cast these elements are 100 % recyclable.

While this chapter presents a column as prototype, the method is in no way dedicated to this element typology. We understand the column as a placeholder for a variety of architectural forms to come. For this reason, we do not test the column for its structural capacity; rather, we test it against precision, ability to cast, and ease of fabrication. This process produces a form that is highly unique to its methods of making. We learned the limitations and constraints of the method are directly aligned with a long history of volumetric carving. This re-insertion of past knowledge into contemporary methods results in a new language that has roots in ancient traditions.

We see robotics as translating gothic craft traditions into a digital environment, full of feedback and variability. While this method could be produced roughly with a number of non-robotic controllable devices, we see it uniquely aligned with robotics for their inclination toward volumetric processes and system feedback. This method is also inherently lightweight and lacks the precision one would expect from CNC subtractive machining. Where it lacks in this precision, it makes up for in efficiency of scale. One must keep this false assumption of precision in consideration when developing a design strategy as the method is embedded with a few potentials for aligning units we are excited to test in future work. In prototyping this hypothesis, we learned a number of “fuzzy” variables that could be better informed by sensing and system feedback, for instance, the over-melt of previous passes and the variation in knife temperature versus the feed.

We see no limit to the forms or elements this method can produce, as it is not dedicated to a scale, material, or style. It is dedicated to an efficiency of scale, a limitation of waste, and the digital desire for variation. This chapter opens the doors of variation to methods previously relegated to the re-production of identical forms.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