Rough Pass Extrusion Tooling

CNC Post-processing of 3D-Printed Sub-additive Concrete Lattice Structures

ABSTRACT

Rough pass extrusion tooling advances the manufacturing precision of full-scale sub-additive 3D-printed concrete lattices in a three-step process that involves spatial 3D printing, high precision 3D scanning, and CNC post-processing. Utilizing robotics and computation, sub-additive manufacturing (Battaglia et al. 2018) leverages digital workflows to produce structurally, materially, and spatially optimized lightweight concrete building components. Instead of further refining the 3D-printing practice towards accuracy, and unlike other research projects that investigate 3D printing and subsequent post-processing, the method proposes to deliberately print a “rough pass,” accommodating any fabrication inaccuracy inevitably resulting from the concrete material and nozzle extrusion process. In a second step, supported by the advancement of 3D scanning, accuracy and geometric intricacy are achieved through locally post-processing components along edges, in pockets, on surfaces, and in areas of joinery. Rough pass extrusion tooling enables the incorporation of higher fabrication tolerances as well as the integration of building systems, hardware, and complex connections. The method takes full advantage of the 3D-printing process while introducing means to dramatically increase fabrication precision. Procedural infidelity—not aiming to solve accuracy through 3D printing alone—enables the development of a technically, methodologically, aesthetically, and performatively progressive multi-process fabrication method that opens up a new realm for concrete printing accuracy. This paper closely examines CNC post-processing for sub-additive concrete print assemblies, addressing methodologies, opportunities, and shortcomings of such an approach.
INTRODUCTION
Sub-additive Concrete 3D Printing
Concrete 3D printing advances at rapid speeds, moving towards commercialization and implementation at full scale. Since the development of Contour Crafting (Khoshnevis 2004), various research projects and initiatives have emerged that further investigate the translation of small-scale filament-based 3D-printing processes to large-scale concrete assemblies. To name only a few recent examples, TU Eindhoven’s 3DCP program (Bos et al. 2018) or XtreeE (Gosselin et al. 2016) explore concrete 3D printing in two-dimensional layers. When stacked horizontally, these layers create three-dimensional forms, as originally described in the Contour Crafting project (Hwang and Khoshnevis 2004). In contrast, the sub-additive concrete printing method (Battaglia et al. 2018) developed at Cornell University and the Robotic Construction Laboratory (RCL) proposes a spatial 3D-printing process of non-horizontal layered material deposition (Figure 1) in a two-step process: (1) a support material aggregate is first mechanically shaped by the robot (subtractive), and (2) concrete is then robotically deposited on top of the stable sub-surface mold (additive). Within the limits of certain angles of repose, which are determined by the type of gravel aggregate used, a wide range of double-curved and single-curved sub-surfaces can be produced using this method. Sub-additive 3D printing enables the printing of complex double-curved geometry—either surfaces or lattices—without the need for costly formwork (Figure 2). Utilizing robotics and computation to integrate a streamlined workflow from digital design to physical fabrication, sub-additive manufacturing leverages digital workflows to produce structurally, materially, and spatially optimized lightweight building components while dramatically reducing waste material and increasing the sustainability of concrete construction.

As an example of land-forming to cast shell structures, the Philips Pavilion by Le Corbusier at the Brussels Expo ’58 serves as an important precedent for sub-additive manufacturing. The pavilion was one of the first modern building examples to panelize a large double-curved surface through land-forming (Zephir 2005). On a shaped hyperbolic sand form, multiple panels were produced as sections of the surface, transferred to the site, and post tensioned to create the structure. Other seminal references for sand pile forming include the work of Heinz Isler (1961) and Mutsuro Sasaki (2005).

More recently, the Flexible Mold project at TU Delft has advanced casting methods for precast concrete construction (Schipper and Vambersky 2010), with research now moving towards flexible molds and concrete printing (Borg Costanzi 2016). Other examples of spatial printing include Filligree Robotics, which explores 3D printing normal to a curvilinear surface though clay by first scanning an unknown surface and then applying the technique of over-forming (Tamke et al. 2016). The process of sub-additive manufacturing in concrete is currently being further developed at the Cornell Robotic Construction Laboratory (RCL), with a recent focus on CNC post-processing and reinforcement to enable structural applications for spatial concrete printing. This paper closely examines CNC post-processing for sub-additive concrete print assemblies, addressing and exploring methodologies, opportunities, and shortcomings of such an approach.

BACKGROUND
Precision in Sub-additive Lattice 3D Printing and Fabrication
Across materials and scales, layer resolution and overall printing precision are important parameters when determining the quality of a 3D print. When compared to filament-based PLA or ABS printing methods, concrete 3D printing encompasses drastically different tolerances. The material is highly complex and has a lot of variables: water–cement ratio, additives, fiber reinforcement, and aggregates all determine critical characteristics such as open-time, workability, slump-flow, self-adhesion, and self-support during printing. Various rheological factors influence precision and the ability to successfully print with concrete: (1) once mixed, concrete starts setting and changes its material properties, making it difficult to print consistently; (2) concrete workability and characteristics depend on global environmental factors such as temperature and moisture content in the air, necessitating constant adjustment of the material mixture; and (3) when printing continuously for long periods of time, small build-ups of printing material in the nozzle, pump, or delivery hoses change the characteristics of the print.

There are multiple methods—often combined—to enhance the precision of concrete 3D prints, such as careful mechanical nozzle design (Khoshnevis 2016), the adjustment or management of rheological material properties through additives (superplasticizers and accelerators), or the implementation and integration of advanced feedback and monitoring systems into the entire robotic printing setup. However, despite those efforts, most research projects exhibit rough print resolutions, and there are currently few convincing internal methods to enable high degrees of fabrication precision in filament-based concrete 3D printing. While precision improvements are possible and likely to be developed in the future, there is very little
research on combinatorial methods and post-processing of concrete 3D prints. This observation is particularly valid for sub-additive lattice concrete 3D printing (Figure 3), an intricate method with many variables where accuracy is even more difficult to achieve due to the curvature and geometry of components as well as varying sub-surface aggregates.

Multi-platform Fabrication & 3D Print Post-processing
One of the main fallacies of large-scale 3D printing is the attempt and temptation to resolve all project issues with one material system and within one method of advanced manufacturing. However, methods for multi-process fabrication and post-processing of 3D-printed assemblies have been preliminarily explored. Research projects such as Compound Fabrication, developed at the Mediated Matter Group at the MIT Media Lab (Keating and Oxman 2013) investigates a robotic setup with multiple end-effectors, capable of horizontally 3D printing foam and CNC milling surfaces for component refinement where higher resolution is required. Along with the SMU RCAM Multi-Fab project (Kovacevic and Valant 2006), Compound Fabrication is an important precedent for this new method of refined multi-platform sub-additive manufacturing, which the authors have named rough pass extrusion tooling. While a combination of 3D printing and CNC-post processing has been previously demonstrated in horizontal layer prints (metal, foam, and plastic), the authors believe this paper expands on the mentioned precedents by investigating important new paradigms and methodologies such as (1) post-processing of spatially complex and structurally optimized sub-additive lattice 3D prints as opposed to horizontal solid assemblies, (2) post-processing of concrete as a printing material, (3) the integration of high-precision 3D scanning to increase manufacturing accuracy and allow for high degrees of flexibility during the fabrication process, and most importantly, (4) the observation that deliberate rough and “messy” printing in concrete produces potentially stronger layer composites and has potential other advantages over “clean” 3D printing.

METHODS
Robotic System Specification, Software, and End Effectors
The open source robotic platform used for this project is a KUKA KR200/2 with a KRc2 control unit, a setup formerly deployed by GM as an automotive welding robot (Zivkovic and Battaglia 2017). The robot has a reach of 2400 mm and a repeatability of ±0.3 mm. KRL code is generated in Rhino Grasshopper using the KUKA|prc plugin (Braumann and Brell-Cokcan 2011) for concrete 3D printing as well as custom CNC-milling path generation. An end-effector nozzle was built to accommodate a high pressure 1.5 cm diameter hose that connects to the progressive cavity pump, a Hy-Flex HF-15 Spray Buddy. A Changsheng 220V 4.5KW Air Cooled ER32 Spindle Motor in combination with a 4.5KW VFD Driver Inverter is used for concrete CNC milling.

Rough Pass 3D Printing
Linking spatial sub-additive concrete lattice 3D printing with CNC post-processing and high-precision 3D scanning allows for high degrees of accuracy in fabrication. While there are other methods to increase accuracy in 3D printing, this combinatory method does not require the use of patented nozzle systems or special concrete mixtures.
Although each of the deployed methods—spatial concrete 3D printing, high precision 3D scanning, and CNC milling of concrete—has been explored and described separately, their combination resolves critical issues of manufacturing accuracy for complex concrete 3D printing. High degrees of manufacturing precision are imperative when moving from digital models to full-scale physical prototyping. Current concrete 3D printing—in both horizontal layer printing or sub-additive printing—is highly insufficient for precise connections and joinery.

A critical discovery in this research project—particular to concrete but applicable to other materials—is a shift in methodology for producing highly precise sub-additive concrete prints. The authors previously focused on developing a cleaner 3D print through nozzle modifications and material design, which came with shortcomings such as increased delamination between layers due to lower water–cement ratios, subsequent structural collapses, and yet likewise meager print results. The new approach allows for a “rough pass” of more viscous concrete 3D printing, which drastically increases layer bonding, reduces print time, can be facilitated using simpler robotic setups, and can better accommodate changing material properties of the concrete material (Figure 4). While the printed pieces are rough, they are generally more structurally sound and can be produced in quick succession. In a second step, the addition of 3D scanning and CNC post-processing enables superior fabrication precision with multiple benefits for surface-finishing and edge treatments.

Sub-additive Robotic Concrete 3D Printing

In a first step, a series of spatial concrete arches and panels were printed, applying the sub-additive concrete printing method and using the aforementioned robotic setup, progressive cavity pump, and simple extrusion nozzle (Figure 5). The custom concrete mixture includes locally available aggregates and Portland cement compounds. One batch of material contains 11.5 kg Portland cement, 19.5 kg fine sand, 25.2 kg Mortar Mix Type S, 110 g Thermo-Lube, 35 g Superplasticizer #5, 10 g nylon fibers, and 11.5 kg of water. Gravel of 3–6 mm diameter was used as a supporting aggregate for its jagged geometry, which offers a relatively high angle of repose. The loose mound of granules on the print bed can easily be reshaped using a slightly modified robotic printing end effector. At a 40-degree surface incline, the material can only be printed perpendicular to the slope. If the extrusion line travels parallel across the slope, the concrete material rolls off the constructed mound. At an angle of 35 degrees in slope, multi-directional printing becomes reliable.

One of the advantages of sub-additive printing is the high degree of flexibility for creating subsurface geometries in combination with computationally optimized printing patterns. Highly intricate and performative lattice patterns can be printed using this method. While the printed geometries fabricated for test milling in this research project are not structurally optimized, the Cornell Robotic Construction Laboratory (RCL) recently demonstrated that sub-additive lattices can be structurally optimized using Rhino Grasshopper plugins such as Millipede or deploying finite element analysis tools (Battaglia et al. 2018).
As described, “wet” printing constitutes an advantage for the particular robotic setup and concrete mixture used in this research project. Accurately printing concrete with a higher viscosity ratio in immaculate three-dimensional layers is not required when planning to refine geometries with CNC post-processing. Utilizing easily accessible materials and a simple pump/nozzle, the team drastically reduced printing and preparation times (50%) by switching to rough pass printing. At the same time, the rough assemblies demonstrate superior structural bonding between layers. At Cornell RCL, the process of sub-additive concrete 3D printing is currently further refined, addressing critical issues of reinforcement and testing structural abilities of components and connections.

High-Precision Laser 3D Scanning & Analysis
Concrete is a material with long curing times, which affects post-processing practices. After an initial curing period of two days, components are stable enough to be moved off the print bed. To increase the speed of fabrication, a system of rolling platforms has been developed that allows the removal of parts after the print is completed. In order to avoid concrete sludge mixing in with the gravel, components have to be moved off the gravel bed into a waterproof bed to perform the CNC post-processing. High-precision rapid laser scanning enables geometric evaluation, toolpath development, and repositioning of parts during this process.

A FARO Focus 3D S120 laser scanner with a resolution of up to 1/32” (0.79 mm) and a range of up to 120 meters was used in a two-step process to digitally evaluate 3D-printed results and precisely position the prints in the CNC mill bed. (1) In a first step, high-resolution 3D scans of the printed geometries are made to evaluate deviations between the intended optimal toolpath geometry and the physical printed results. To generate precise geometries, eight scans in four cardinal directions above and below the print are required to ensure there are no blind spots. Each scan takes approximately four minutes to complete and multiple printed pieces can be scanned together. The scans are compiled and processed using the FARO Scene software and subsequently exported to Rhino as pointclouds where they can be meshed if necessary. The process reveals that, on average, printed geometries volumetrically deviate (35%) from the intended result in plan, with material spills ranging from 5 mm to 42 mm (Figure 6).

However, sectional deviations are minimal, which demonstrates the feasibility and precision of the sub-additive method. (2) In a second step, the scanner was used to evaluate the location of the printed geometry in relation to the robotic arm and CNC mill end effector (Figure 7). Two scans were taken to then orient and match the digitally generated toolpaths and initial high-precision digital component scan, with the new digital scan of the 3D print’s physical location in the waterproof CNC bed. This two-step process allows for an easy, highly accurate, and reconfigurable setup of the component in relation to the robotic arm.

CNC Post-processing
For CNC post-processing of sub-additive lattice components, a custom water supply system and waterproof
milling bed was constructed out of off-the-shelf parts (Figure 8). The self-weight of printed concrete pieces and the rough surface texture of the waterproof milling bed permits the placement of components without additional fastening. To determine appropriate milling speeds, an initial arch milling test was conducted with a 1/2˝ (12.7 mm) 46 grit round shank diamond profile router bit for granite stone. Testing the feasibility of CNC milling 3D-printed concrete lattices, various stepover, speed, and depth parameters were applied to determine optimal milling speeds (Figure 9). The test established that optimal milling speeds range from 3 to 10 mm for this type of rough gritted large diameter bit, depending on the amount of material removal. Entry paths and angles are derived from standard stone milling practices. Common diamond-coated CNC routing bits and burrs can be used to mill the concrete. The research team successfully tested a variety of router bits and speed parameters, a process that requires further adjustment and optimization (Figure 8).

Custom toolpaths were generated using Rhino Grasshopper and the KUKA|prc plugin and then sent to the robot for milling. Code components were assembled into standardized parametric protocols to enable rapid adjustment of milling parameters such as speed, entry-path angles, type of surface treatment, and type of edge treatment. In general, standard stone milling practices apply, albeit the material is much softer than hard stone and could potentially be milled at much higher speeds with a more professional stone-milling CNC setup.

RESULTS AND REFLECTION

Surface Tests

Various surface typologies were physically tested, deploying a range of milling methods. Manipulating milling speed, toolpath orientation, and stepover parameters enables the creation of a large variety of surface conditions for the sub-additive concrete lattice structures. A number of surface articulations were physically tested: (1) global milling perpendicularly across the grain with maximum stepover, (2) global ripple milling across the grain, (3) localized milling along the structural ribs of the print, and (4) localized milling across the structural ribs of the print (Figure 10).

Various other combinations and surface finishes are possible: smooth finish milling with additional cross passes, distinct and shifted ripple patterns, more pronounced and deeper mill patterns, gradients from smooth milled surfaces to original printed patterns, as well as stippled surface patterns using a large ball bit (Figure 11). Strategically utilizing the geometry of different mill bits adds fabrication intelligence and opens new possibilities for surface articulation. Aesthetically, the CNC post-processing method elevates the 3D print, allowing for radically different resolutions and surface appearances, some of which are conceptually reinforcing the print patterns.

Surfaces have the potential to become performative: water drainage channels can be milled into the printed concrete, strategic local milling enables the integration of hardware fasteners for building systems, and deep milled channels...
can be used to cast composite materials that provide additional reinforcement or can be used for the integration of electrical conduits, HVAC system lines, or radiant heating that activates the concrete’s thermal mass. The physically milled surfaces resulting from the tests all drastically increase the precision of the 3D-printed components and enable a level of detail that is difficult to achieve with filament-based extrusion method alone.

Pocket Tests
Two major strategies were tested to create clean pockets within the lattice structures: the first strategy relies on a spiraling toolpath, starting from an offset that is determined by the maximum depth of excess material detected during the scanning process, then incrementally offsetting the toolpath until the desired pocket geometry is achieved. This strategy allows for faster milling speeds of up to 20 mm per second for each individual toolpath but can increase overall milling time depending on the amount of layers and chosen stepover rates. The second strategy utilizes a single toolpath at a speed of 1–2 mm per second, which starts within the pocket void, perpendicularly carving into the concrete until the desired depth and then carving out the concrete in one continuous motion. For the geometries tested, this method proved to be the more reliable and faster approach, reducing vibrations and preventing failures of the concrete lattice pieces. Both pocketing strategies aim to take full advantage of the abrasive diamond-coated profile of the bit, avoiding an operation that primarily makes use of the tip of the tool to prevent premature wear of the equipment.

A number of pocket types were physically tested: smooth edge pockets, smooth edge pockets with a decorative profile, and beveled edges (Figure 12). One structural failure occurred during a pocket test at the apex of an arch that was printed too thin. Other possible pocket profile strategies are possible with this method: bevels, undercuts, undulating edge cuts, gradient cuts that expose the printed layers, coffered ceilings geometries, or cuts that enable the inlay of planar or non-planar surfaces (Figure 13). There are multiple functional advantages when tooling the edges of printed pockets: the lattice geometry can be clearly articulated and manufactured to precise dimensions, glazing can be integrated using the planar surface cut strategy, window profiles can be milled into the pocket geometries, or lighting and ventilation systems can be integrated.

Connection Tests
Due to the resolution of the printing nozzle, in 3D-printed concrete assemblies connections between components frequently remain bulky and unresolved. One of the big advantages of CNC post-processing is the potential for precise connections between parts, enabling manufacturing accuracy and the integration of common hardware components. A series of connections were physically tested using the CNC-milling methods previously developed for surfaces and pockets: interlocking male–female pocket connectors between panels, and long surface cuts that create a flush edge connection (Figures 14 and 15). Depending on the type of mill bit used, a large variety of other connection geometries are possible: interlocking surface undulations, finger joints, bevel cuts, or pockets for...
casting precast concrete connectors, among others.

Similar to casting processes, highly complex joinery can be achieved with the CNC post-processing method. While the 3D-printed edge is highly insufficient to allow for the design and implementation of precise connection details, the proposed post-processing method has great advantages for developing customizable and accurate connections between individual parts. Deploying the robotic system’s potential for mass customization, these joints can be analyzed and optimized for structural performance to reflect the respective structural forces acting upon each individual component. The integration of hardware components and fasteners used in precast concrete construction links spatial robotic concrete 3D printing to current building industry standards and practices. While current research had to omit structural performance tests, future research will critically investigate structural joinery performance as well as assembly possibilities for aggregated complex curvature panels.

**Reflection and Future Development**

In general, it can be recognized that rough pass extrusion tooling is a practicable and beneficial process that broadens the repertoire of large-scale concrete 3D printing and potentially a wide range of other materials. Adding to a lineage of research projects that explore 3D printing and subsequent tooling, the project expands upon the notion of accuracy within large-scale 3D-printing processes and spatial concrete 3D printing. There is great performative and economic potential to deliberately “rough print” and then “fine tool” 3D-printed concrete components. Future research will continue to explore and take advantage of the relationship between “rough–messy” and “fine–accurate” practices.

Limitations of the self-built milling platform (short mill bits, low HP spindle) presently prevent the physical development of more advanced pocket and edge articulations, but overall the physical test results are very promising and highlight the potential to radically elevate the performance of 3D-printed lattice structures and integrate common, off-the-shelf building systems. Milling times vary for the outlined strategies—the methods that acknowledge the input geometry and closely follow the printed toolpath reduce mill time by approximately 50%, in direct relation to the amount of surface covered. To advance the surface-milling process in future research, fabrication times have to be further optimized, and printed components need to be reinforced for better stability. Comparing methods, results between milled and non-milled components differ, as seen in Figure 16.

Future research strategies will involve a more deliberate deployment of the “messy” printing method to then have more material to mill pockets and integrate building systems. Beyond parameters of performance, aesthetics, and accuracy, the rough pass extrusion tooling method allows for the precise integration of off-the-shelf building components and connectors. Future research will focus on continuing to develop the 3D-scanning protocol towards real-time feedback and the integration of long continuous...
fiber reinforcement during the printing process for better overall structural stability of parts (pieces are currently largely unreinforced). To improve connections, joints will be structurally analyzed and optimized for structural performance. Large prototypes that build on connection strategies outlined in this paper are a future next research goal. Initial large-scale printing tests have been conducted at RCL (Figure 17).

CONCLUSION
Rough pass extrusion tooling provides a new fabrication methodology that dramatically advances the accuracy of full-scale spatial concrete 3D-printed lattices and other forms of concrete printing (Figure 18). Instead of refining the 3D-printing practice itself, and unlike other research projects that investigate 3D printing and subsequent post-processing, the method proposes to deliberately print a “rough pass” that can accommodate any fabrication inaccuracy that inevitably results from the material mixture and nozzle extrusion process. Utilizing common material mixtures, critically increasing structural bonding between concrete layers of higher viscosity, and reducing fabrication time, the method takes full advantage of the 3D-printing process by utilizing reusable gravel formwork, customizable surfaces, and structurally optimized tool-paths. In a second step—supported by the advancement of 3D scanning—accuracy and geometric intricacy is achieved locally along edges, in pockets, on surfaces, and in areas of joinery. The potential and advantage of this method is the incorporation of fabrication tolerances in full-scale concrete 3D printing, enabling concrete 3D printing to move beyond continual nozzle and material refinement, which often proves inadequate for complex connections and the integration of building systems. Exploring the notion of precision and inprecision in fabrication, the process recalibrates when and where either strategy might be adequately implemented. Procedural infidelity—not aiming to solve accuracy through 3D printing alone—enables a technically, methodologically, aesthetically, and performatively progressive multiprocess fabrication method that opens a new realm for concrete printing accuracy.

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REFERENCES


311 Full-scale prototype of sub-additive 3D-printed arch. Large prototypes that build on connection strategies outlined in this paper are a future next research goal.

312 Rough pass extrusion tooling provides a new fabrication methodology that advances the accuracy of full-scale spatial concrete 3D-printed lattices and other forms of concrete printing.

**IMPRECISION IN MATERIALS + PRODUCTION**


**IMAGE CREDITS**

All drawings and images by the authors.

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