



Robotic concrete surface finishing: a moldless approach to creating thermally tuned surface geometry for architectural building components using Profile-3D-Printing

Joshua Bard¹ · Dana Cupkova¹ · Newell Washburn¹ · Garth Zeglin¹

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Abstract

This paper focuses on describing a novel hybrid concrete printing/casting process we term Profile-3D-Printing. Profile-3D-Printing is an additive/subtractive manufacturing process that combines deposition of concrete for rough layup with precision tooling for surface finishing of architectural building components commonly found in the architectural precast industry. Our research team from Architecture, the Robotics Institute, and Material Science invented this novel hybrid manufacturing process for robotically printing architectural facade panels with complex surface geometries. This effort was motivated by previously validated research focused on calibrating the thermal exchange rate of vertical surface geometries for the purpose of improving both the esthetic and thermodynamic performance of passive heating and cooling systems in buildings. Our hybrid approach to concrete 3D printing is unique because it combines high-volume material deposition, multi-resolution surface finishing, and the ability for high customization without significant increases in production time. Our project will significantly advance systems integration between energy-based building performance design and advance additive manufacturing, enabling precast concrete suppliers to design and manufacture innovative architectural products with added value for end users in energy savings. This project serves as a template for other industries to adopt hybrid additive manufacturing systems to transform traditionally mold-based approaches. The goal of our project is to develop and test robotic 3D-printing systems that enable customization for high-resolution parts. Hybrid additive manufacturing (Hybrid-AM) enables automated tooling of soft and phase-changing materials to achieve fine feature resolution and finish quality independent of print nozzle size. Currently, speed of printing, control of finish quality, and flexibility of application are three of the most significant barriers for industries seeking to adopt additive manufacturing for part production. This project highlights how Hybrid-AM techniques, built on robotic work cells, address these challenges to enable customization of value-added products.

Keywords Additive manufacturing · High-performance design · Digital concrete · Thermal performance · Robotic fabrication

1 Introduction

Profile-3D-Printing is a process that explores the intersection of high-performance building design and advanced robotic manufacturing. This paper describes Profile-3D-Printing, a novel robotic fabrication process developed by our research team at Carnegie Mellon University. This hybrid additive/subtractive process combines deposition of concrete for rough layup with precision tooling for surface finishing. The

motivation for inventing this technique is rooted in previous research by the authors (detailed in Sects. 1.1 and 1.2) regarding the design of geometrically actuated high-performance building components and the robotic manipulation of soft materials for hybrid additive manufacturing (Hybrid-AM). In validating the fabrication approach, we champion forward design for building performance—in contrast to reverse engineering after initial design—through the design and fabrication of an array of concrete façade panels, thermally tuned to passively reduce heating and cooling loads through precise definition of surface geometry. The robust implementation of our Profile-3D-Printing method could positively impact not just the range of creative expression in

✉ Joshua Bard
jdbard@cmu.edu

¹ Carnegie Mellon University, Pittsburgh, PA 15213, USA

architectural form making, but also the ecological footprint of the built environment at large.

For the architectural precast industry, the merit of a Hybrid-AM approach to the production of concrete building components compared to other manufacturing approaches is twofold. First, our technique is moldless, saving expenses in wasted materials and increasing the possibility for part customization in production runs. Second, our tooled-deposition approach negotiates the constraints of rough and finish construction in a single process, producing high-quality surface finish of complex and variable surface geometries. Many other large-scale additive manufacturing techniques are single step and cannot achieve the required finish quality for usable parts.

Our initial testing with Profile-3D-Printing that targets the building facade industry is becoming a commodity market with little differentiation between prefabricated products. In this climate, value-added thermal design and greater customization give companies the technical advantage they need to excel in this space. Molds represent a low percentage of the unit-based cost of mass-produced concrete facade panels, but they can represent up to 80% of the unit cost for customized concrete products. By reducing the need for dedicated molds in the production of custom concrete products, architectural precast producers will gain a significant advantage.

Similar to many other industries, the precast industry is seeking to incorporate additive manufacturing approaches to produce usable parts at scale with high-quality surface finish. As we formalize the interaction of smart robotic tools with soft materials, adaptive robotic path planning in collaborative scenarios, and machine learning-based quality control, our systems could provide insight into other manufacturing sectors, such as culinary, aerospace, and biomedical industries, where the finish quality of phase-changing materials and composites is a concern. Although we focus in this paper on planar facade panels, Profile-3D-Printing can be applied to more free-form geometries, or used as a pure post-processing finishing technique. For instance, it could be applied as a finish surface in combination with emerging concrete mesh-mold technologies (Hack et al. 2014, <https://www.branch.technology/>). The authors plan to validate free-form applications in future work.

1.1 High-performance building component design and advanced manufacturing

This project builds on research exploring the seamless design of high-performance, passive building systems that are rooted in the combination of form and matter: topologically complex shapes using engineered materials. The authors have previously demonstrated that these components can be designed as passively activated thermal mass panels,

optimized for local climate and tuned to specific heat transfer coefficients through the articulation of surface geometry. In the previous measured experiment, we fabricated 45 panels with varied surface geometry features, but equal weight and volume. Topological surface variation of concrete panels with constant mass and surface area produced varied results in the rate of thermal transfer. The surface features, using varied smoothness and roughness of surface figuration, were optimized within five surface area families. This allowed us to measure the effectiveness of thermal mass and identify geometrically varied thermal profiles for each panel, within specific volume-to-surface area ratio group. The mass, material (UHPC concrete mixture) and surface area were exactly the same for each measured panel group, so there should be an expectation of the same thermal profile for each panel. However, this is not the case. There are significant differences in measured data for both cooling and heating rate that are caused purely by the surface geometry itself. We used the lumped capacitance method (LCM) (Holman and McGrawhill 2010) in combination with measured data to determine individual thermal profile for each panel, and to identify individual h (heat transfer coefficient) values, which contain average value of the differentiated thermal behavior caused by surface geometry only. (Cupkova et al. 2017) We have argued that by using the passive behavior of thermal mass more aggressively, it is possible to manipulate the surface geometry (Yao 2006) of architectural elements to strategically tune the thermal performance of building envelopes to specific climate while reducing heating and cooling loads (Cupkova and Azel 2015). However, such surface geometry results in complex form design that requires the bespoke mold-based manufacturing procedures.

Current building practices struggle with high levels of building component customization, because they heavily rely on mold-based production and subtractive milling (Fig. 1). Mold-based fabrication methods limit the diversity of construction due to the economics of mold reuse and material waste. Thus, current building practices exclude the greater formal range often required for high-performance building components that are both site and solar geometry specific. High-performance building design puts pressure on the building industry to develop new methods for the automated manufacturing of custom components. This research suggests direct formal relationships between the behaviors of airflow to toolpath planning for a robotic arm, to create an effective design to manufacturing path for geometrically complex and passively driven building designs.

1.2 Additive manufacturing for construction

Additive manufacturing (AM) techniques afford geometric complexity across scales, the possibility for customization, and the elimination or reduction of costly molds (Lim et al.



Fig. 1 (Left) Prototyping and (right) thermal testing of mold-cast UHPC panels with complex surface geometry

2012; Zhang et al. 2015). These technologies applied to construction (AMc additive manufacturing for construction) hold promise for the manufacture of high-performance building components, but are not yet ready for large-scale industrial production. Over the past two decades, AMc research has addressed some of the barriers to entry for architectural 3D printing in terms of build volume, production time, and economically viable mix design (Soar and Andreen 2012). Soar and Andreen, early pioneers in AMc, argue that if AMc is to have a larger impact on the construction industry, “It must realize greater performance than free-form esthetics alone. It will enable design freedom combined with greater function, and it must address sustainability head-on” (Soar and Andreen 2012). Thermally informed robotic topologies address these research challenges with particular emphasis on the creation of novel robotic construction processes and simulation-driven design tools.

Our team has developed and tested a hybridized additive manufacturing system for high-performance, modular concrete building components. The workflow is a complete path from modeling and simulation of thermally efficient surface geometries to the robotic deposition and finish tooling of concrete facade panels. The work explores the linkages between the geometric affordances of high-performance panel design and the kinematic freedoms of robotic motion and tooling. This connection between forward design for performance and robotic construction suggests a viable model for addressing the challenges related to the demand for customization of high-performance building components.

2 Methodology

2.1 Mix design

As part of producing an initial concrete mix for application in a tooled-deposition process, we considered the three

factors of workability, strength and aggregate size. It is known that lower water-to-cement ratios (w/c) increase the ultimate strength of concrete (Mehta and Monteiro 2006); however, this reduces the workability of concrete. Workability is a measure of yield stress and consistency that is difficult to measure quantitatively, but is usually evaluated in terms of slump or slump spread (Marar and Eren 2011). For Profile-3D-Printing, the concrete has to remain workable enough for effective and efficient deposition, while being stiff enough to maintain its shape after being troweled. Due to this factor, concrete sand with a large percentage of aggregate fines was selected for easy deposition and smooth incorporation into the concrete panels through troweling.

To reduce the w/c ratio while improving workability, admixtures were added to the concrete mixture. One such type of chemical admixture to obtain workability at low w/c ratios is superplasticizers (SP). During the 1980s, a copolymer of polymethacrylic acid and polyethylene glycol methacrylate (PEG) formed polycarboxylate ether (PCE) superplasticizers. These became one of the most widely used admixtures due to their ability to lower yield stress at low dosages in low w/c ratio cement (Marchon et al. 2017; Yamada et al. 2001). For our mix, a commercial-grade superplasticizer was obtained from BASF. We also included a viscosity-modifying agent (VMA), used to both reduce segregation and bleeding along with modifying flow properties (Leemann and Winnefeld 2007). A commercial VMA was also obtained from BASF and added to allow a thicker concrete for more controlled flow and to not allow separation to occur between the aggregate and water.

Type I/II Saylor’s cement was obtained and used for testing and ordinary tap water was used. The table below (Fig. 2) shows the mix for a typical optimized batch.

At these proportions, a 0.4 w/c ratio was used to tune workability. Both the superplasticizer and viscosity modifier were added in ratios consistent with BASF recommendations, and a delayed addition of SP and VMA was utilized.

Batch Mix	
Material	Amount
Aggregate (kg)	10
Cement (kg)	5
Water (kg)	2
SP (ml)	32
VMA (ml)	45



Fig. 2 (Left) Table: proportions of materials for a batch mixture, (right) early mix tests and finished panel prototype

Addition of 10% of the total water content was followed by 1 min of mixing until the rest of the water and additives were added and mixing was completed.

2.2 Component design and simulation

Our approach to high-performance passive thermal mass design is based in designing specific mass to surface area ratios for each panel. This requires variation of distributed mass depth across the surface, combined with control of surface smoothness or roughness that results in varied heat absorption and re-radiation rates (Cupkova et al. 2017). Our team's implementation of Profile-3D-Printing serves as a proof of concept in a larger effort to explore a highly customizable design space that links performance-based design to large-scale additive manufacturing. In contrast to the common design-to-construction pipeline which relies on reverse engineering of design intent to meet performance and fabrication criteria, our project stresses forward design for performance and fabrication. This approach requires the incorporation of computational methods to integrate simulation and construction planning with generative design tools.

The principles for modeling the geometry to produce controlled thermal delay in thermal mass have been described by the authors in previous publications (Cupkova and Promopatum 2017; Cupkova and Azel 2015; Cupkova et al. 2015). To summarize this approach, we used genetic algorithms to optimize the key geometric constraints of surface geometry related to area to mass distribution that directly affect thermal performance. Critical factors are the ratio between panel mass and surface area; smoothness of surface features varied through curvature degree of drive geometry; and increase of

surface area over identical mass through point-vector displacement constrained to u , v subdivision of base surface. Through multiple rounds of physical testing and thermal simulation, we identified a set of modeling principles that rely on curvature degree, scale, and orientation of surface pattern to delay or speed up heat re-radiation. As a result, we were able delay heat re-radiation of 35 °C by 75 min within 3 h (Cupkova et al. 2017). This is a significant thermal effect that argues for architecture and manufacturing that is tightly tuned to its thermodynamic design framework, while utilizing logics of computational geometry.

Thermal performance can be generalized through the difference between surface geometry and airflow geometry. Thermal pockets and their size play a significant role in thermal behavior. The visualization of thermal pockets and their relationship to curvature degree is shown in Fig. 3. The link between the modeling of performance-based geometries and the possibility for robotic construction was natural in the case of thermally tuned building components with thermal pockets. Panel geometries produced by Profile-3D-Printing are a combination of tool motion and profile knife geometry. Robot tool paths can be directly translated from target surface contours, and custom tool profiles can be directly back-engineered from surfaces generated based on thermal principles. While the direct link between thermal simulation and robotic fabrication is not yet fully automated, tool paths and tool profiles that produce surface geometry based on principles of thermal performance were tested extensively.

Based on this rubric, we generated a simulation test set to validate the concept of robotic surface figuration guided by performance logic. Design modeling of surface geometry using the UV constraints described above leads directly to

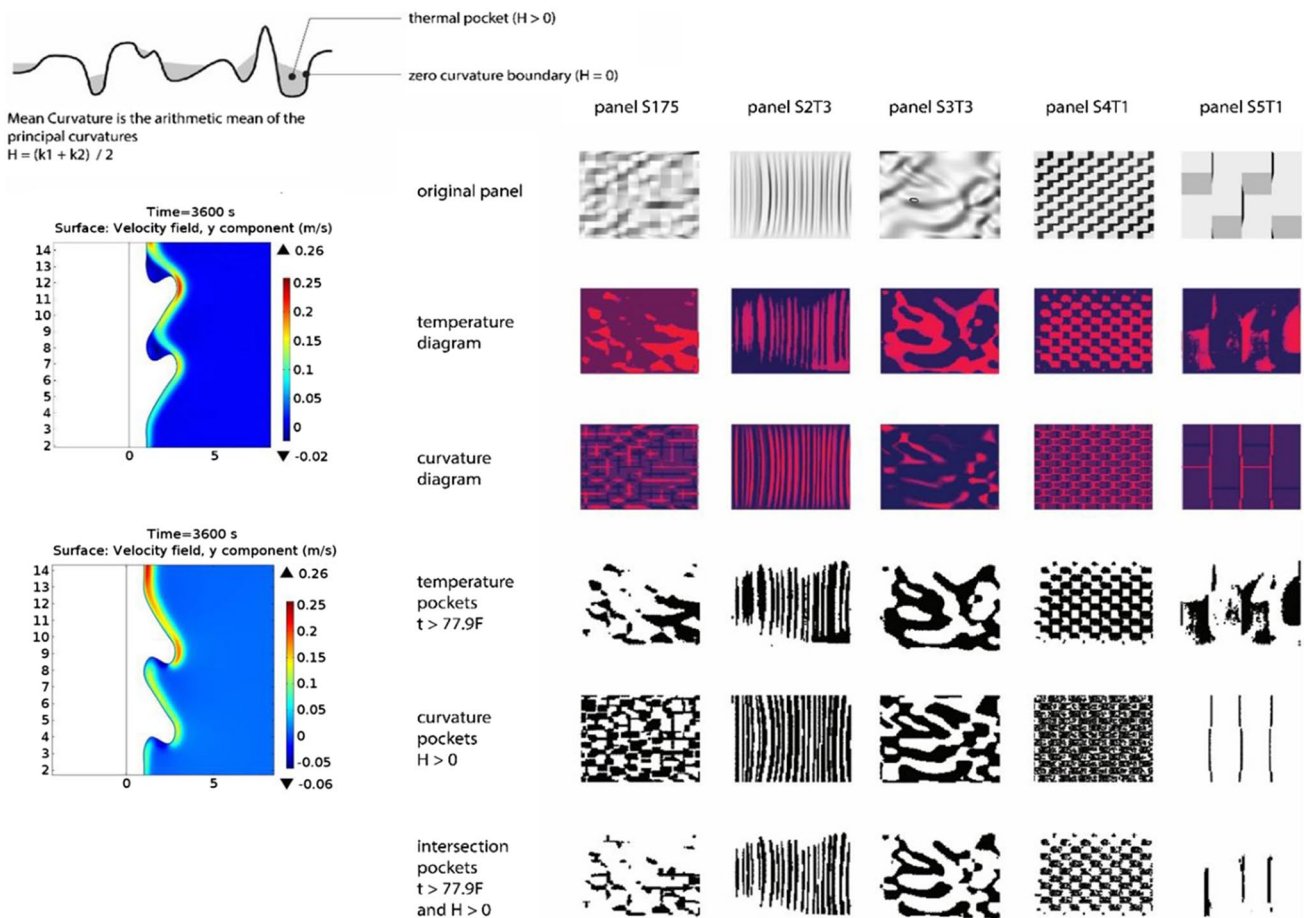


Fig. 3 Surface analysis and simulation of thermal behavior actuated by surface geometry. The difference between the geometry of airflow and surface geometry can be analyzed through mean curvature maps

toolpath and tool profile generation—the combination of which determines panel figuration. Our team captured a matrix of recorded simulations achievable with this fabrication approach (Fig. 4). As a set, the simulations explore performative parameters of the system related to size, depth and feature slope. A subset of these simulations were physically fabricated using Profile-3D-Printing and are discussed in the results section below.

2.3 Fabrication approach

Current AMc approaches are not well positioned to address the unique set of challenges inherent to constructing high-performance building components with thermally actuated surface geometries. All AMc must overcome the difficulties of building large objects at an economically viable time-scale. This typically entails a course contact zone—combining higher material delivery rates, larger step sizes, and expanded surface contact where finish tooling is involved. Larger contact zones result in a lack of resolution where global form can be approximated, but surface features are

not always possible. Thermally actuated surfaces, however, often require a high ratio of surface features to overall surface area. Traditional AM approaches address the need for higher resolution through fine contact zones, sacrificing build time. Fabrication approaches like Profile-3D-Printing address these competing constraints of high-volume output and fine surface feature resolution and could be broadly applicable to high-performance component construction requiring surface detail.

2.4 Tooled deposition

Our team has developed a novel approach to the construction of high-performance concrete building components with complex, thermally driven surface geometry. Profile-3D-Printing is a hybrid additive and subtractive process combining automated delivery of concrete for global layout and a profile knife with interchangeable heads for precise shaping of finish surfaces. A profiling knife is used to achieve finish shape by removing a small amount of material as the tool is swept across the rough layout. The removal

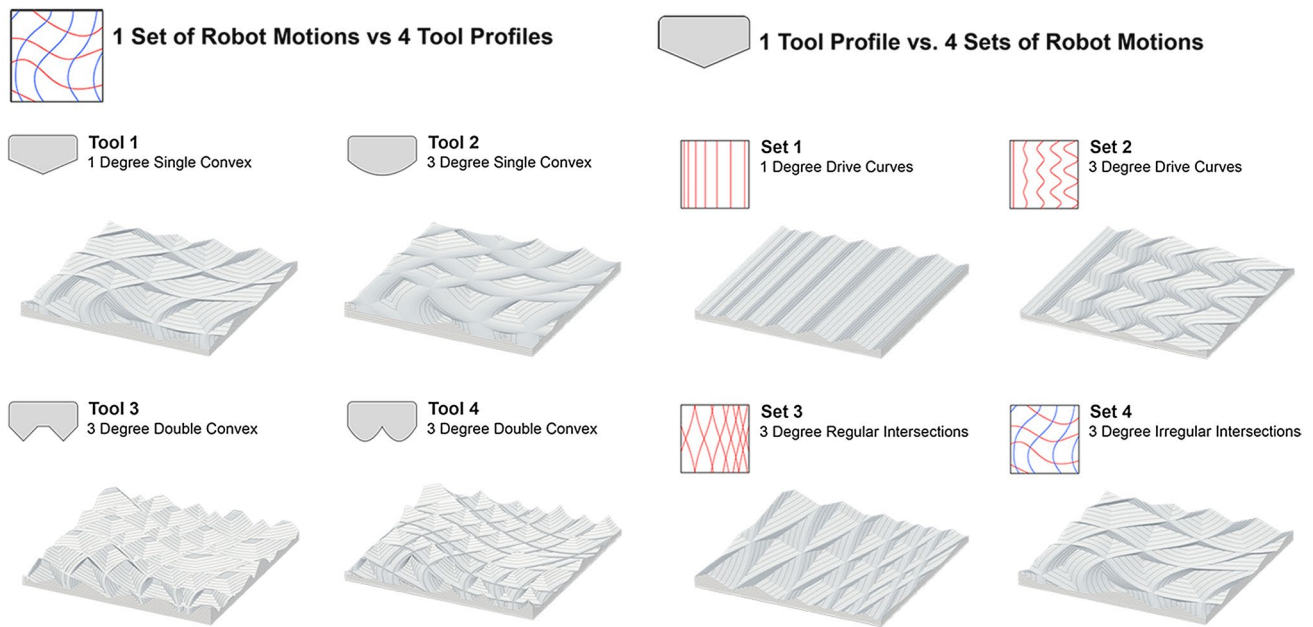


Fig. 4 Large geometric constraint space combining two main parameters of robotic fabrication process: tool profile and toolpath

process can be represented as the union of a set of sweeps of the tool profile along a collection of motion paths (Fig. 5). Sweep curves are ordered, subdivided based upon desired toolpath resolution, and populated with tool frames where tool Z is always normal to the target surface and tool Y is tangent to the path of travel.

This approach is closely related to traditional running molds commonly used in architectural plastering and benefits from the high level of surface detail and variation

common to these techniques (Bard et al. 2013) (Fig. 6). Unlike traditional running molds, however, Profile-3D-Printing incorporates the kinematic freedom and repeatability of robotic motion planning. The profile can be swept with 6 DOF and multiple sweeps can intersect each other to aggregate over larger areas. For architectural building components, like the facade panels demonstrated by the authors, the process results in seamless construction with near perfect fit to target geometry. Although not tested in this

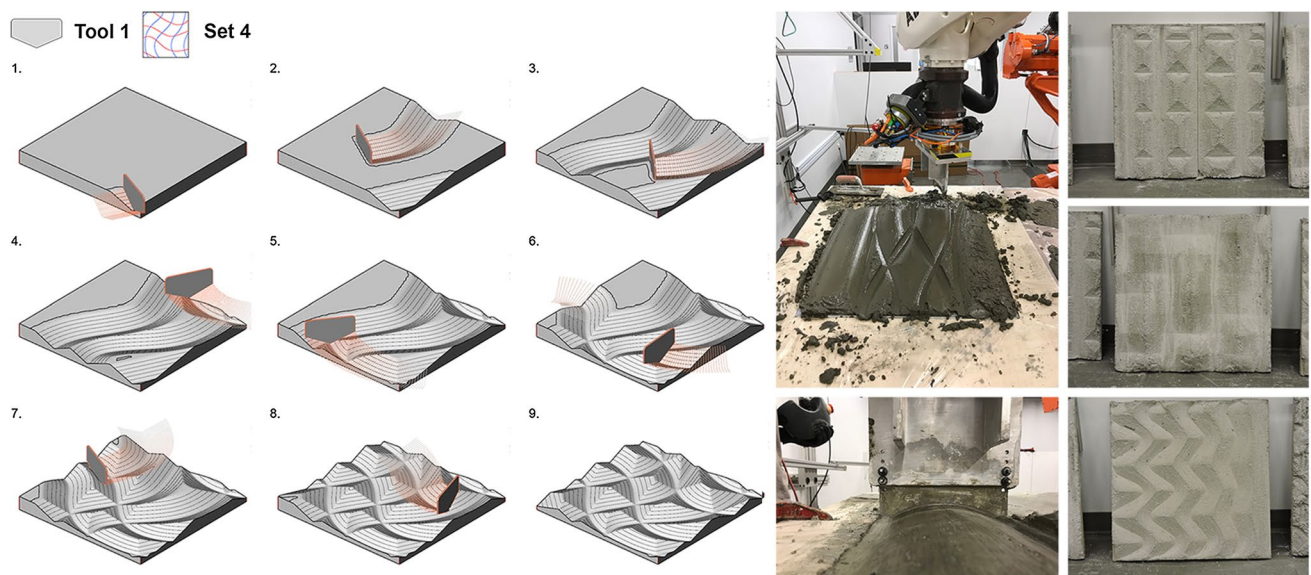


Fig. 5 (Left) Trowel toolpath for surface geometry. (Right) Sample concrete panel prototypes built with robotic work cell

(Only the self-weight of the float compacts the material as it skims across the surface.)

4. *Troweling* After floating, a series of troweling passes can be completed based upon the desired finish qualities. The size of the trowel and angle of attack change with each pass and regulate the amount of compacting pressure at the surface, leading to the degree of final compaction of surface fines. Smoothness and durability of finish are directly related to troweling. (Extra downward force is applied to the trowel to further compact the material.)

The precise timing of these steps varies with mix design, and environmental conditions at the time of finishing including relative humidity, temperature, and sun exposure. The ability to successively smooth the concrete surface as it cures, pushing larger aggregate below the finish surface, and compacting the surface fines are all relevant in the robotic finishing of concrete. Due to the prevalence of small, non-planar surface features in Profile-3D-Printing, industrial machines for floating and troweling floor slabs are not relevant for this robotic process. Instead, the constellation of hand tools and techniques traditionally used to finish concrete promise the most transferable lessons for robotic finishing of concrete. Section 3.4 will discuss the design and testing of a hybrid robotic tooling approach based upon the lessons learned from traditional concrete finishing.

2.6 Troweling vs. profiling

Profile-3D-Printing is similar to but distinct from contour crafting, a pioneering technique in the AMc domain combining mechanized extrusion and surface troweling (Khoshnevis 2004). Both processes apply bulk material along precise computed paths using robotic motion control and subsequently shape the material using a profiling tool. However, Contour Crafting exclusively uses a flat troweling tool in a single deposition-and-shaping pass with a single trajectory, and consequently contacts the surface only once. Profile-3D-Printing uses multiple tooling passes to both decouple the deposition and shaping trajectories and allow iterative refinement of the tooled surface.

The contrast between flat troweling and featured profiling of plastic materials is stark when considered through the lens of AMc resolution. With troweling approaches similar to contour crafting, there is a near one-to-one correspondence between extrusion step height and tool contact, where the smoothing action of a straight trowel is used to refine global shape resulting from layered buildup. As a result, seams between layers are often visible and cold joints between layers can be an issue (Wangler et al. 2016). In contrast, Profile Printing uses a profiling technique to shape fresh concrete that can be rapidly deposited. For any given tool

step, the knife profile can be shaped with smaller features than a trowel. As evidenced by historical molding profiles, profile knives can be fairly intricate. In the case of concrete fabrication, the limit for profile detail is constrained by the aggregate size used in the mix design. Thus given tools of equal width, a profile knife can render significantly finer features than a trowel with the same path of travel (Fig. 7). Another affordance of Profile-3D-Printing is that tooling and deposition can be asynchronous. This allows the profile knife to revisit areas to improve finish quality and for greater freedom in motion planning for panel form generation. All of these characteristics combine to make Profile-3D-Printing high output and high resolution.

3 Results

3.1 Workcell development

Our team has prototyped a robotic Profile-3D-Printing workcell using an ABB IRB 6640 robotic arm. Custom end-of-arm tooling includes an aluminum tool chassis to receive manually interchangeable profiling plates. The 175 mm-wide profiling plates are waterjet cut from 1.5 mm-thick stainless steel. A custom 3D printed nozzle mounted in front of the profiling knife produces even material distribution across the width of the blade for concrete delivery. Concrete material is delivered from a pressurized canister (5–10 psi) mounted off-arm. Material flow is controlled via an inflatable bladder located in the delivery nozzle. Canister pressure and bladder inflation are actuated using digital outputs from the ABB robot controller. Material flow rate at peak delivery is roughly 15 L/min with a maximum tool traverse speed of 30 mm/s. Depending on overall panel thickness and edge geometry, reusable formwork can be used to support boundary walls. Layup without perimeter formwork is possible, but requires robotically trimming panel edges with the profile knife after finish shaping. Where panel boundaries are repetitive, sidewalls are preferable. Where panels are irregular, robotic post trimming is more suitable.

3.2 Panel test series 1: testing for process constraints

After initial setup and verification of the Profile-3D-Printing process, our team conducted empirical tests on eight different test panel geometries. The goal of the physical prototyping was to develop heuristics for estimating material behavior and choosing tooling constraints. These constraints impact overall fabrication quality and directly inform the design space of potential surface geometries. Key parameters of the process related to finish quality and panel design include: maximum depth of panel per

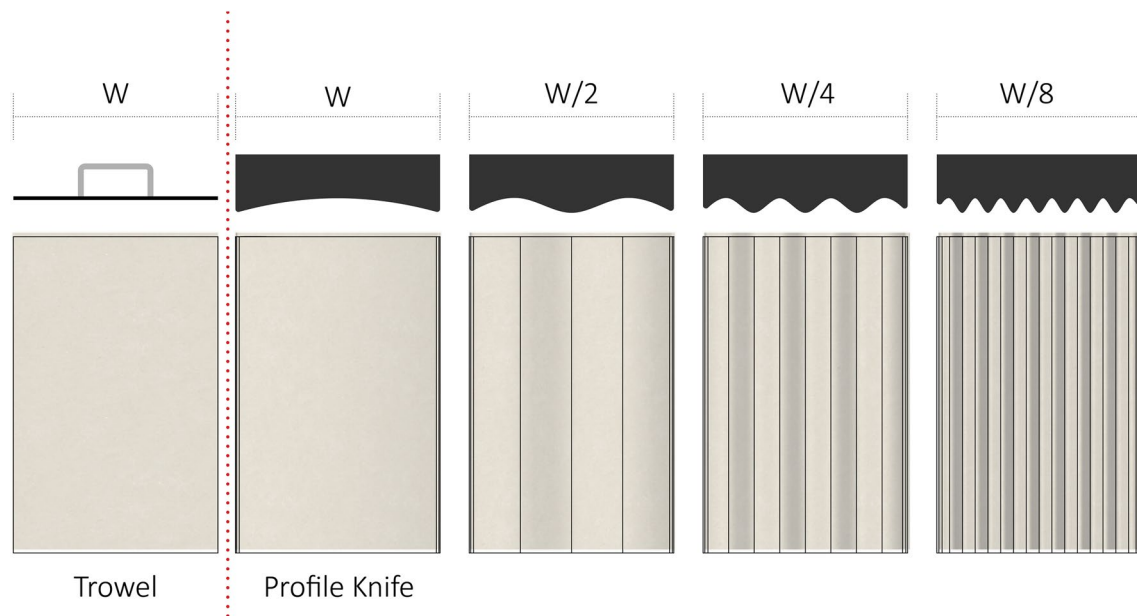


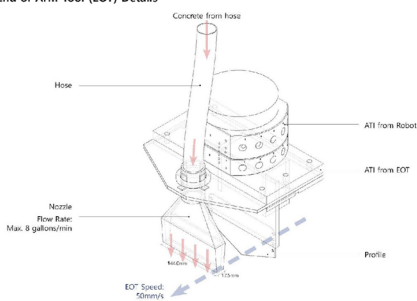
Fig. 7 (Left) Profile knives can have significantly more features than a trowel of identical width

build (determined by tool Z translation of profile knife), maximum slope of surface features (determined by profile shape and tool X rotation during travel), and maximum rotation of the profiling knife out of plane with the frame perpendicular to the direction of tool motion (determined by tool Z rotation during travel) (Fig. 8).

3.3 Panel test series 2: demonstration of tool-deposition geometry space

To explore and demonstrate the geometric constraint space of Profile-3D-Printing, our team created a design system for panel generation and tested the physical fabrication of eight panels from a series of digital target models, selected from the design simulation process described in Sect. 2.2. These

End of Arm Tool (EOT) Details



Material and tooling constraints for tool-deposition	
Max tool slope (toolX)	45 degrees
Profile Knife Attack (toolY)	Normal to drive surf.
Max tool rotation (toolZ)	60 degrees
Max build depth	150 mm
Max traverse rate	30 mm/s

Heuristics developed from physical tests panels.

Robotic Workcell and End of Arm Tool Development

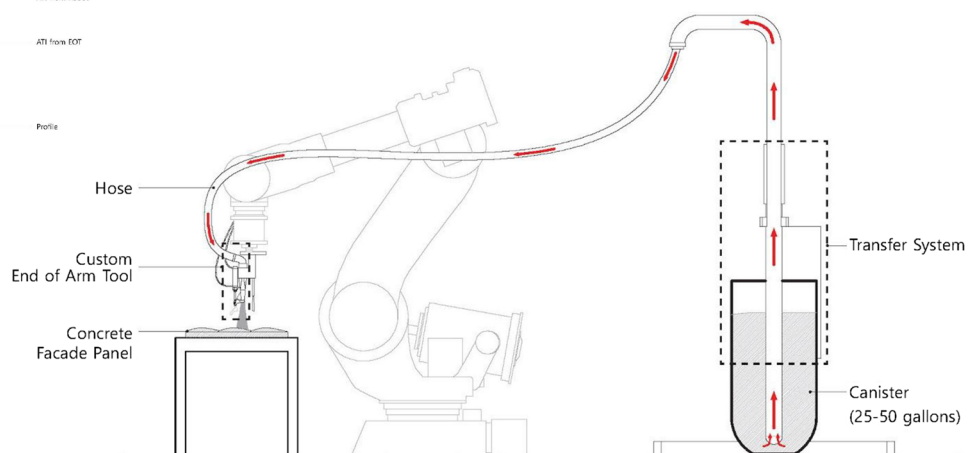


Fig. 8 Heuristic material and tooling constraints garnered from empirical testing of panel creation and diagram of robotic workcell and tooling

tests confirmed that Profile-3D-Printing affords the ability to create varied surface geometries with fine to coarse resolution control of surface features relative to total panel area. Designers can interact with two primary drivers to explore overall panel geometry: (1) knife profile geometry and (2) toolpath controlled through robot motion planning (Fig. 9). The combinatorial results of these two drivers creates a robust space for design and thermal performance.

3.4 Testing multi-step finishing tools

To improve build speed and finish quality, a number of custom tooling heads were designed (Fig. 10) and tested to parallel the salient features of traditional concrete finishing. In addition to testing tool geometry, we tested external vibration and oscillations into the path planning

approach. Combining the results from these tests contributed to improved finish quality and increased speeds in overall tooling. This section briefly summarizes the results of our physical testing and their impact on the finishing process (Fig. 11).

1. *Vibration* We added an external vibration device to the end-of-arm finishing tool, hoping it would reduce tearing of the top surface during initial material removal. While it did reduce tearing, the vibration exceeded the yield stress of the fresh mix and induced material flow, deforming the target geometry.
2. *Sawing* We introduced a sawing motion into the rough finishing tool pass to help reduce tearing of the top surface during initial material removal and increase tooling speeds. This was achieved by adding a tool Z offset

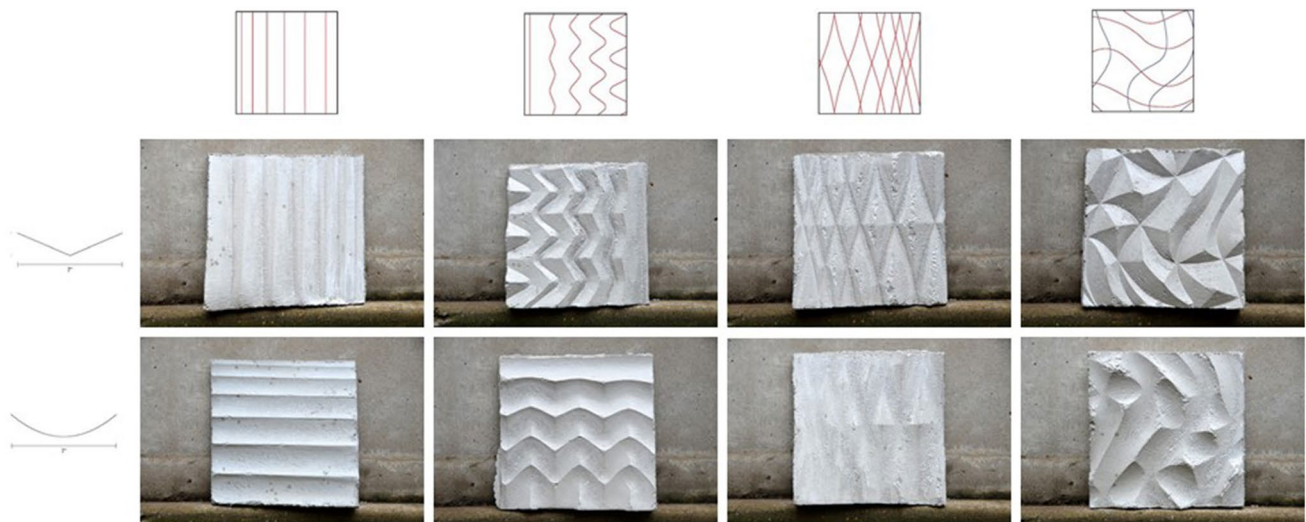


Fig. 9 Tested panels (0.6 m×0.6 m) printed without the use of molds using two profiles and four sets of drive curves



Fig. 10 Examples of interchangeable, custom 3D printed tool heads for rough and finish surfacing of concrete tested by authors with inset of finished pattern

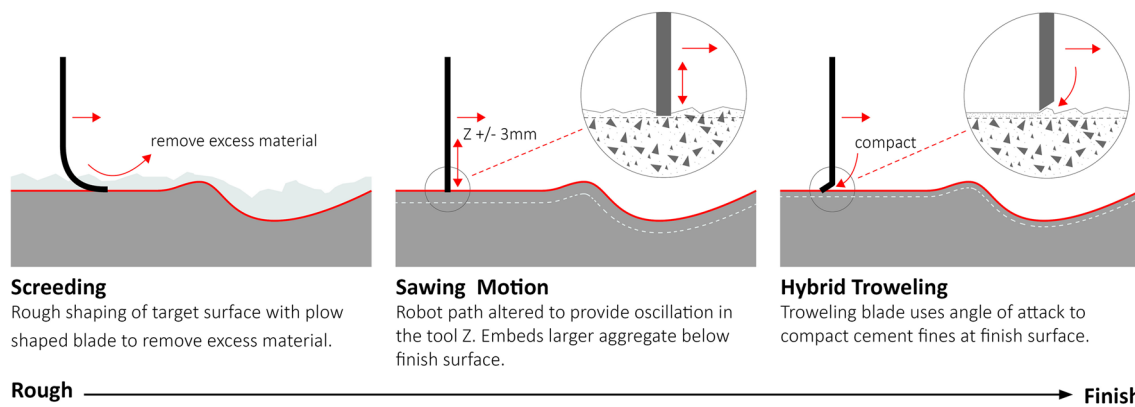


Fig. 11 Diagram illustrating hybrid approach to robotic finishing of concrete, from rough shaping to surface finishing

of -3 mm to alternating robot targets along the path of travel. The altered path planning did improve rough layup finish quality and increased acceptable traverse speeds. It also had the added benefit of embedding larger aggregate below the finish surface.

3. *Screeding tool head* We designed and tested a tool head that would mimic the screeding process in traditional finishing. The tool head removes excess material for rough shaping of the target geometry. The tool also uses a plow like shape to move material up and away from the cutting edge of the tool. This feature keeps excess material from building up at the point of cutting.
4. *Hybrid troweling/profile tool head* We designed a hybrid finishing tool head that increased surface contact at finishing, compared to a thin gauge metal profiling blade and introduced a chamfered edge to compact material during travel. This geometry mimicked the angle of attack for finish troweling and helped to compact cement fines at the finish surface.

The combination of these path planning techniques and interchangeable tool heads increased the maximum finishing speed to 100 mm/s , a roughly 300% improvement compared to earlier tests and improved the visual finish quality of the tooling process. The ACI designates four concrete surface categories (CSC) to evaluate architectural concrete surface finish (ACI Committee, American Concrete Institute, and International Organization for Standardization 1988). Our finishing technique currently meets two of the four criteria for the highest finish designation, CSC4. These are: color uniformity, and surface irregularities (less than 3 mm deviation under 1.2 m straightedge). We still need to improve in the solid to void ratio (less than 0.3%) and texture (offsets below 3 mm) categories. Our results in these categories are currently above 1.0% solid to void ratio and offsets up to 6 mm , which is designated as CSC3. Future work in surface touch-up will address these limitations.

4 Conclusion

4.1 Outlook

Our interdisciplinary team is still actively engaged in furthering this research and currently working to develop a number of key project trajectories. These include: (a) quantifying the timing and forces applied to concrete by robotic tooling during the curing process; (b) implementing a pump-based delivery system for larger batch production and less mix separation induced by the current pressurized delivery approach; (c) developing collaborative toolkits for humans and robots to participate in surface touch-up and secondary part placement in the concrete matrix during printing; and (d) developing a design and simulation plugin to harness machine learning for part production and knife design.

4.2 Summary

Our central hypothesis is that a forward approach to facade panel design can simultaneously achieve high-performance thermal design and cost-effective manufacturability in individually customized components. The forward approach closely integrates geometric optimization with a parameterized fabrication process to satisfy thermal objectives within the space of feasible tooled surfaces. Our prototyped system demonstrates a forward design workflow using geometrically induced thermal rate coefficient values and the novel Profile-3D-Printing robotic fabrication process. Our experiments to date have produced concrete panels with high geometric tolerance and fine surface finish within acceptable fabrication costs (Fig. 12). We believe this represents a scalable solution with strong potential for future commercial production in the architectural precast industry.

While there have been many advancements in concrete rheology for 3D printing to improve material delivery and avoid cold joints during the layerwise printing process,



Fig. 12 Tooling process and finished panel demonstrating Profile-3D-Printing

surface finishing remains an important issue for producing usable parts economically at scale. Profile-3D-Printing provides a framework for robotic concrete finishing with clear implications for the building industry's transition to additive manufacturing. Lessons learned from this process can also provide insight for other industries and material processes including ceramics, plaster, terracotta, and biocomposites. Profile-3D-Printing points to the fact that advances in hybrid tool design, robotic path planning, and advanced material design could make moldless production of custom products logistically and economically viable in industry.

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