Janus Printing

Coextrusion based Multi-material Additive Manufacturing for Ceramics

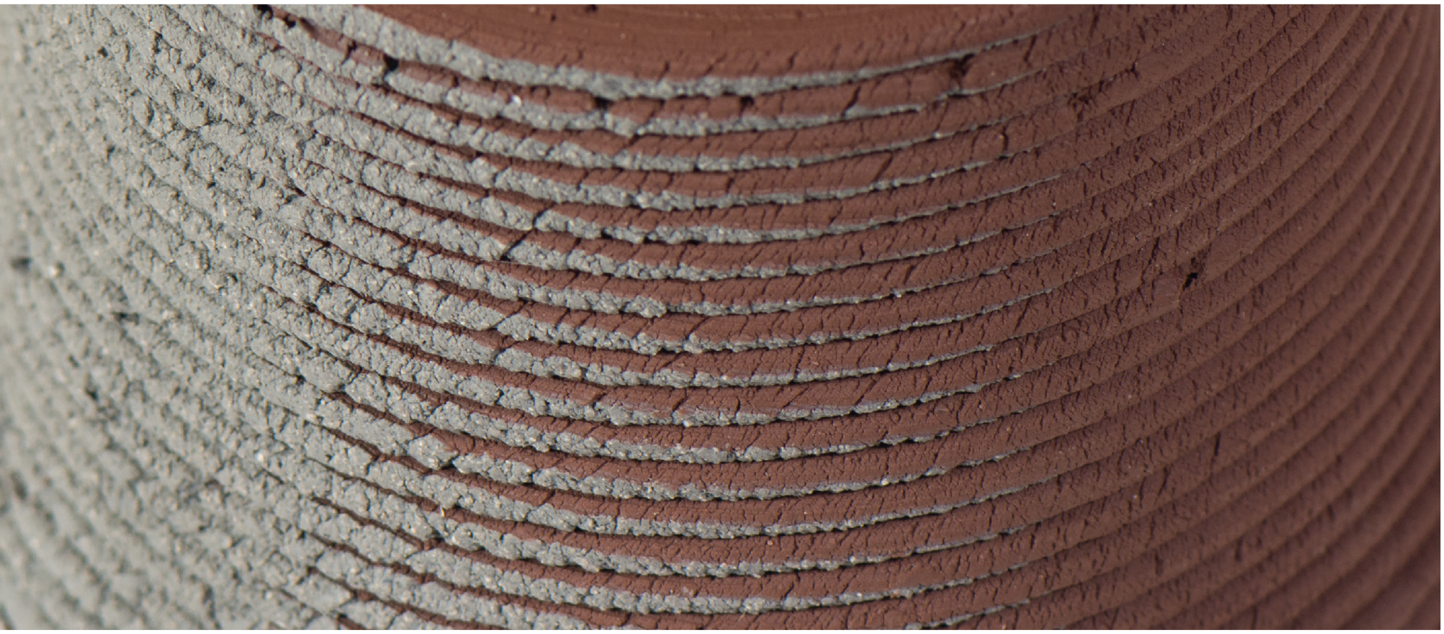
Zach Seibold
Material Processes + Systems Group (MaP+S), Harvard GSD

Saurabh Mhatre
Harvard Center for Green Buildings and Cities & MaP+S , Harvard GSD

Suleiman Alhadidi
Material Processes + Systems Group, Harvard GSD

Jose Luis García del Castillo y López
Material Processes + Systems Group, Harvard GSD

Martin Bechthold
Material Processes + Systems Group, Harvard GSD



1 Close-up of the material transition in a printed toolpath.

ABSTRACT

The benefits of additive manufacturing technologies for the production of customized construction elements has been well documented for several decades. Multi-material additive manufacturing (MM-AM) enhances these capacities by introducing region-specific characteristics to printed objects.

Several examples of the production of multi-material assemblies, including functionally-graded materials (FGMs) exist at the architectural scale, but none are known for ceramics. Factors limiting the development and application of this production method include the cost and complexity of existing MM-AM machinery, and the lack of a suitable computational workflow for the production of MM-AM ceramics, which often relies on a continuous linear toolpath.

We present a method for the MM-AM of paste-based ceramics that allows for unique material expressions with relatively simple end-effector design. By borrowing methods of co-extrusion found in other industries and incorporating a 4th axis of motion into the printing process, we demonstrate a precisely controlled MM-AM deposition strategy for paste-based ceramics. We present a computational workflow for the generation of toolpaths, and describe full-body tiles and 3D artifacts that can be produced using this method. Future process refinements include the introduction of more precise control of material gradation and refinements to material composition for increased element functionality.

INTRODUCTION

The benefits of additive manufacturing technologies (AMT) have been well documented and explored since the invention of the process nearly 30 years ago (Huang et al. 2013). Multi-material additive manufacturing (MM-AM) expands AMT by equipping 3D printed objects with an additional layer of region-specific functionality. Doing so potentially increases the design and performance scope for AMT (Bandyopadhyay and Heer 2018). MM-AM processes have been explored by architects and designers for a variety of materials, particularly in the realm of functionally graded polymers (FGMs) (Oxman, Keating and Tsai 2011; Tibbits et al. 2014; Huang 2016), but the current development status is largely academic in nature, with little to no work ready for applications in actual buildings.

Functionally graded materials have been defined as materials that vary in structure or composition gradually over a volume. Several processing techniques have been established for FGMs, with much recent focus on AMT as a method of FGM production (Kieback, Neubrand and Riedel 2003). The basic structural unit of a printed FGM component is referred to as a maxel, a discrete 3D volume with a specific material composition, the scale of which is defined by print resolution, or voxel size.

Ceramic tile has not been of much interest to AMT because industrial production methods of flat clay shapes are highly advanced, and surface ornament is applied through colored glazes. There seems little need to advance AMT for tiles - a myriad of flat tile designs are easy to generate and produce economically. Glazed tiles, however, can fail through glaze cracking or chipping, and damaged glazed tiles cannot be repaired. This often leads to the re-tiling of entire tile surfaces. Full-body tiles offer a solution in that such unglazed tiles can be reground and restored to deal with staining or minor surface wear and tear. Indeed, the industry has recently refocused on large full-body tiles for furniture or countertops, or unglazed full-body porcelain tiles used in applications requiring high wear resistance (Bechthold, Kane and King 2015). But such tiles - extruded or dry-pressed – are limited to single colors and cannot accommodate more intricate decorative patterns.

The present study advances MM-AM in the context of printing decorative unglazed tiles whereby the design is achieved through depositing different color clay bodies in accodance with the desired design. There are presently no digitally supported methods for producing such full-body tiles. Historic precedents include encaustic tiles that were especially popular at the turn of the 20th century. They featured rich full-body ornamentation produced by manually impressing a stencil pattern into unfired clay tiles. The resultant intaglio pattern was subsequently filled with a clay body of another color to produce ornamental tiles without the use of a glaze, resulting in elaborately detailed and durable products (Clay Record 1893). This process, however, is labor intensive and not economically feasible today. The authors present a digital solution to this traditional approach, replacing steel stencils with robots, a multi-material printing system and the associated digital workflow.

The presented research, titled Janus Printing, incorporates a new nozzle that extrudes two clay bodies such that a 4th axis rotation generates different visible colors on the part surface. We demonstrate the process through multi-color full body flat tile prototypes and several 3D objects. The name Janus alludes to Roman mythology, wherein Janus represented a two-faced god (Gagarin and Fantham 2009).

Future work will expand this approach to modify the thermal and structural properties of clay bodies to achieve results that produce not only aesthetic, but also performative gradation throughout a volume or part surface. The design of the robotic printer and certain features of the workflow, under development at the moment, build on and expand what is being presented here.

BACKGROUND

Customization of Ceramic Tiles

In the past decades digital tools for design and production, coupled with advances in material science and production technology, have facilitated the customization of ceramic building elements. The tile industry has focused on digital inkjet printing technologies as the most economical approach to systematically customize the surface appearance of ceramic tiles (Hutchings 2010; Dondi et al. 2014). More academic research has explored numerous methods of formal customization of ceramic construction elements, using both established production processes such as extrusion or slip casting (Weston 2013; Andreani and Bechthold 2014), as well as more novel forms of production, such as additive manufacturing (Bechthold 2016).

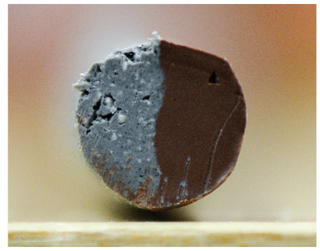
Additive Manufacturing of Ceramic Design Elements

AMTs for ceramics have been under development since the 1990s, including slurry-based processes such as stereolithography and inkjet printing, powder-based processes such as selective laser sintering, and bulk solid-based processes such as fused filament fabrication (FFF) (Chen et al. 2019). The research presented in this paper focuses on paste-based extrusion, a process in which successive beads of viscous ceramic slurry are deposited on a printing surface to form a 3D object in a process similar to coil pottery. Paste-based ceramic AMT has been explored at the scale of the architectural component since the early 2000's. Research by or under the guidance of Khoshnevis established a method known as Contour Crafting, whereby moist clay was deposited onto a flat printing surface and smoothed by a small trowel that rotated on the 4th axis to reduce the striated appearance of the prints (Kwon 2002; Khoshnevis 2004).

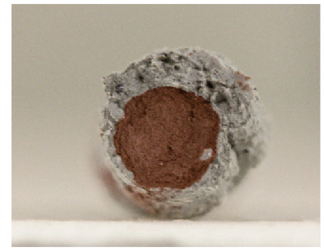
Like FFF, Paste-based ceramic AMT is notable for its relatively low cost, simple tooling and accessibility, yet many challenges remain (Bechthold 2016). Material viscocity makes clean start and stop points difficult to achieve, often requiring a continuous flow of material and careful toolpath planning for printed parts (Li et al. 2017). High viscosity also produces a lag between material transitions in multi-material printing configurations. While the process is notable for its ability to produce complex 3D shapes without significant fixed tooling costs, paste-based ceramic AMT has not yet been adapted to industrial production. Cost and precision remain problems when considering the process at the industrial scale (Bechthold 2016).

Recent research has expanded the potential of paste-based ceramic AMT in several ways. Multiple research teams have paired novel computational workflows with material-centric research methods to develop strategies for non-layerwise material deposition (Friedman, Mesa and Kim 2014; Rosenwasser, Mantell and Sabin 2017; AlOthman et al. 2018; Im, AlOthman and García del Castillo 2018). These projects have focused on material economy or sought to leverage the inherent plasticity of moist clay to produce expressive forms. Examples of dual or multi-material paste-based ceramic AMTs exist in the arts, such as Olivier Van Herpt's Arcanum project or the Bad Ombres project by Emerging Objects. However, material variation is not precisely controlled, as it is achieved by pre-mixing multiple types of clay as it is loaded into the extrusion cartridge (Van Herpt n.d.; Rael and San Fratello 2018).

Techniques for multi-material fabrication in other FFF 3D printing processes have been developed for single and multi-nozzle processes (Song and Lefebvre 2017; Kuipers, Doubrovski and Verlinden 2017). Multi-material direct ink writing processes have been developed for ceramics, such as Robocasting by Cesarano and others and the CODE process by Li and others, though both applications were developed at a relatively small scale (Cesarano, Segalman and Calvert 1998; Li et al. 2018). The general promise of multi-material printing is the potential for enhanced part functionality and the reduction of multiple fabrication steps



2



3

into a single approach. The present research advanced our technical knowledge of this emerging area for printing of construction-scale ceramic components.

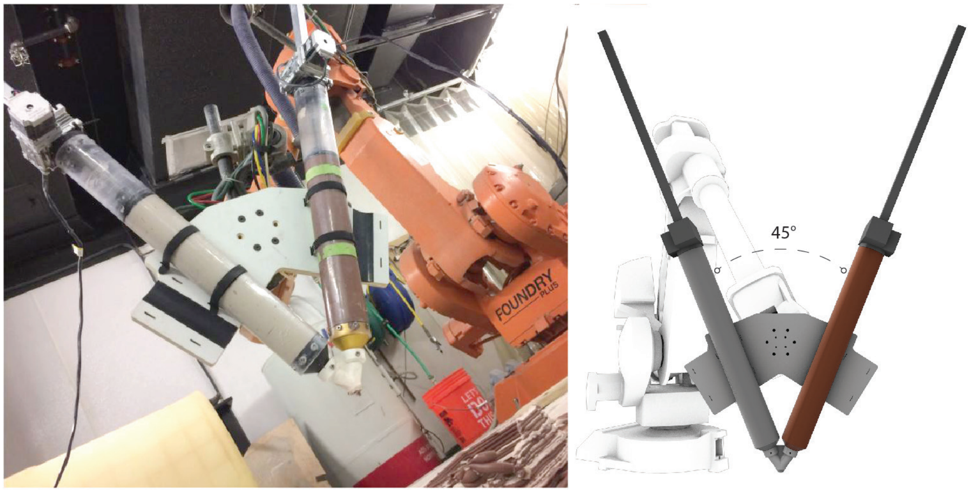
Coextrusion

To develop a low cost, simple means of multi-material fabrication for ceramic pastes, the research team looked to established extrusion techniques for viscous materials in other industries. The process of coextrusion is most notable, defined as the simultaneous extrusion, through the same die, of two or more materials in combination (Atkins and Escudier 2013). Typically used to manufacture complex material assemblies in a single process, coextrusion technology was first patented for the production of pencils in the 19th century, where presswood and graphite were extruded simultaneously. The process was later adopted by the plastics industry in the 1940's. Coextrusion remains a common fabrication method for a variety of pipe, panel and core-shell profiles (Maniruzzaman 2013). Recently, the process has been adopted by the food industry to produce products with variable texture flavor or color (Simitchiev, Nenov and Lambrev 2010). In the context of paste-based ceramic AMT co-extrusion has not been researched.

Janus Printing

The term Janus has been adopted by the scientific materials community to describe particles exhibiting two distinct physical or chemical properties on opposing sides. The first published use of the term by Casagrande referred to glass spherical particles with one hemisphere hydrophilic and the other hydrophobic (Casagrande 1989). Materials composed of Janus particles exhibit different properties on the front and back, and have been used in various fields as interfacial membranes, 2D sensors or actuators, or oil/water separation membranes (Ng, Noor and Zheng 2018).

Conceptualizing the print bead as a coextruded, Janus-type arrangement of material provides several new design opportunities that have not yet been explored for paste-based Ceramic AMT. Incorporating a 4th axis in the print setup expands these opportunities, enabling unique material expressions that are impossible to manufacture by other means and embedding the process of ornamentation within the production of the tile itself.



4

2 Cross section of janus bead with diameter 6mm.

3 Cross section of center core bead with diameter 8.3mm.

4 Photograph of the printing setup (left) and diagram of the end effector showing the angled configuration of the extrusion cartridges (right).

METHODS

This section describes the digital workflow and the related printing process using clay bodies of two different colors. While nozzle design and print parameters are specific to the clay bodies of the study, the workflow is able to support a range of different clays with additives that modify porosity, shrinkage and other properties. In the present study, the combination of the janus bead and 4th axis rotation produces novel ceramic components (Figures 1 and 2).

Physical Setup

Print samples were produced using a custom-designed end-effector mounted to a 6-axis ABB IRB-4400 robot. The end-effector integrated two commercially available, electromechanically actuated piston extruders with a cartridge capacity of 2000 ml. A Y-shaped 3D printed ABS nozzles combined the material flow from each extruder into a single print bead. The extruders were mounted at a 45 degree angle in order to minimize the flow distance of the clay bodies within the nozzle (Figure 3).

Clay Selection

Several clay bodies were tested to determine overall printability and compatibility with one another. The primary goal was to find two clays of different colors that would produce predictable results when fired together. Early studies determined that clays with notably different firing ranges, aggregate contents or shrinkage rates could be successfully coextruded and dried, through careful attention needed to be paid during the firing process. Parameters for the clays used in the presented research are summarized in Table 1. Prior to printing, the moisture content of clay was adjusted by adding 16-20oz of water per 25lb of moist clay, resulting in a hardness of 1.8-2.0kg/cm2 measured using a standard pocket-style penetrometer with a 25mm diameter plunger.The initial firing of print samples to cone 6 (1200° C) resulted in substantial cracking of the samples. A slow firing program to cone 04 (1050° C) was far more successful, with only minimal hairline cracks in some printed samples.

Table 1: Parameters of Clay Bodies Used During Printing

Manufact.	Clay Body	Firing Range	Shrinkage	H_2O Abs.
Standard	103	C/06-2	9% (C/06) 14% (C/2)	12% (C/06) 6% (C/2)
Standard	420	C/2-6	7% (C/2) 8% (C/6)	8% (C/2) 1.5% (C/6)

Computational Workflow

The authors developed a new computational design-to-fabrication process that allows for precise control of the print bead orientation along the toolpath (Figure 4), which in turn produces the desired colors in a printed component. Rather than modifying the ratio of one clay body to another, the rotation of the 4th axis determines color tonality. Developed using the Grasshopper plugin for Rhino 6.0, the workflow streamlined the prototyping process by producing RAPID code directly in Grasshopper, and connecting to ABB Robotstudio software in real-time to simulate robot movement prior to printing.

Computational multi-material deposition workflows exist for voxel-based modelling engines such as Monolith (Michalatos and Payne 2013), however such workflows are not designed to create the continuous toolpaths needed for paste-based ceramic AMT. The workflow presented in this research allows for the janus bead exiting the nozzle of the double extruder to be rotated such that ceramic surfaces appear in clay color A, clay color B, or as a mix of both colors. The bead orientation, controlled by an axis 4 rotation, can be generated using either 3D surfaces or grayscale images as an input. For surface input, the script converts one or multiple surfaces to toolpaths with bead orientations that turn the desired clay A or B towards the visible side of the component. Based on the surface selected, the script converts the change in material to a rotational vector value; at each toolpath target, the script checks for a change in material orientation and determines the amount of axis 4 rotation needed. For the image input, the degree of rotation is determined by the grayscale value at a given location in the image (Figure 5). Print fidelity can be controlled by adjusting the number of toolpath subdivisions/sample points.

Utilizing Machina, an open source Grasshopper add-on (García del Castillo 2019), the sequential list of targets (linear toolpath) and material assignments (axis 4 rotations) is designed through a high-level language of actions, which are later compiled to robotic instructions in ABB's native RAPID language. Machina also provides control of multiple robot properties such as tool definitions, speed, zone (blending radius) and I/O control. The RAPID program can be simulated in an ABB Robotstudio environment to confirm the intended printing outcome.

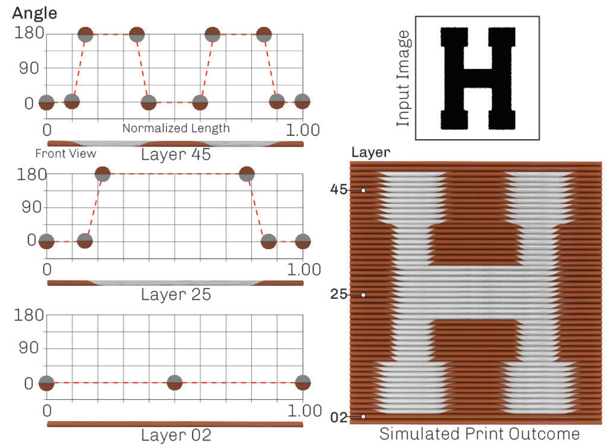
Toolpath Design

Process parameters from previous research by the MaP+S Group informed printing speed, nozzle size, and print bead dimensions (Seibold et al. 2018). Early tests established parameters specific to the 4-axis coextrusion process, such as the rotation speed of the 4th axis (Table 2). Several parameters were determined by the characteristics of the material while others were a function of the limitations of the robotic arm.

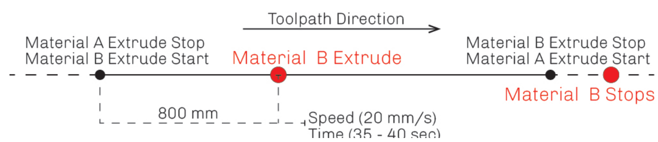
Table 2: Process Parameters

Parameter	Amount	Units
Print Speed (Layer 01)	18 - 20	mm/s
Print Speed (Other Layers)	35 - 40	mm/s
Rotation Speed	255	deg/s
Rotation Extents (4th Axis)	-90 - 90	deg
Layer Height	1.8 - 2	mm
Bead Width	6 - 10	mm

Prior research has shown the difficulty of stopping and starting the material flow of non-newtonian viscous materials such as ceramic paste, a constraint that often leads to a continuous toolpath for successful 3D printing in clay. Similar challenges were found while co-extruding two clay bodies through the Y-shaped nozzle. A dedicated study was conducted to shed further light on how material flow can be alternated as an alternative to rotating the janus bead. The robot parameters and material behaviors are summarized in Figure 6. Switching between the two materials required 35-40 seconds of printing, equivalent to 700 - 800 mm of printed bead. Residual pressure in the non-extruding



5



6

5 Computational logic for nozzle orientation, showing the relationship between image tonal value (upper right), simulated print (lower right), and axis 4 rotation of the end effector along several typical print layers (left).

6 Diagram showing parameters for transition between material A and B.

cylinder, combined with flow friction within the nozzle, led to a small portion of the extruding material essentially dragging out the non-extruding material. Even with one cylinder completely stopped the bead therefore contained traces of the material contained in the non-extruding cylinder.

Several studies tested the feasibility of compensating for the delay when switching or transitioning between clays. Offsetting the material transition points within the toolpath produced unpredictable results, as the distance required to transition between materials varied by up to 100 mm. Moving the end effector to a "home" position during the transition phase dramatically increased printing time and produced undesirable artifacts at stop/start locations.

Simultaneous co-extrusion avoids several of the problems encountered when transitioning between clay bodies. Rotating the 4th axis can produce printed artifacts that reliably and precisely display the desired clay colors merely through the rotation of the janus bead, thus circumventing the shut-off problems in paste-extrusion.

RESULTS

Nozzle Design

Several customized nozzle designs were developed in response to the material and process-specific constraints described above, enabling the production of multi-material assemblies by combining material flows from two separate extruders (Figure 7). An initial prototype mounted the extruders parallel to one another. In this version, the distance between the end of the cylinders and the end of the nozzle lead to significant friction between clay and nozzle walls. A subsequent version oriented the two cylinders tilted at an angle of 45 degrees to each other, reducing material travel distance and minimizing resistance. Computational flow simulations turned out to be less useful for this preliminary optimization compared to iterative physical testing. The nozzles produced two distinct configurations of material within a single print bead, a bifurcated "Janus" bead and a concentric "Center-core" bead (Figure 8). The designs were evaluated through a standard set of test prints.

For the Janus Nozzle, the end of the two linear extruders were merged into a single 6 mm diameter nozzle. Figures 8 and 9 summarize the design affordances of the nozzle.

The center core nozzle used the same 45 degree angle configuration of two linear extruders as the Janus nozzle, but encapsulated one nozzle inside of the other. This novel type of nozzle is capable of producing 3 unique types of extrusion - one material encapsulated in the other, a single-material hollow bead, or a smaller (3mm) diameter solid bead (Figure 8).

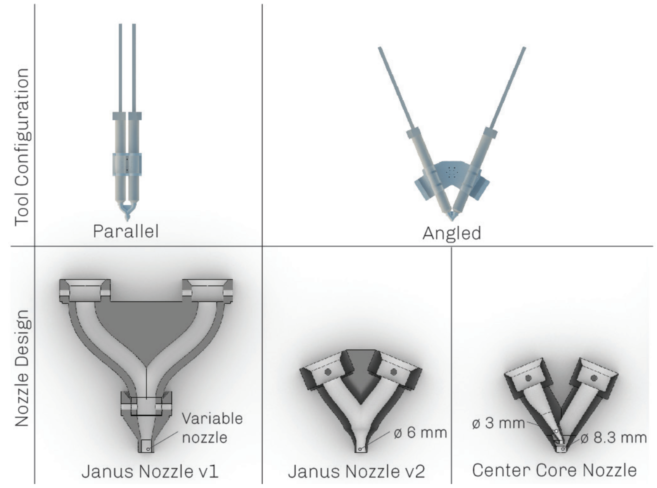
Potential design affordances of the center core nozzle include: the ability to print a softer interior material supported by the stiff outer shell, or printing at multiple resolutions where the larger diameter nozzle could be used for high-volume printing and the smaller nozzle for detailing. Further study of material behavior is required for this nozzle, but initial tests show promising results. For good print quality rheology matching of the two materials is especially important.

PRINTED PROTOTYPES

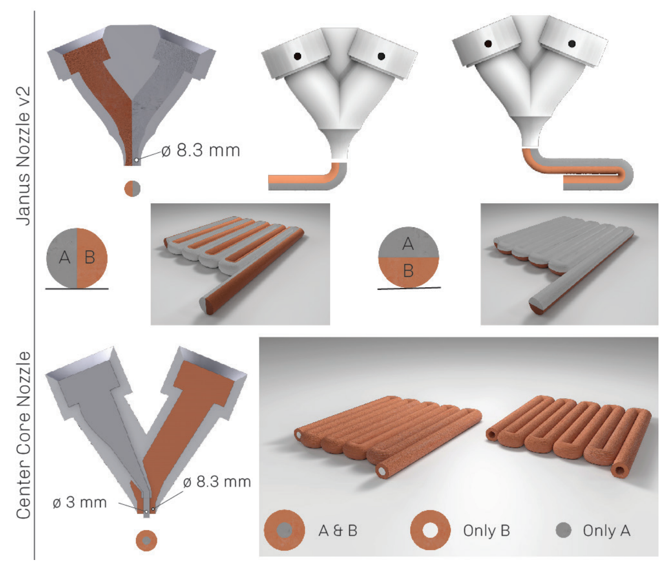
The research team produced a range of 3D printed artifacts to explore the capabilities of the computational workflow and nozzle designs described above. The artifacts can be categorized into 3 object types, the advantages and disadvantages of each are described below.

Horizontally Printed Tile

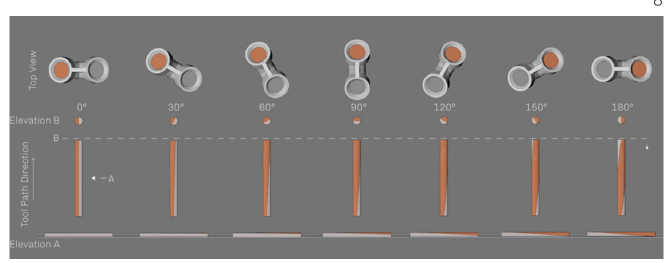
Orienting objects parallel to the printing surface enabled the research team to produce relatively large flat elements similar in dimension to commercially available ceramic facade panels and tiles. Two toolpath layering strategies were explored for this production technique. 2D layering maintained a consistent nozzle height for each layer (Figure 10). 2.5D layering changed the nozzle height throughout a



7



8



9

7 Diagram showing the various nozzle prototypes produced. The large travel distance of the Janus Nozzle v1 prevented clay from extruding. Janus Nozzle v2 oriented extruders at a 45 degree angle to one another in order to reduce the travel distance from the end of the clay cylinder to the tool tip. Center Core Nozzle retained the general form of Janus Nozzle v2 but adjusted material flow to provide a concentric extrusion.

8 Diagram showing the range of material configurations produced by varying nozzle orientation. A) Shows the effect when the Janus Nozzle is oriented parallel to the printing direction and B) shows when it is oriented perpendicularly. C) Shows capabilties of the center core nozzle.

9 Design affordances of the janus nozzle showing the relationship between nozzle orientation and toolpath direction, as well as the impact of gradual orientation angle change over the length of a toolpath.

10

11

10 Sample horizontal tiles produced using 2D methods and the janus nozzle. Each fired tile measures 125-130mm per side.

11 Photographs showing a range of print samples produced with by varying nozzle height within each layer. Careful manipulation of layer height allowed for a variety of surface relief and porosity patterns. Each fired tile measures 125-130mm per side.

layer (Figure 11). The latter method demonstrated potential in developing dual material tiles with porous multi-layered structures and high degrees of surface relief. The visual patterning produced on these tiles is a function of toolpath direction and the orientation of the 4th axis during printing. While this printing configuration allowed for the production of relatively large tiles, the resolution of the linear halftone pattern was lower than that of other methods, as it was dictated by nozzle size rather than layer height . This is a function of the aspect ratio of a typical print bead, which has a height-to-width ratio of 1:3-4 once deposited onto the printing surface. Thus, a print bead viewed from the side will contain 3-4 lines of print material for every one line viewed from above. This relationship directly translates into the resolution achievable with a linear halftone pattern. Warping and cracking during drying was observed on some of these tiles - a result of the clay layers exposed to the air drying faster than those portions adhered to the print bed. Increasing the duration of the drying process, and increasing the overall thickness of the tile minimized these effects.

Vertically Printed Tile

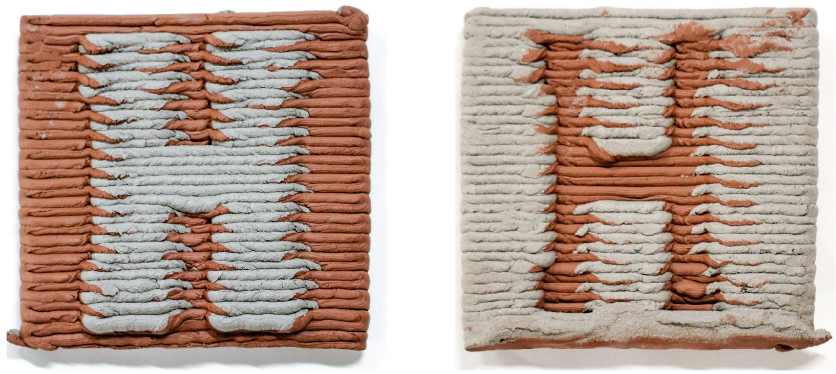
Printing thick tile vertically was tested in order to allow for uniform drying, thus reducing the chance of tile cracking or warping. Vertical printing also allows more flexibility in printing multi gradient tones based on the ability to 'switch materials', through gradual rotation, for each tile face during printing. Figure 12 shows a vertically printed tile. This method allows for up to 30 cm print in height for flat pieces. Angular or curved tiles can likely be printed at a greater height given the added form-stability. Other parameters that determine the stability of vertically printed tiles include the thickness of the print bead and the clay viscosity.

Three-Dimensional Artifacts

Three dimensional artifacts printed with the Janus Nozzle allow for material variations that are similar to those of the vertically printed tiles. Unique to the 3D artifacts however, is that the specific characteristics of a material transition are influenced by two interrelated parameters - the geometric characteristics of the part geometry, and the relationship between robot target orientation and part geometry. Figure 13 shows several artifacts printed using this method. Prints with a fixed target orientation exhibit material transitions that directly correspond to changes in surface normals. Varying the relationship between part geometry and target orientation allows for additional material expressions, such as the sinusoidal line of material transition in the artifact 2nd from right. The vertical orientation of this print type allows the clay to dry uniformly along the exposed surfaces.

DISCUSSION/FUTURE WORK

The research reveals several applications and future avenues for development. The present research relies on clay types that are visually different from one another but otherwise have similar performative and flow characteristics. A potential application of the process in its current state is the customizable coloration of full-body tiles - a growing market for the ceramics industry. Developing compatible clay mixes with measurably different performance characteristics (e.g density/porosity) could increase



12

13

12 H Prototype' front and back and 3d view showing extent of control on the computational and printing workflow.

13 Sample 3D objects produced using the janus nozzle. In the object third from left, the sinusoidal distribution of material transition points for each print layer was achieved via small rotations of robot target orientations. The other objects pictured maintained a fixed target orientation througout the print. Here, material transition is a function of part surface geometry.

the application space for this fabrication technique into thermally, acoustically, or structurally varied components. Control over the local deposition of these two clay bodies can result in the control over the global physical and performative characteristics of the printed form. Additionally, a denser body can act as a scaffold for a body less viscous and not easily printable on its own.

From a material mix standpoint, potential developments to end-effector/nozzle design include: a means of mixing materials A + B, and the ability to selectively incorporate material additives into a primary extrusion material. Refinements to the nozzle itself include incorporating infinite rotation into the 4th axis of motion, eliminating the need to "unwind" the extruder after a certain rotation threshold. Further developments to the design of the core/shell nozzle includes the ability to produce hollow ceramic elements.

CONCLUSION

We present a novel approach for paste-based ceramic additive manufacturing, developed in the context of full-body tile. By incorporating a dual-material nozzle and 4th axis into the printing setup, we introduce a low-complexity, controlled means of multi-material paste-based ceramic AMTs. A bespoke computational workflow provides the means of generating recognizable images in printed samples, demonstrates a degree of control of the printed material, and generates unique visual effects that are difficult or impossible to produce by other means. We describe 3 approaches to produce printed artifacts, and examine the benefits and challenges of each approach. Future work includes refinements to material mixes, and developments in end-effector/nozzle design.

NOTE

1. The first three authors contributed equally to the work presented in this manuscript.

REFERENCES

"3D Printing Porcelain - Olivier van Herpt." n.d. Accessed July 8, 2019. http://oliviervanherpt.com/3d-printing-porcelain/.

AlOthman, Sulaiman, Hyeonji Claire Im, Francisco Jung, and Martin Bechthold. 2018. "Spatial Print Trajectory." In Robotic Fabrication in Architecture, Art and Design 2018, edited by Jan Willmann, Philippe Block, Marco Hutter, Kendra Byrne, and Tim Schork, 167–80. Springer International Publishing.

Andreani, Stefano, and Martin Bechthold. 2014. "[R]Evolving Brick: Geometry and Performance Innovation in Ceramic Building Systems through Design Robotics." In FABRICATE: Negotiating Design & Making, edited by Fabio Gramazio, Matthias Kohler, and Silke Langenberg. Zurich: gta Verlag.

Atkins, Tony, and Marcel Escudier. 2013. Dictionary of Mechanical Engineering. Oxford: University Press.

Bandyopadhyay, Amit, and Bryan Heer. 2018. "Additive Manufacturing of Multi-Material Structures." Materials Science & Engineering R 129: 1–16.

Bechthold, Martin. 2016. "Ceramic Prototypes – Design, Computation, and Digital Fabrication." Informes de La Construccion

68 (544): 167.

Bechthold, Martin, Anthony Kane, and Nathan King 2015. Ceramic Material Systems: In Architecture and Interior Design. Basel: Birkhäuser.

Casagrande, C. 1989. "Janus Beads: Realization and Behaviour at Water/Oil Interfaces." EPL (Europhysics Letters) 9 (3): 251–255.

Cesarano, Joseph, Rachel Segalman, and Paul Calvert. 1998. "Robocasting Provides Moldless Fabrication from Slurry Deposition. Ceramic Industry 148 (4): 94–102.

Chen, Zhangwei, Ziyong Li, Junjie Li, Chengbo Liu, Changshi Lao, Yuelong Fu, Changyong Liu, Yang Li, Pei Wang, and Yi He. 2019. "3D Printing of Ceramics: A Review." Journal of the European Ceramic Society 39 (4): 661–687.

Im, Hyeonji, Sulaiman AlOthman, and Jose Luis García del Castillo. 2018. "Responsive Spatial Print. Clay 3D Printing of Spatial Lattices Using Real-Time Model Recalibration." In ACADIA // 2018: Recalibration. On Imprecision and Infidelity. [Proceedings of the 38th Annual Conference of the Association for Computer Aided Design in Architecture (ACADIA)] Mexico City, Mexico 18-20 October, 2018, Pp. 286-293.

Dondi, Michele, Magda Blosi, Davide Gardini, Chiara Zanelli, and Paolo Zannini. n.d. "Ink Technology for Digital Decoration of Ceramic Tiles: An Overview." In Proceedings of the 13th World Congress on Ceramic Tile Quality, 1–14.

"Encaustic Tile." 1893. Clay Record (1892-1910) 2 (4): 10.

Friedman, Jared, Heamin Kim, and Olga Mesa. 2014. "Woven Clay." In ACADIA 14: Design Agency [Projects of the 34th Annual Conference of the Association for Computer Aided Design in Architecture (ACADIA)]Los Angeles 23-25 October, 2014), Pp. 223-226. CUMINCAD.

Gagarin, Michael, and Elaine Fantham. 2010. The Oxford Encyclopedia of Ancient Greece and Rome. Oxford: University Press.

García del Castillo y López, Jose Luis. 2019. "Robot Ex Machina: A Framework for Real-Time Robot Programming and Control." In Ubiquity and Autonomy, Proceedings of the 39th Annual Conference of the Association for Computer-Aided Design in Architecture. University of Texas at Austin.

Huang, Alvin. 2016. "From Bones to Bricks: Designing the 3D Printed Durotaxis Chair and La Burbuja Lamp." In ACADIA // 2016: POSTHUMAN FRONTIERS: Data, Designers, and Cognitive Machines [Proceedings of the 36th Annual Conference of the Association for Computer Aided Design in Architecture (ACADIA)] Ann Arbor 27-29 October, 2016, Pp. 318-325.

Huang, Samuel, Peng Liu, Abhiram Mokasdar, and Liang Hou. 2013. "Additive Manufacturing and Its Societal Impact: A Literature Review." The International Journal of Advanced Manufacturing Technology 67 (5): 1191–1203.

Hutchings, Ian. 2010. "Ink-jet Printing for the Decoration of Ceramic Tiles: Technology and Opportunities." In Proceedings of the 13th World Congress on Ceramic Tile Quality, 17.

Khoshnevis, Behrokh. 2004. "Automated Construction by Contour Crafting—Related Robotics and Information Technologies." Automation in Construction 13 (1): 5–19.

Kieback, B., A. Neubrand, and H. Riedel. 2003. "Processing Techniques for Functionally Graded Materials." Materials Science & Engineering A 362 (1–2): 81–106.

Kuipers, Tim, E. L. Doubrovski, and J. C. Verlinden. 2017. "3D Hatching: Linear Halftoning for Dual Extrusion Fused Deposition Modeling." In 1st Annual ACM Symposium on Computational Fabrication, SCF 2017.

Kwon, Hyonkyu. 2002. "Experimentation and Analysis of Contour Crafting (CC) Process Using Uncured Ceramic Materials." Ph.D. diss, Universtiy of Southern California.

Li, Wenbin, Amir Ghazanfari, Ming C. Leu, and Robert G. Landers. 2017. "Extrusion-on-Demand Methods for High Solids Loading Ceramic Paste in Freeform Extrusion Fabrication." Virtual and Physical Prototyping 12 (3): 193–205.

Li, Wenbin, Austin J Martin, Benjamin Kroehler, Alexander Henderson, Tieshu Huang, Jeremy Watts, Gregory E Hilmas, and Ming C Leu. 2018. "Fabricating Functionally Graded Materials by Ceramic On-Demand Extrusion with Dynamic Mixing." In Proceedings of the 29th Annual International Solid Freeform Fabrication Symposium – An Additive Manufacturing Conference, 13. Austin, TX.

Maniruzzaman, Mohammed. 2013. Practical Guide to Hot-Melt Extrusion: Continuous Manufacturing and Scale-Up. Shrewsbury: Smithers Rapra.

Michalatos, Panagiotis, and Andrew O. Payne. 2013. "Working with Multi-Scale Material Distributions." In ACADIA 13: Adaptive Architecture [Proceedings of the 33rd Annual Conference of the Association for Computer Aided Design in Architecture (ACADIA)] Cambridge 24-26 October, 2013), Pp. 43-50.

Ng, Sze-Wing, Nuruzzaman Noor, and Zijian Zheng. 2018. "Graphene-Based Two-Dimensional Janus Materials." NPG Asia Materials 10 (4): 217–237.

Oxman, Neri, Steven J. Keating, and Elizabeth Tsai. 2011. "Functionally Graded Rapid Prototyping." In Proceedings of the 5th International Conference on Advanced Research in Virtual and Rapid Prototyping, 483–89. Leiria, Portugal.

Rael, Ronald, and Virginia San Fratello. 2018. Printing Architecture: Innovative Recipes for 3D Printing. New York: Princeton Architectural Press.

Rosenwasser, David, Sonya Mantell, and Jenny Sabin. 2017. "Clay Non-Wovens: Robotic Fabrication and Digital Ceramics." In Disciplines & Disruption: Proceedings of the 37th Annual Conference of the Association for Computer Aided Design in Architecture. edited by T. Nagakura, S. Tibbits, M. Ibanez, and C. Mueller. 502- 511. Cambridge, MA, ACADIA.

Seibold, Zach, Kevin Hinz, Jose Luis García del Castillo y López, Nono Martínez Alonso, Saurabh Mhatre, and Martin Bechthold. 2018. "Ceramic Morphologies. Precision and Control in Paste-Based Additive Manufacturing." In Recalibration. On Imprecision and Infidelity: Proceedings of the 38th Annual Conference of the Association for Computer Aided Design in Architecture. 350-357. Mexico City, Mexico. ACADIA

Simitchiev, Apostol, Ventsislav Nenov, and Atanas Lambrev. 2010. Coextrusion of Food Products – Essence and Technical Characteristics. Vol. LVI (2). Food Science, Engineering and Technologies. Scientific Works.

Song, Haichuan, and Sylvain Lefebvre. 2017. "Colored Fused Filament Fabrication." ArXiv:1709.09689 [Cs], September. http://arxiv.org/abs/1709.09689.

Tibbits, Skylar, Carrie McKnelly, Carlos Olguin, Daniel Dikovsky, and Shai Hirsch. 2014. "4D Printing and Universal Transformation." In ACADIA 14: Design Agency [Proceedings of the 34th Annual Conference of the Association for Computer Aided Design in Architecture (ACADIA) Los Angeles 23-25 October, 2014, 539-548.

Weston, Mark. 2013. "Prime Negatives: Parametric Sponge-Forming and Slip Casting for Ceramics." In SIGraDi 2013 [Proceedings of the 17th Conference of the Iberoamerican Society of Digital Graphics. Chile - Valparaíso 20 - 22 November 2013, Pp. 396 - 399.

IMAGE CREDITS

All drawings and images by the authors.

Zach Seibold is a Lecturer in Architecture at the Harvard Graduate School of Design and a Research Associate with the Material Processes and Systems (MaP+S) Group. His research focuses on the impact that novel fabrication techniques and material technologies can have on the production of architectural form. Zach holds a B.Arch from Syracuse University and a MDeS with a concentration in Technology from the Harvard GSD, Zach is also adjunct faculty at the Wentworth Institute of Technology, where he teaches courses in digital design and fabrication.

Saurabh Mhatre is a Research Associate with the Center for Green Buildings and Cities and the Material Processes and Systems (MaP+S) Group at the Harvard GSD. His current research deals with the 3d printing of ceramic and concrete, deployable mechanisms, smart materials and geometry and folding robots in collaboration with Harvard SEAS & Wyss Institute of Biological Engineering.

Suleiman Alhadidi is an architect, researcher, and engineer. He is a Research Lead at the City Science - MIT Media Lab. His research focuses on developing the next generation of affordable robotically-enabled buildings that promote more entrepreneurial, livable, and high-performing built environment and cities. Suleiman has a private Australian based architecture practice called O(n) Studio that aims at building the next generation of smart environments. Alhadidi has an affiliation with Harvard University GSD, Material Processes and Systems Group (MaP+S) whereby he is conducting his doctoral research. He is also an Adjunct Senior Lecturer at University of New South Wales in Australia.

Jose Luis García del Castillo y López is an architect, computational designer, and educator. His current research focuses on the development of digital frameworks that help democratize access to robotic technologies for designers and artists. Jose Luis is a registered architect, and holds a Master in Design Studies on Technology and Doctorate in Design from the Harvard University Graduate School of Design, where he is currently Lecturer in Architectural Technology along the Material Processes and Systems Group (MaP+S).

Martin Bechthold is the Kumagai Professor of Architectural Technology at the Harvard Graduate School of Design, and Associate Faculty at the Wyss Institute for Biologically Inspired Engineering. He directs the Doctor of Design Program and co-directs the Master in Design Engineering (MDE) program. Bechthold is the founding director of the Materials Processes and Systems (MaP+S) Group, a collaborative team that expands the role of materiality in the built environment, leveraging design computation and robotics. Recent focus areas have been 3D printing and ceramics. Bechthold collaborates with Allen Sayegh and Joanna Aizenberg in the context of the Adaptive Living Environments (ALivE) group on the development of adaptive solutions for products and buildings.