Additive Casting of Mass-Customizable Bricks

Workflow for Design and Robotic Fabrication

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1 Physical prototype showing bricks produced through additive casting

ABSTRACT

The strength of general-purpose fabrication tools is in the ease of repeatability and reconfiguration of geometry. However, there are some material processes that are difficult to directly integrate into fabrication processes with these machines. In particular, the common methods of material configuration through horizontal deposition in 3D printing exclude other types of material processes such as casting. This project demonstrates an additive manufacturing technique paired with a design input process for generating a wall of customized cast bricks. Taking advantage of the precision and adaptability of a robotic arm, the fabrication process pairs this general-purpose tool with a specialized auxiliary device to create variation in concrete casts.

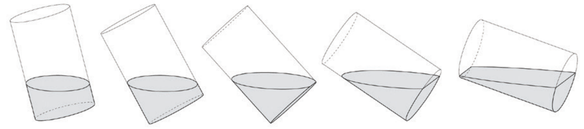
INTRODUCTION

In machine workflows for fabrication and manufacturing, there is often a set of trade-offs between the ability to repeat identical tasks and the potential for efficient reconfiguration. This trade-off is reflected in a range of machines that exist on a spectrum from single-purpose devices, which are only capable of repeating a fixed action, to general-purpose machines that are highly adaptable to change. Among the general-purpose machines that are now commonplace, 3D printers, CNC mills, and robotic arms all possess the ability to reconfigure for new input geometry with little effort.

However, there is sometimes a conflict between generalized purpose and the ability to produce all geometries with the same efficiency; in particular, 3D printers and additive manufacturing devices often exchange the efficiency of production for greater geometric neutrality. For simple geometries such as planar surfaces, there are often faster ways of producing a similar shape that use different machines, but not without trading the ability of a 3D printer to repeatedly reconfigure to new geometric input. In addition to trade-offs in the ability to efficiently produce certain geometries, there are limitations to the material palette that is accessible through this type of manufacturing. In order to access a greater variety of material properties, some research seeks to address this limitation through adapting the 3D printing process to a wider range of materials (Friedman, Kim, and Mesa 2014; Klein et al. 2015).

In addition to material limitations, there is a dominant strategy of material deposition in additive manufacturing devices in which material is extruded through a nozzle into horizontal layers. Existing projects seek new strategies that expand geometric possibilities; typically, these investigate additional axes of motion (Buswell et al. 2018; Huang, Garrett, and Mueller 2018) or by applying alternative machine configurations (Peng et al. 2016; Zivkovic and Battaglia 2018). However, there is further room to explore additive techniques with entirely different material attributes while continuing to leverage computational tools and machine control. Likewise, there is also room to explore the specialization of additive manufacturing machines to increase the efficiency of specific types of geometry and to further identify the role of robotics in the production and assembly of architectural components (Baudisch and Mueller 2017; Silver 2018)

This project seeks an alternative method of additive fabrication achieved through the use of an intermediary device with an existing robotic fabrication tool. The strategy represents a productive balance between general-purpose production machines and process-specific devices, resulting in an expanded potential for an alternative material process. In this project, we demonstrate a simple "additive casting" method that produces planar cast surfaces within a cylinder. Here, the primary mode of geometric control is limited by the two possible attributes: the volume of deposited liquid in the cylinder and the gravity-assisted plane that forms when liquid solidifies (Figure 2). This process is repeated as the plane angles are adjusted until a final geometry is formed (Figure 3). This process outlines a strategy for accessing a material process (casting) that is not typically available in additive manufacturing.



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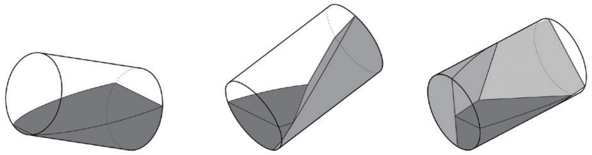

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2 Volume of liquid in a rotating cylinder

3 Object formed by changing the plane of liquid in a cylinder after the other plane(s) solidify

Objective

The process is intended to demonstrate a proof-of-concept that links each component of a workflow for producing mass-customized bricks into a functioning design and additive fabrication process. Among the challenges to be solved are the method of digitally generating the initial geometries, controlling input variables, providing an accurate visual representation of the items to be produced, and developing an efficient fabrication method. The overall process investigates the limitations of such a system in order to identify the future potential for fabrication systems that employ customizable additive casting techniques.

METHOD

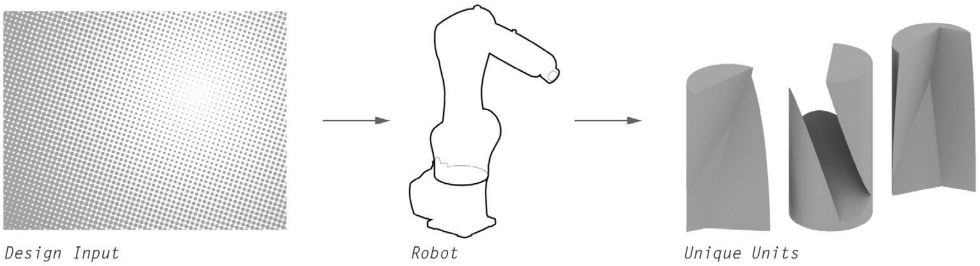
The project consists of several components that are linked together to form a comprehensive workflow for the design and fabrication of cast elements (Figure 4). A computational tool offers a handful of variables for controlling the geometry, provides visualization of the intended output, and generates a tool path for a 6-axis robotic arm.

The fabrication configuration consists of a 6-axis robotic arm and an array of seven identical molds each held in place by an adjustable "curing station". Each mold consists of an empty cylindrical volume into which three separate installments of liquid material are added; each installment of material is held in place to cure at a specific angle before the next installment is added and the cylinder is re-positioned. The robotic arm controls the positioning of each mold while the new installment of material is in a liquid state, while the curing station holds the mold in position. The curing stations are manipulated at precise angles by the robotic arm to generate the geometries visualized in the digital model. The fabrication process leverages the precision and versatility of the robot but also benefits from the efficiency offered by the array of devices specialized for the method of material formation.

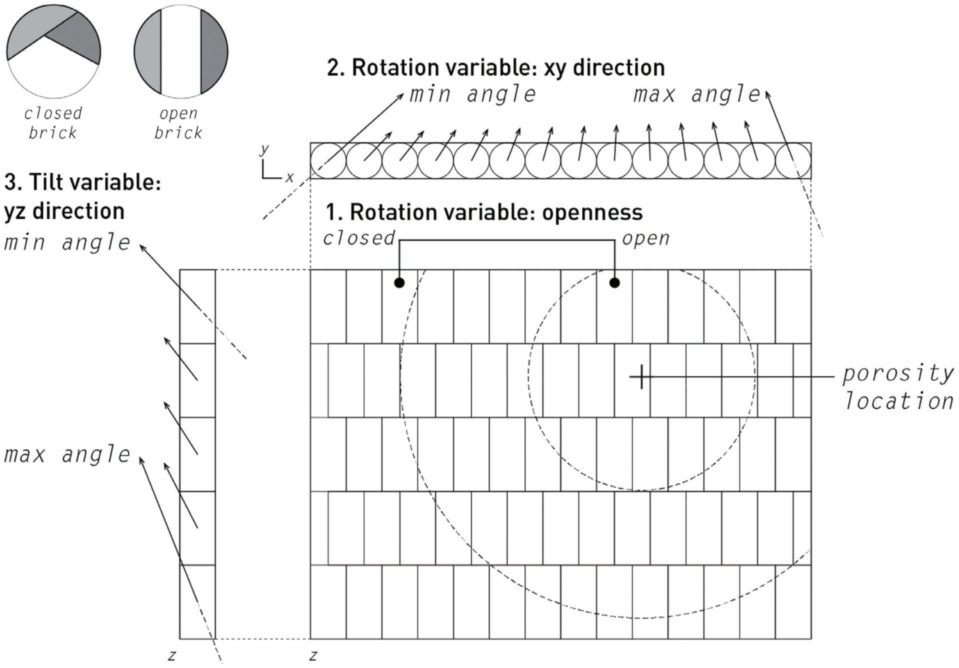
Design Inputs

The digital model offers a selection of variables that control the individual geometry of each brick. The objective of these inputs is to control the desired angle of three planes within each cylindrical volume (Figure 3). The relationship between each component in the workflow enables the designer to work with information that corresponds to direct visual feedback; using the workflow, the designer can manipulate the high-level inputs without providing direct instructions to the machine and the corresponding casting device. The primary variable that drives the overall appearance of the brick assembly is visual porosity, which is initially selected as a point location anywhere on the wall (porosity location in Figure 5).

First, the geometries are distributed on a spectrum between open and closed (variable 1 in Figure 5). Useful as a method of generating variety in the experimental process, the system generates some bricks with visible openings and others that are fully closed (opaque). Open bricks consist of parallel and opposite positions of the first and second pours of material that forms an opening between the solidified segments. Closed bricks consist of a configuration of three planes that fully intersect, preventing openings from forming in the centers of the volumes; see top-left of Figure 5 for examples of open and closed bricks. Other bricks fall on a spectrum between the minimum and maximum openness.



4 Workflow: design input is converted into machine instructions that produce unique units



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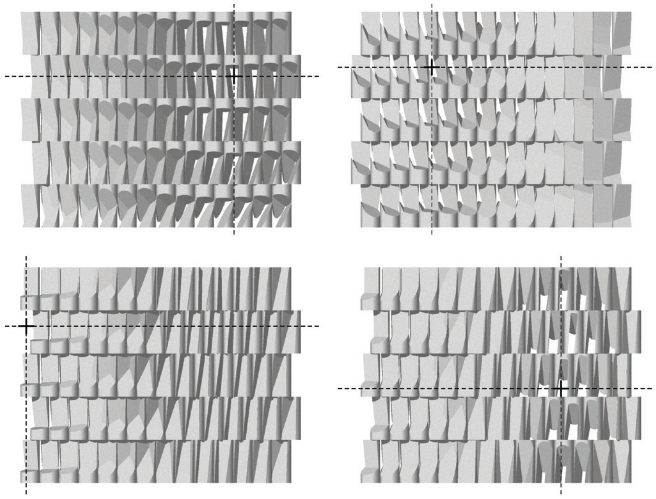
5 Design inputs for controlling wall and brick geometry based on overall visual porosity

6 Variation in brick geometries produced through selection of different design variables

7 Visualization of two different volume selections for the same geometry

After each brick is assigned an initial configuration depending on its amount of openness, the designer can further choose inputs related to direction; this input allows for control over the overall orientation of plane geometries selected for each brick. These adjustments to direction can be applied to both the XY and ZY plane, which introduces an additional layer of subtle complexity which enables both porous and closed configurations of geometry to tilt and rotate within each brick. In each plane, the designer can choose a minimum and maximum of rotation (in the XY plane, variable 2 in Figure 5), or tilt (in the YZ plane, variable 3 in Figure 5). Some examples demonstrating the design varieties are shown in Figure 6.

The last variable that visually affects the system is a selection for volume of liquid material that is to be provided in each individual pour. This affects the final appearance of the previously selected variables by altering the thickness of the resulting cast (Figure 7). The digital model generates a visualization of volume for each material deposit, achieved by displaying the correct location for the angled planes selected by the previous design inputs.



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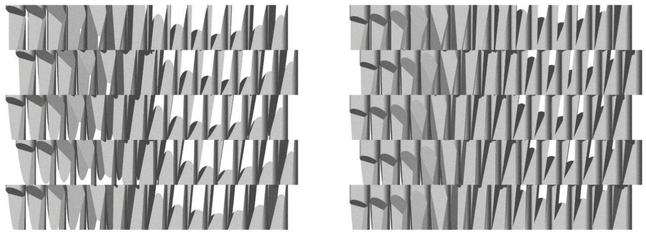

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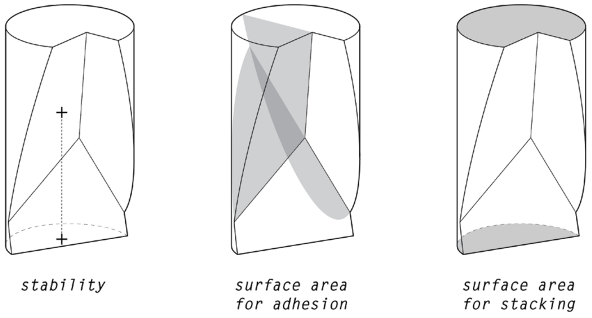

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8 Three conditions for a brick to be physically viable

9 Exploration of viable (dark grey) and non-viable (light grey) brick geometries produced by varied design inputs

Visualization and Evaluation

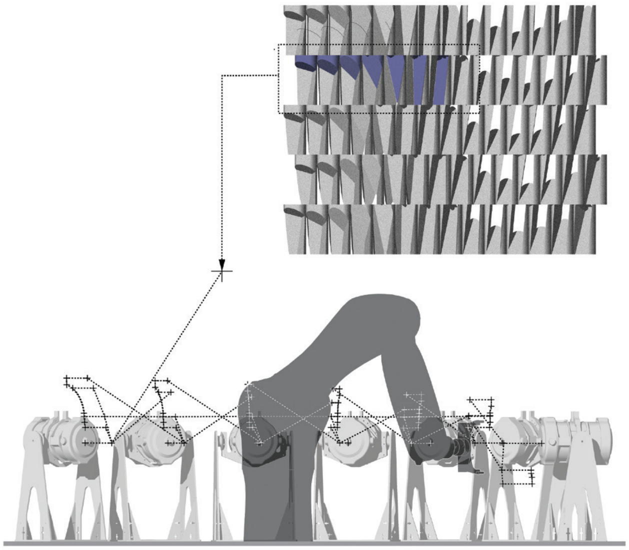
The visualization enables subjective evaluation of design quality as well as indication of "viability" of each brick. Bricks are determined to be physically viable if they have a stable center of mass, adequate surface area for adhesion of the material deposits, and sufficient material at the top and bottom of each brick to allow stacking (Figure 8). In the current version of this work, it is possible to visualize the stability of a single brick but not to visualize this for the entire stacked assembly. This allows us to explore the design space of a unit-brick in terms of fabrication viability (Figure 9). Future work may include a fabrication viability-guided design space exploration (Brown and Mueller 2019), (Schulz et al. 2018) that involves global stability constraint of the stacked aggregation (Whiting, Ochsendorf, and Durand 2009).

Translation to Machine Instructions

After the geometries are selected in the digital model and approved using the visualization, the set of angled planes are converted to machine instructions. During this process, the design inputs are converted to the two constituent motions that are possible to execute with the adjustable molds: rotation around the longitudinal axis of the cylinder; and tilt in a perpendicular axis to the rotation (Figure 10) The design inputs are consolidated into the resulting rotation and tilt value for each individual material installment, converting the initial design intent into a simple set of mechanical motions (Figure 11).

Robotic Arm and Fabrication Device

During fabrication, the robot accesses each mold and positions it to the selected angle. For each set of seven bricks (the current number of curing stations), the robot executes three passes across the curing stations; once for each new installment of liquid material. The curing station is responsible for interfacing with the robot so that its tilt and rotation angles can be precisely adjusted. To do this, the end of the mold that faces the robot has a set of prongs that register with two positions of the robot's end effector; one position controls the canisters rotation, while the second position controls its tilt (Figures 11, 12). The robot receives these two pieces of information from the digital model, which are directly transferred to the rotation and tilt operations on each curing station. Between the two actions, each mold is capable of 360 degrees of rotation in two axes and is held in place by friction.



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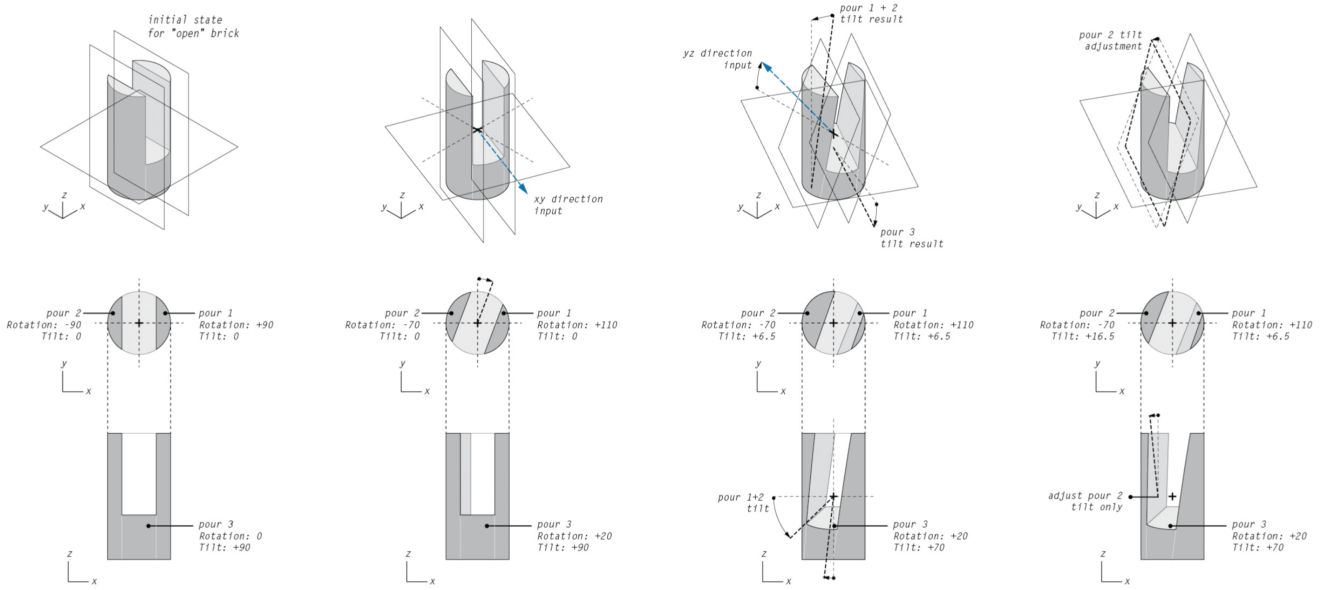
11 The robotic arm performs Tilt and Rotation manipulations across seven curing stations to produce one set of cast planes



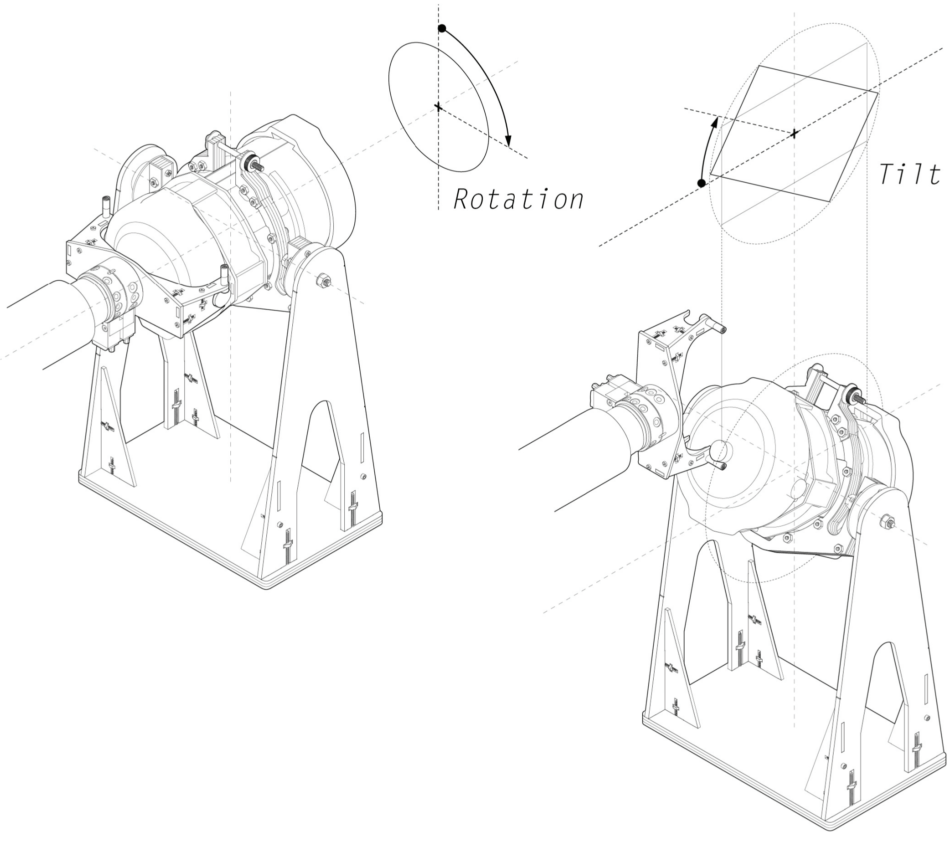
inital state for porosity input

x - y direction input input applied to rotation

y - z direction input input applied to tilt

optional aesthetic input adjustment

10 Process of converting design inputs into machine instructions for Tilt and Rotation



12 Two motions by robotic arm correspond to Tilt and Rotation instructions for each brick

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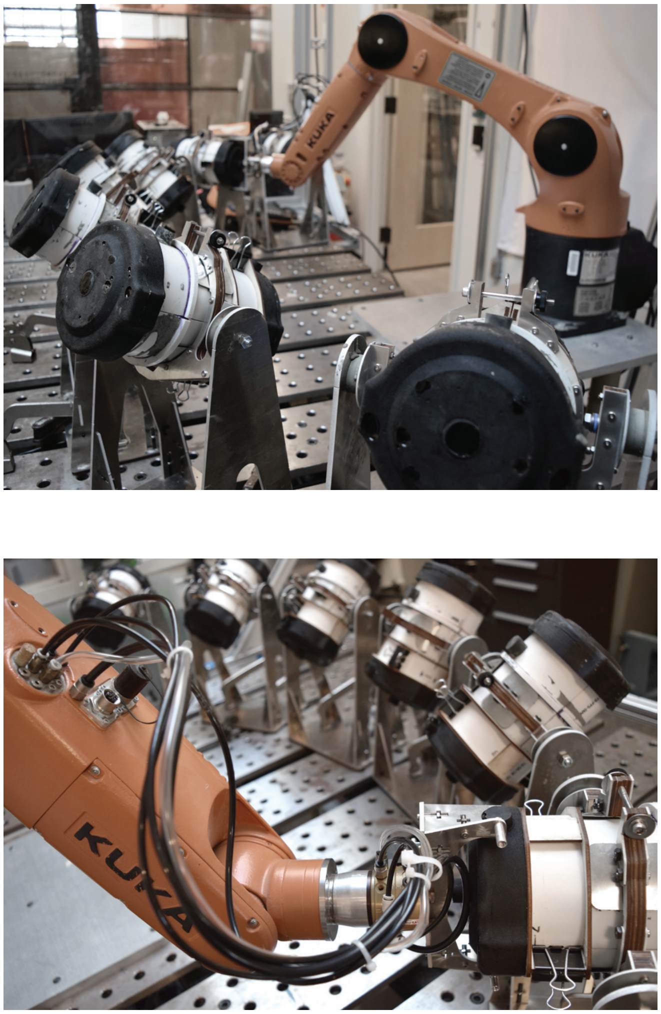
Material

The project presents a set of unique requirements for the behavior of the concrete mixture: these include the consistency which must be extremely liquid to be easily poured; a fast initial setting time that enables efficient timing of mold re-positioning and reliable removal from the mold; and maximized adhesion between each deposit of concrete to minimize breakage. The final mixture employed in the prototype resembles a typical concrete mixture but is modified with a ratio of expansion cement along with several admixtures that address liquid consistency, bonding strength, and set time (table 1). The initial setting of the mixture is timed to begin immediately after the last mold has been positioned by the robot.

Fabrication and Assembly Process

Currently, the fabrication routine consists of hand-deposited and hand-measured installments of liquid concrete that are manually distributed into each mold immediately before the robotic tool path is executed for each installment. This process is repeated three times for each set of seven bricks (the current number of curing stations), after which the molds are removed from the curing stations, emptied, and reinstalled for the next set of bricks (Figure 14). The top and bottom of each brick are imprinted with the same interlocking geometry by the ends of the molds so that the overall rotation of each stacking element is precisely registered in position to its neighbors in the full assembly (Figure 15).



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13 Fabrication in process with robotic arm and array of curing stations

T. 1 Concrete mix recipe for the production of cast bricks

Mix for One Pour-Set	Total Dry Mixture	Portland Cement	Expansion Cement	Sand	Liquid			
					Water	Plasticizer	Bonding Admixture	Set Retarder (drops)
Amount Per Batch (g)	3800	950	950	1900	532	17	181	9
Percent Weight Dry Mixture	100	25	25	50				
Ratio of Cement					.38 (water/ cement)			.0046 (drops/g cement)

Table 1

RESULTS AND NEXT STEPS

The prototype demonstrates an initial success of the basic premise, showing a start-to-finish workflow between design and fabrication of additive-cast elements. The assembly of bricks also demonstrates requisite precision over the selected planar angles between the visualization and the physical prototype. However, there are numerous challenges presented by the current material and fabrication process that could be reevaluated in future explorations. Since concrete produces brittle edges, the material selection is often at odds with the types of geometries the system is most likely to produce. Furthermore, much of the fabrication process is extremely manual; though the robot is used when precision is required most, future iterations could integrate further automation of manual tasks such as mixing, measuring, and depositing precise quantities of liquid material.

Now that a first proof-of-concept is complete, the fabrication technique of additive casting could be more broadly investigated in future projects. This could include exploration of more complex geometries, further integration of 3D modeling, and specific visualization and output tools for machine instructions that interpret liquid volume and curing angle as the primary method of material formation. Together, these steps could determine if there are new applications for additive-cast fabrication methods.

CONTRIBUTIONS

The prototype and accompanying workflow demonstrate the potential for the design of the fabrication process itself to augment both material and geometric possibilities (Figure 15). Through outfitting the capabilities of generalized fabrication tools with mechanisms specialized for a specific material process, it is possible to gain a wider range of available techniques that are typically unavailable in additive manufacturing devices. The pairing of a design tool with the specialized material device can enable unique interaction between design possibilities and mechanical constraints, enabling a reintroduction of material presence into the digital fabrication process.

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14 Detail view of prototype showing sections of open and closed bricks

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IMAGE CREDITS

All drawings and images by the authors.

15 Prototype

Lavender Tessmer is a PhD student in the Design and Computation group at Massachusetts Institute of Technology, where her recent work explores the relationship between design, mass customization, and manufacturing. She holds a Master of Science in Architecture Studies from the same group, and she received her Master of Architecture from Washington University in St. Louis in 2011, where she taught as a lecturer from 2012-2017.

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