ROBOSENSE 2.0

Robotic Sensing and Architectural Ceramic Fabrication

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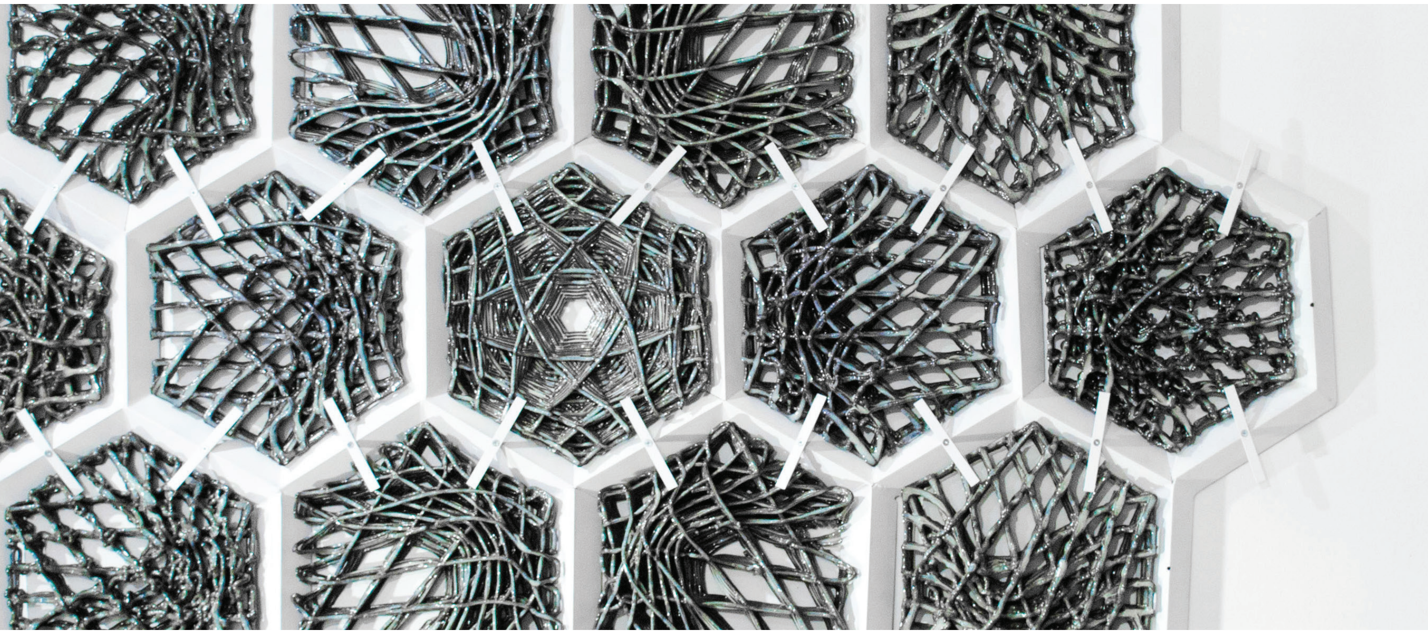

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1 Facade mock-up of physical prototypes, showing how user input (beginning at the central component) can affect pattern and line quality of subsequent components.

ABSTRACT

"Robosense 2.0: Robotic Sensing and Architectural Ceramic Fabrication" demonstrates a generative design process based on collaboration between designers, robotic tools, advanced software, and nuanced material behavior. The project employs fabrication tools that are typically used in highly precise and predetermined applications, but uniquely thematizes the unpredictable aspects of these processes as applied to architectural component design. By integrating responsive sensing systems, this paper demonstrates real-time feedback loops that consider the spontaneous agency and intuition of the architect (or craftsperson) rather than the execution of static or predetermined designs. This paper includes new developments in robotics software for architectural design applications, ceramic-deposition 3D printing, sensing systems, materially driven pattern design, and techniques with roots in the arts and crafts. Considering the increasing accessibility and advancement of 3D printing and robotic technologies, this project seeks to challenge the erasure of materiality: when mistakes or accidents caused by inconsistencies in natural material are avoided or intentionally hidden. Instead, the incorporation of material and user-input data yields designs that are imbued with more nuanced traces of making. This paper suggests the potential for architects and craftspeople to maintain a more direct and active relationship with the production of their designs.

INTRODUCTION

Unlike robots in industry, which execute predefined and repetitive tasks in a controlled environment, robotics in design and architecture are becoming increasingly involved with uncertain tasks within more complex and dynamic contexts. Manufacturing machines and robots have now started to gain intelligence—actively communicating, monitoring, and sensing—and with this, the ability to react (Menges 2014). To facilitate the feedback between design and robotic fabrication, a Python-based interface, encapsulating communication protocols and robotic manipulation libraries, was created in Robosense 1.0 (Moorman, Liu, and Sabin 2016). The interface seamlessly bridges the gap between physical and digital environments and allows for a feedback-oriented robotic fabrication paradigm. Building upon Robosense 1.0, Robosense 2.0 steps forward and integrates the interface into design software Rhinoceros 3D and Grasshopper.

Since 2009, the Sabin Design Lab has innovated digital ceramics through 3D-printed ceramic bricks and nonstandard componentry (Sabin 2010). The plastic nature of clay offers a potent material solution to contemporary generative design processes in architecture, which frequently feature organic and natural forms of increasingly complex expression and ornamentation (Sabin et al. 2014). The use of clay to integrate the designer's intuition and to rationalize complex data and geometries has been incorporated into the design process in alternate industries such as car and boat design for decades, but professionals in the broader field of architecture have yet to widely explore the potential for these materials and tools to augment the efficiency and quality of built design work. This paper explores the transfer of information and data, including real-time feedback via sensing technologies, through the hybridization of crafts-based ceramic techniques with contemporary digital design, robotic 3D printing, and nonstandard component–based architectural assemblies.

We propose the development of a responsive feedback system that provides the designer/maker with information about the material, allowing for intuitive, on-the-fly modifications to the design process during the course of fabrication. Reciprocally, the designer's choices and changes are registered, and the software responds in real time to create a fluid workflow that informs and unlocks the potential for more a nuanced understanding of 3D-printed clay as an architectural fabrication technique.

BACKGROUND

Robotically Fabricated Ceramics

Robosense 2.0 uses the material language of clay deposition 3D printing, the extruded clay bead, as a medium for developing physical case studies (Figure 1). Existing precedents that investigate clay deposition printing tend to use a technique borrowed from other forms of 3D printing: predetermined extruder motions create fine stacked layers to produce volumetric forms, similarly to how coil pots have traditionally been constructed, and to how low-cost plastic deposition 3D printers are able to produce objects with high efficiency. The Institute for Advanced Architecture Catalonia (IAAC) is innovating the use of robotically fabricated clay components for large-scale applications with exceptional results for the purpose of creating architectural enclosures. While their work is innovative in scale, clay body, and precision, the production methodology and extrusion techniques do not significantly vary from typical 3D-printing operations. The outcomes of these prints have a high level of predictability because all of the material deposited is fully supported, constraining designs to entirely enclosed volumetric forms that lack more advanced material intelligence (Chronis et al. 2017).

Other precedents have used the extruded clay bead to develop more expressive architectural screens that allow for deviation from preprogrammed behavior, but often with difficult-to-control outcomes. As a result, the complexities of drying, firing, and glazing these components at a large scale of production make them difficult to envision as applied to architectural building systems. Both Harvard GSD's Woven Clay project and Cornell University's Clay Non-Wovens use techniques influenced by textile manufacturing in order to develop these patterning and screen systems, which can negotiate circumstances of light through thin ceramic panels. Both projects are successful in challenging ideas of patterning and demonstrating potential for robotic fabrication in clay (deviating from the process of printing layer on top of layer). The challenges discovered in these projects relate to unpredictable tolerances and warping due to the firing process. Furthermore, joinery and connection detail in both projects are unresolved, inhibiting either from becoming truly scalable (Rosenwasser, Mantell, and Sabin 2017; Friedman, Kim, and Mesa 2014).

Ron Rael and Virginia San Fratello of Emerging Objects have worked extensively with 3D-printed ceramic material, both powder-based using Z Corp 3D printers and with delta bot machines (2018). Emerging Objects' emphasis on G-code "glitch" focuses on code manipulation of traditional 3D-printing methods to create textures and coded mistakes within clay material. This paper presents an alternative to preprogrammed "glitches" through a sensing-based process that engages the mistake, error, and inconsistencies through human interaction and natural material response during the process of fabrication.

Existing 6-Axis Robotics Software

When engaging in architectural fabrication using a 6-axis robot, a designer or technician must first create a toolpath using computer-aided machining (CAM) and or/computer-aided design (CAD) software for the robot to execute. There are a handful of robotics software programs for Rhinoceros and Grasshopper, including HAL, TACO and KUKA|prc. HAL provides reverse kinematics solving, simulation, and code generation. TACO is similar to HAL and offers the ability to generate code to coordinate multiple robots and upload RAPID code to the robot controller directly. KUKA|prc provides a similar feature set to HAL for KUKA robots. While these software products are excellent for simulating and generating code, there are no existing software interfaces readily accessible to the design and architecture community that allow human or environmental input to adjust and redesign the toolpath as the robot is executing code. Thus, opportunities to understand the vast potential of designing alongside robotic tools remain largely inaccessible to design professionals; unincorporated into the typical workflow of an architectural design practice.

METHODS

Software for Robotic Motion Design

In order to produce a ceramic building component using a material deposition system (a three-dimensional or 3D printing system) on the end of a robotic arm, design intent must be translated from the architect's ideas into data that controls the motion of the robotic arm. The transition from design to code (executable by a robotic tool) is often understood by architects and nonexperienced users on a very rudimentary level.

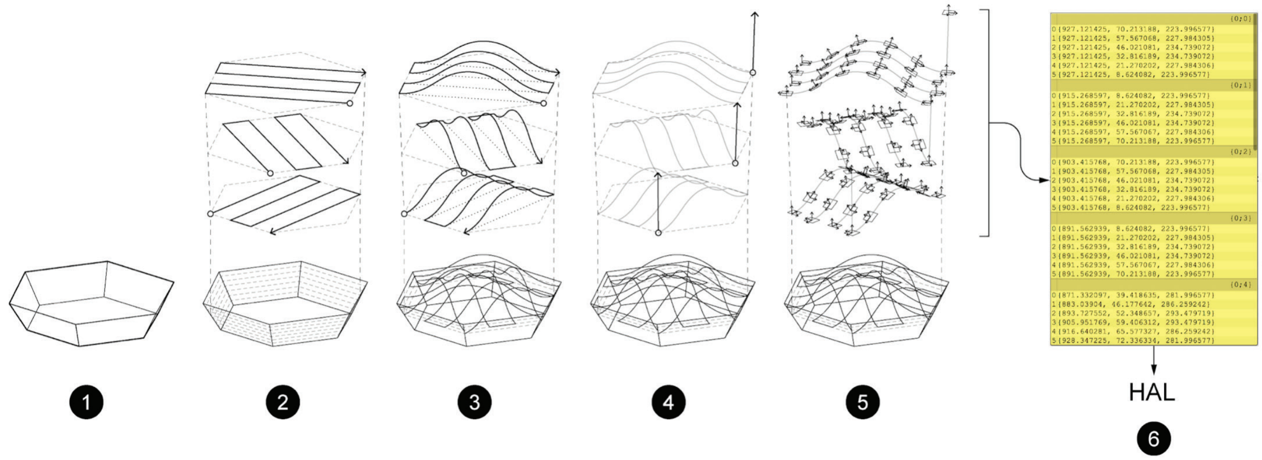
Generating the Toolpath

To fluidly translate design intent into robotic movement, a script for generating bespoke warp and weft bead patterns is developed. Instead of starting with a three-dimensional model that is then translated into a toolpath, the designer understands the design process beginning with the toolpath itself, informed by the nature of the continuous bead. By using an easily accessible visual scripting interface such as Grasshopper, one is able to generate continuous-line toolpaths for ceramic extrusion while simultaneously considering the limitations and constraints of the robot's motions. A script is developed to function in the following way, depicted visually in Figure 2:

- A bounding volume is assigned, either sourced from the Rhinoceros 3D modeling workspace or generated using the script. This volume may be modified and adapted throughout the design process.
- The Grasshopper script produces a series of horizontal layers within the bounding volume at an assignable interval, each consisting of a line that weaves back and forth across the bounding volume (like the warp and weft of a textile). The script ensures that each layer reaches the extents of the bounding volume.
- Each layer is manipulable in three dimensions; the print is not constrained to flat, two-dimensional layers. In the script developed for these tests, points on each layer's edges are fixed to the bounding volume to ensure proper adhesion to a plaster mold in which the clay is to be printed; the portion of each layer in the center of the print may be assigned a differing spacing (Z-coordinate value), or may be translated into different positions altogether. The potential for complex, multi-axis motion (4, 5, 6 or more axes moving simultaneously to produce) is not limited by the script.
- The script connects each layer to the next, regardless of three-dimensional manipulations, ensuring that the toolpath remains continuous. The endpoint of each layer is necessarily adjacent to the start point of the next in order to produce a continuous path for the robot end effector to follow.
- The script determines orientation planes for every target point (ordered coordinates that guide the robot's motion) in the toolpath, prescribing the end effector's orientation in space. The designer is able to access, parse, and manipulate this data in order to design specific orientations for the tool based on his or her intent or knowledge of the fabrication process.
- HAL receives the continuous line toolpath from the Grasshopper script and translates it into RAPID code, displaying the code to the user/designer in real time. The user may preview the motion of the robot before beginning, using a built-in visualizer paired with HAL's robot simulation tools.

Sending the Toolpath

Next, RAPID code (containing joint positions and/or target coordinates) is sent to the robot. Robosense 1.0 used the open source software Open ABB to communicate directly with an ABB IRB 4600 from Processing, a programming language for visual art (Moorman, Liu, and Sabin 2016). Open ABB provides the benefit of sending individual commands such as speed adjustments, cartesian moves, and joint positioning directly to the robot rather than executing an entire list of static commands produced by HAL. The motivation of this project is to communicate directly with the robot from design software such as Rhino and Grasshopper. A server, written in the ABB robot

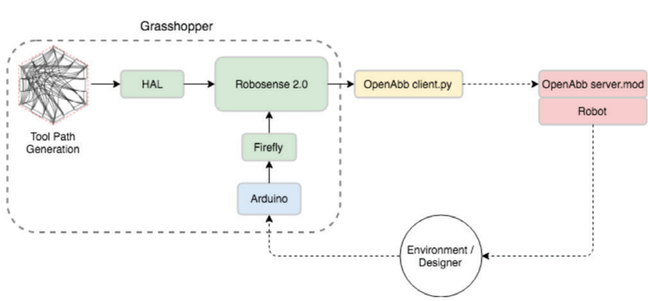


2 Diagram of the process of generating a toolpath.

language RAPID, is loaded onto the robot controller and a Grasshopper component creates a client in GH Python to connect to the Open ABB server on the robot controller. Grasshopper can directly control an ABB robot without the use of expensive proprietary software.

Sensing and Adjusting the Toolpath Using Material Behavior

With the ability to intervene in the execution of a toolpath, changes to the robot's motion can be made based on the state of the fabrication environment. This is realized by reading sensor data into Grasshopper using an Arduino and the Grasshopper plugin Firefly (Payne and Johnson 2013). A relationship is defined between the sensor value and a toolpath adjustment. For instance, an increase in clay body moisture content can be mapped to a decrease in robot travel speed. A series of exercises, described in the Exercises section, were performed to test the software and understand the relationship between sensors, software, and material feedback. Figure 3 is a system diagram of Robosense 2.0.



3 Once a toolpath is generated, the Robosense plugin sends a move command to the robot, the robot executes the command, an Arduino reads a sensor, the toolpath is updated, and the feedback loop continues.

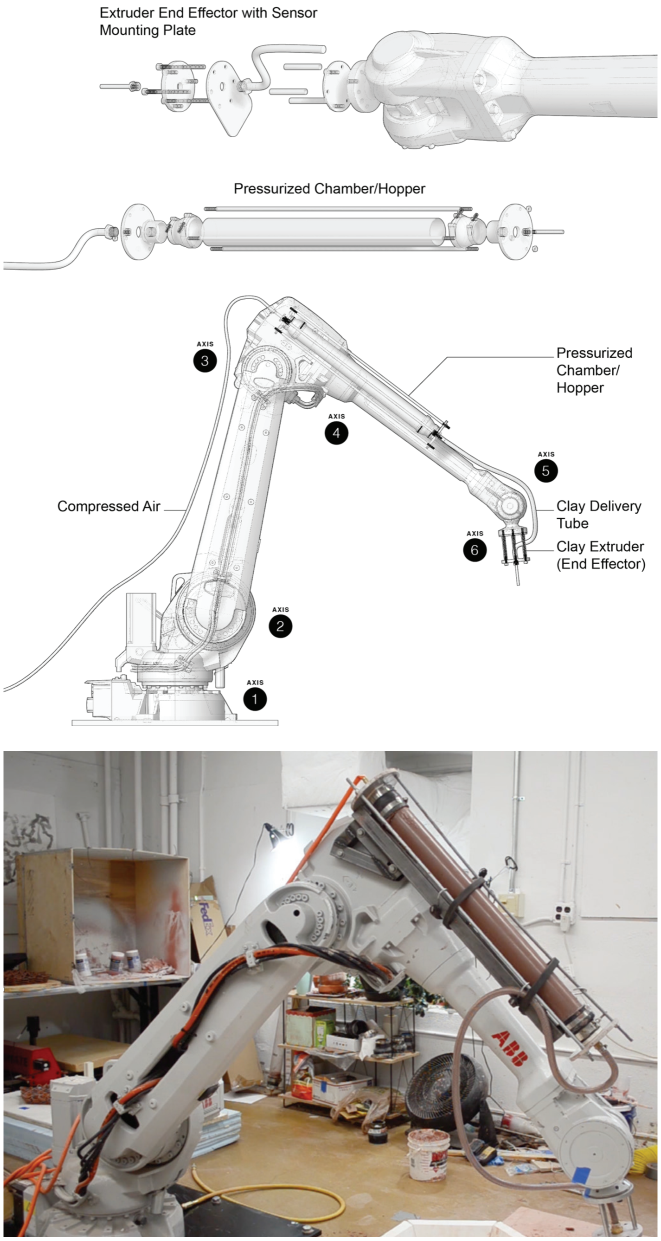
Extruder 2.0

In order to seamlessly integrate clay extrusion into the robotic sensing environment, a previously designed custom extrusion system was significantly adapted for the purpose of engaging a variety of sensors, and allowing for uninhibited 6-axis motion of the robot arm (Rosenwasser et al. 2017). These revisions include a newly designed end effector, Extruder 2.0, which is modular in its construction. One improvement includes the addition of aluminum mounting plates, which facilitates infrared temperature sensors, cameras for recording extrusion, 3D scanners, or other sensing systems (Figure 4). A hygrometer is used to measure moisture content of clay by registering the electrical resistance or capacitance of the material. This device expands the sensing environment to the clay mixing area, where one may precisely monitor and record the moisture of the clay body during preparation.

Extruder 2.0 discharges clay using compressed air only and does not depend on stepper motors or augers to move material to the end effector. By continuing to use exclusively compressed air, the extruder's compact dimensions are maintained, especially in comparison to alternative systems such as piston-and-chamber.

Designing a Clay Body

To create a fully responsive design environment, material must be considered alongside software and hardware. To select a clay body and recipe for use with the updated extrusion system, a range of clay recipes with multiple viscosities was tested, including porcelain, a standard potter's stoneware with grog, and a higher-plasticity dark brown high fire stoneware. When used in the compressed air extrusion system, a clay body must be thick enough to retain its form and structural integrity once extruded, but must also be thin enough to pass through the hopper



4 (top) Diagram and (bottom) images of modifications to the clay extrusion system and end effector.

chamber and delivery tube without excessive pressure (120 psi).

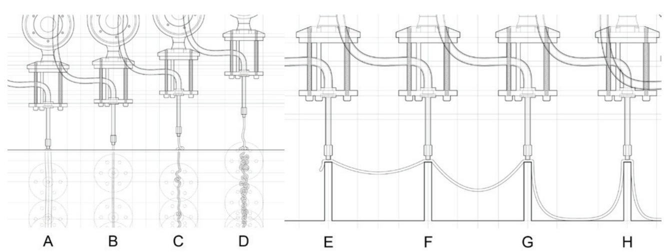
Different clay bodies exhibited a variety of unexpected behaviors when extruded, which have the potential to become elements of a design language informed by feedback in the fabrication environment. Two key behaviors were identified and tested further to examine the potential for understanding these nuanced phenomena using Robosense 2.0: 1) looping behavior and 2) bridging behavior. Looping behavior is defined as what occurs when the clay extrusion rate exceeds the typical rate for a given robot travel speed. This overextrusion of clay produces a bead that creates a looping pattern when the end effector nozzle is raised (Figure 5). The bead falls approximately along the intended path of material deposition rather than precisely along it. Bridging behavior is defined as what occurs when a clay bead is extruded across an unsupported span. The bead's plasticity allows it to remain intact when supported on two ends. The height at which the bottom of the bridge falls has a relationship to the length of the unsupported span, the pressure of extrusion, and the material composition of the clay body itself (Figure 5). A number of tests were conducted to examine the relationships between extrusion pressure and contextual factors (such as bridge span distance or nozzle height), using a variety of clay bodies (Figure 6).

Exercises

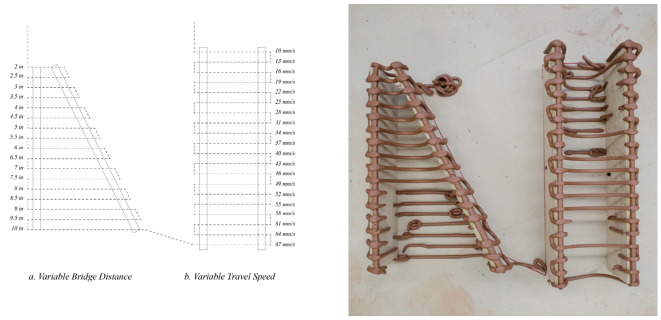
The software, tools, and materials developed in Robosense 2.0 form a new type of responsive sensing environment, facilitating further development of techniques for the design of ceramic building components. Testing physical prototypes in this environment, as outlined in the following sections, clarifies a design process/language that translates sensor input into a unique materiality for architectural ceramics.

Exercise 1: Simple Extrusion Pressure Test

The first test is intended to demonstrate dynamic manipulation of a toolpath based on user input from sensor data. A bead of clay is extruded as air pressure from the extruder is read by a Universal 150PSI Pressure Transducer Solenoid and fed into a Grasshopper script via an Arduino. Changes in air pressure (which controls extrusion rate) are mapped to a resultant change in the Y coordinate of the waypoints in a predetermined toolpath (Figure 7 top). Line 01 is extruded at 100 psi, line 02 is extruded with the pressure gradually increasing from 100 psi to 120 psi, and line 03 is extruded with the Y coordinate being adjusted in the range of 0 mm to 60 mm in response to the pressure gradually increasing from 100 psi to 120 psi. All lines are extruded 10 mm above the work surface.



5 A) Low nozzle height produces a flat, wide layer. B) Bead is deposited accurately but is not compressed. C) Beginning to produce looping behavior. D) Demonstrating significant looping behavior. E) Bridge behavior at a low extrusion pressure. G) Medium to low extrusion pressure. G) High extrusion pressure H) Causes bridge failure.



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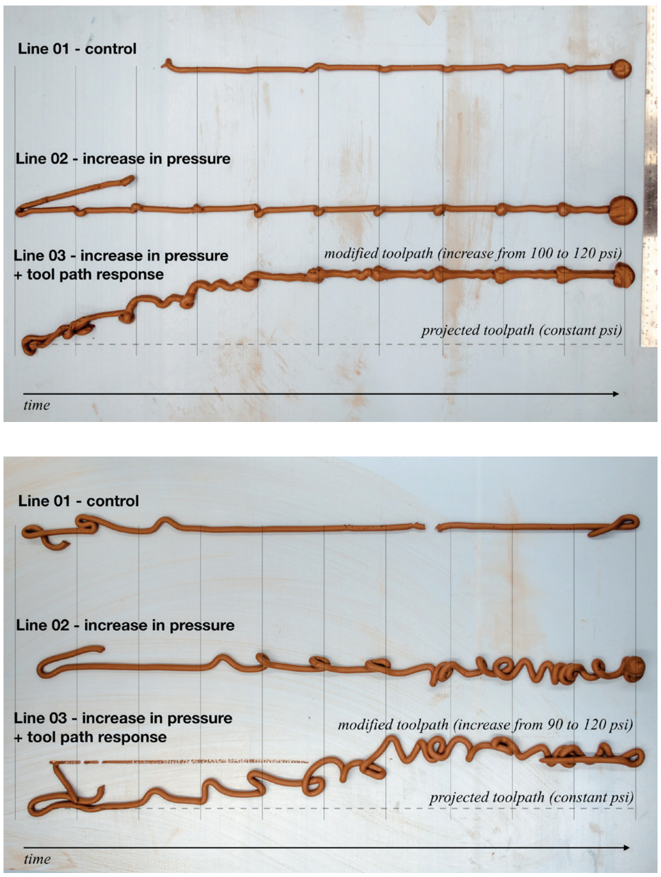

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6 Clay body experiments, which tested increases in the robot's travel speed and potential bridging distance of multiple clay bodies. These tests were critical in differentiating behaviors of each clay body.

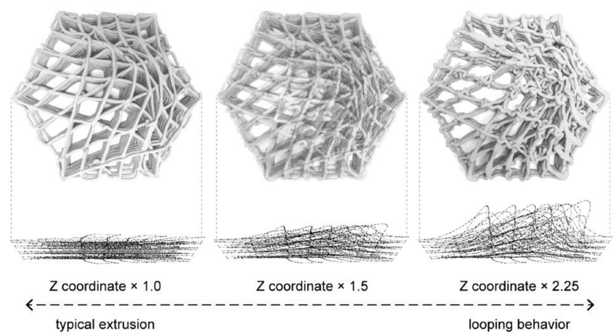
7 (Top) Two lines with change in Y coordinate in response to pressure change. (Bottom) Two lines with change in Y and Z coordinate in response to pressure change.

Figure 7 (bottom) depicts a second line test in which the Z coordinate also increases, along with the Y coordinate, as the pressure increases. The three lines in Figure 7 (bottom) follow the same rules as the lines in Figure 7 (top), with the addition of the pressure being mapped to an increase in the Z coordinate of the end effector in lines 02 and 03. The lower bound of 100 psi is mapped to 10 mm and the upper bound of 120 psi is mapped to 20 mm above the work surface. Increasing the height of the end effector in response to the pressure produces more dramatic looping behavior.

Exercise 2: Extrusion Pressure Adjusts Toolpath

User-controlled changes in the toolpath results in a change in material behavior: a simple, linear toolpath was extruded, but changes in air pressure were chosen to correspond to changes in the Z-value of each target point along the toolpath. By dynamically changing the toolpath's Z-value instead of the Y-value, overextrusion (looping behavior) was encouraged (Figure 8).

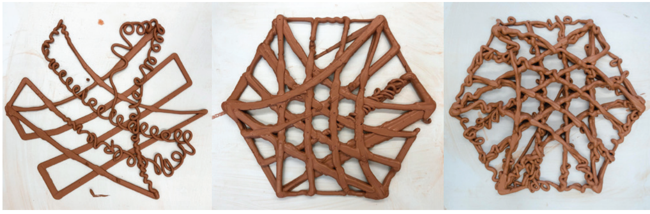
To create the complete panel in Figure 9 (middle), the end effector's height ranges from 0 to 10 mm above the Z coordinate of the initial, unmodified toolpath. While the looping behavior is more subtle in Figure 9 (middle) because of the limited range of the z adjustment, this configuration produces a wider, flatter bead as more clay is extruded. Figure 9 (right) is a component fabricated with the end effector's height ranging from 0 to 20 mm above the unmodified Z coordinate of the initial toolpath.



8 Dynamic modification of a toolpath during fabrication, depicting toolpaths in elevation and corresponding visualizations of the resultant printed beads. As extrusion air pressure is adjusted, the Z-coordinate value of subsequent toolpath target points is multiplied by a factor within a designer-determined range (in this case, 1.0 to 2.25).

Exercise 3: Extrusion Pressure Informs Real-Time Design Changes

The final test develops the idea of utilizing feedback loops as a means of dynamically generating changes in the design of architectural components. Adjustments in air pressure (extrusion rate) now correspond to a change in the design of the toolpath geometry. This allows the architect to redesign the structure of the component during fabrication in addition to making small local adjustments to the toolpath. The Grasshopper script is modified so that the values from Firefly adjust an attribute of the patterning to be translated into a toolpath and executed by the robot. HAL generates new RAPID code from the updated toolpath. Robosense sends the new toolpath one cartesian move at a time until a new update to the patterning has occurred, thus beginning a feedback loop (Figure 10).

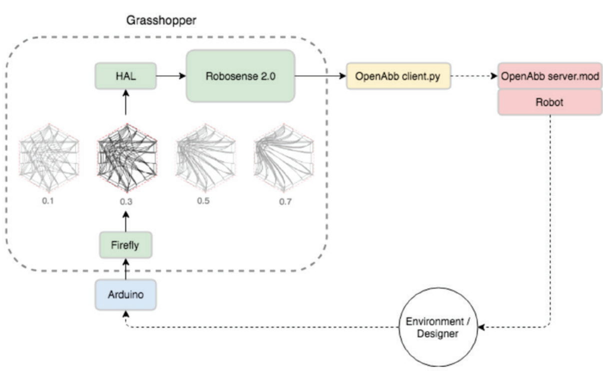


9 (Left) Calibration of a single layer to identify the lower and upper bounds of the air pressure and the end effector height. (Middle) A complete component with a small Z-coordinate adjustment range. (Right) A complete component with a large Z-coordinate adjustment range.

In the case of this test, the parameter adjusted was the distortion of each layer's pattern. With an increase in extrusion pressure, two changes were produced: 1) the design of a panel's toolpath was distorted in the X and Y directions toward an attractor point assigned by the designer, and 2) the clay bead exhibited an increase in looping behavior as the Z coordinate of the toolpath was increased in relation to the air pressure increase (Figure 11).

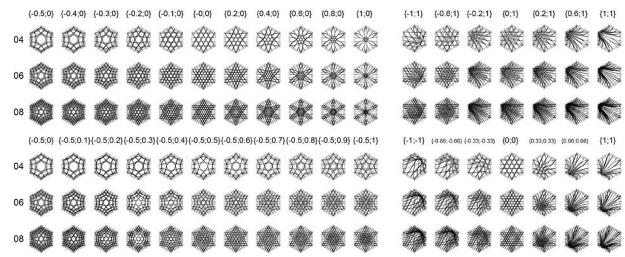
Aggregation and Global Patterning Logics Informed by Real-Time Inputs

The design of a global facade pattern composed of individual ceramic panels is possible by considering air pressure changes and user input during the fabrication process. Unique patterns are designed in which variations in each component's toolpath aggregate to form a global organization. Ceramic screens and facades created using this method have the possibility of great variation in structural integrity, light/visual filtration, and aesthetic novelty depending on the location of looping behavior and pattern density.



10 System diagram illustrating how real-time inputs allow for the creation of bespoke global patterns during fabrication.

A global pattern is generated using the following method (Figure 12): 1) A set of relationships is designed using the toolpath design script, which determines the sequence of the pattern's generation. 2) Attractor locations are determined for each panel that can potentially distort each toolpath in the X and Y directions, depending on user input during fabrication. 3) Panels are fabricated in the sequence determined in step 1. Throughout fabrication, changes in extrusion air pressure are recorded in the Robosense component as they dynamically modify the trajectory of the robot's motion. An increase in air pressure during the fabrication of ceramic panel 01 affects subsequent panels



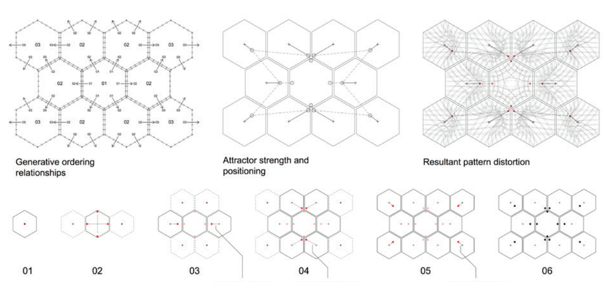
11 Matrix of local pattern possibilities. The numeric ranges indicated refer to distortion strength of the attractor from the bottom layer to the top layer of each toolpath, with a value of −1 representing the strongest repelling influence, and a value of 1 representing the strongest attracting influence.

(numbered 02) by increasing the attractor's distortion of the toolpath (Figure 11).

By incorporating logics of user input and influence not only into the creation of individual toolpaths, but also into the design of global patterns, the designer's agency and responsiveness in the process is further augmented.

RESULTS

The line tests in Exercise 1 show successful real-time manipulation of the Y coordinates of a series of target locations, traced by the robot's end effector. Initially, the Robosense 2.0 component sent cartesian moves in batches of ten points, and a significant delay was observed, which resulted in a large buildup of clay between batches. This delay inhibits an intuitive relationship between the architect and the material behavior during fabrication. The delay was removed prior to performing exercises 2 and 3 by sending cartesian moves individually instead of in batches, allowing



12 (Top) Diagrams of pattern-generation sequence (1), attractor positioning (2), and resultant pattern distortion in printed ceramic panels (3). (Bottom) Diagram of attractor distortion strength as modified during the fabrication of ceramic panels.

13 Porous ceramic tiles composed of bridged and looping clay beads.

for immediate adjustment of the toolpath in response to an architect's input. The extrusion system's pressure regulator, paired with an air pressure sensor, acted as a controller of the robot and a design tool for the user.

The extrusion test described in 3.6.2 was the first test to take advantage of the material behavior control Robosense 2.0 provides. Looping behavior is produced at a high pressure and Z-coordinate value, while a more typical, controlled bead is produced at a low height and pressure value. In all instances, an understanding of bridging behavior allows for the possibility of atypically porous, self-ventilating ceramic components (Figure 13). Drying times and failure rates of these components were found to be lower than is typical for ceramics of this size, with greater than 90% success rate. By increasing the upper bound of the Z-coordinate adjustment, the designer has a larger range of extrusion behaviors to work with during fabrication.

Reflection

Through testing a range of clay bodies, the high-plasticity dark brown stoneware is identified as most suitable given the intent to explore both bridging and looping behavior (Figure 14). The design of a new end effector with entirely modular construction allows for the attachment of sensors, scanners, and documentation equipment. The clay hopper tube can be easily removed from the new mounting system and is held securely away from the work. By using only compressed air without electronically controlled motors, the system is a model for an easy-to-construct clay

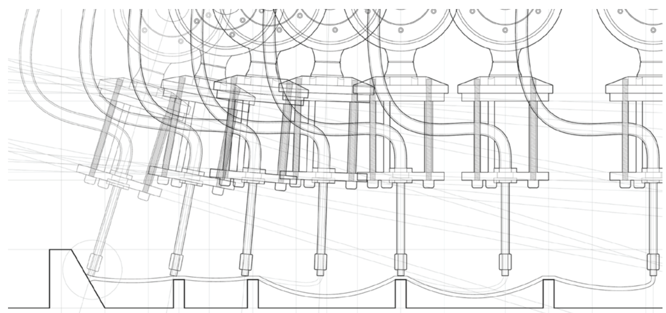
14 (Left) Component geometry and local patterning tests in dark browstoneware. (Right) Detail of unique material behavior in clay.

deposition system that is accessible for a low cost (Table 1).

⅜" Aluminum	½" Aluminum	⅜" Threaded Rod	Polycarbonate Tube	Couplers and Fittings	Hardware	Reinforced Silicone Hose	Nozzle	**Total**
10.00USD	12.00USD	10.00USD	30.00USD	35.00USD	6.00USD	5.00USD	10.00USD	**118.00USD**

Table 1 Porous ceramic tiles composed of bridged and looping clay beads.

By using an interface and toolpath-generation script that begins with the design of a toolpath itself (and not necessarily with a predetermined 3D model), users understand how their changes directly affect the code produced, which controls the motion of the robotic arm; the motion of the arm itself is designed, rather than an object. This unique design process, paired with the ability to make changes in real time (during fabrication), allows for a fluid and dynamic workflow in which the architect has a more direct relationship with the tools being used. These feedback loops not only allow for more precise control and understanding of fabrication processes, but they also



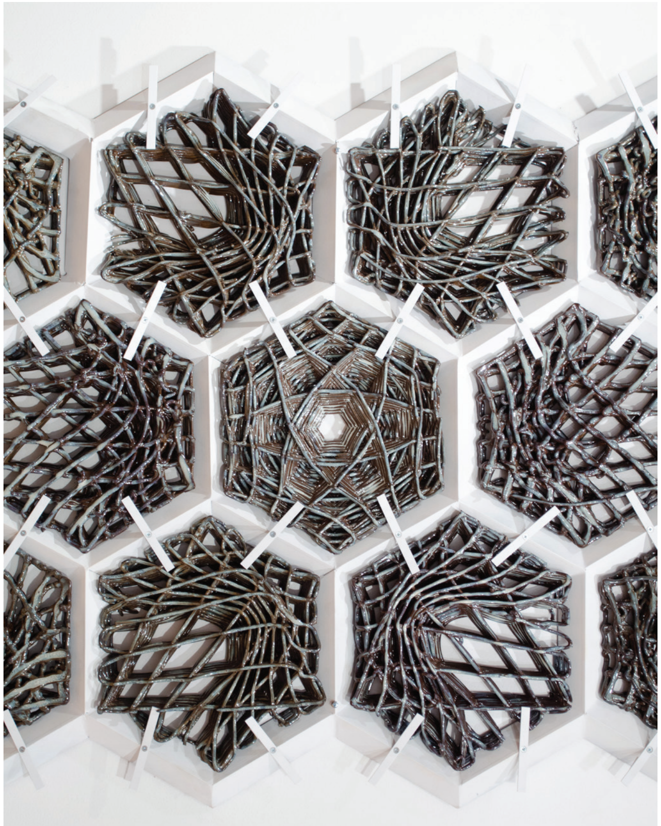
15 Sectional representation of multi-axis clay deposition within a tapered plaster mold. As moisture is wicked from the clay, it adheres to the tapered mold, supporting the ends of peripheral bridges.

suggest the possibility for design to take advantage of more idiosyncratic material behaviors otherwise understood as mistakes or accidents.

Improvements

Robosense 2.0 can be made more user friendly by encapsulating the feedback loops described in Figures 3 and 10. Firefly and code-generation components can be included within the Robosense 2.0 component so the architect only has to design a toolpath and define relationships between sensors and robot movement. Users could then save and reload these relationships to easily recreate complex fabrication setups.

Robosense can also facilitate an expanded breadth of fabrication-based inputs, such as 3D scanning to reference the existing material in real time. By scanning the physical space, the robot could design future formwork to better complement the existing imprecise formwork. Monitoring



16 Detail of facade mock-up.

the physical space and material more closely will be useful for controlling new material behaviors introduced when using more than 3 axes for clay deposition (Figure 15).

CONCLUSION

Robosense 2.0 integrates informed material feedback into the design and production of ceramic architectural componentry. The conceptual framework and software can also be applied to other materials and architectural assembly logics. This paper implements three experiments and case studies in clay, which showcase the potential for responsive sensing in an architectural fabrication environment. Building upon research from Robosense 1.0, the project moves its software into Rhinoceros/Grasshopper with help from the software Open ABB and HAL, thus liberating architects to engage responsive feedback loops at a more accessible level. By leveraging extruded ceramic 3D printing research in Robosense 2.0 case studies, resultant components suggest a new age of digital craft within our built environment.

By integrating the design process with the fabrication process, Robosense 2.0 allows each piece of an architectural component system (Figure 16) to better leverage the nuances of a material's behavior, as well as the designer's input, imbuing traces of making into the creation of crafted components. The designer is able to use real-time fabrication data to generatively inform subsequent parts of a fabrication project (whether the implications are functional, structural, or aesthetic), demonstrating the potential for an unprecedented level of involvement that architects and designers may have in the realization of their designs.

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