Ceramic Forest

Robotic Die-Extrusion Variable Forming for Architectural Ceramics

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1 Controlling extrusion with collaboration of two operators. It is further discussed in Results and Discussions section of this paper.

ABSTRACT

Extrusion is a well-established industrial production technique for making ceramic clay parts in high-volume, mass-production lines, using an auger to push the clay out from a reservoir through a die profile onto a conveyor belt. While the method enables elaborately profiled extrusions, the extrusion and die allow for no degree of variability across the production of several parts. *Ceramic Forest* explores how robotic fabrication and clay extrusion techniques can be integrated into a variable production process by mounting an extrusion die and extrusion system on an industrial robot end-of-arm tool. Experiments exploring fabrication parameters including the clay body water content, die geometry, air pressure, and a robot's motion trajectory were conducted, and demonstrated the merits of the approach. The fabrication method is also demonstrated through the production of a series of geometrically distinctive parts that are utilized in a full-scale, assembled, façade screen prototype. A computational design method was also developed for an architectural façade screen that generates design outcomes that align with the research's established fabrication constraints. Together, these developments demonstrate an approach to die-formed ceramic extrusion and an aligned computational design tool for its use on architectural façade screens.

INTRODUCTION

Four hundred years ago, the emergence of die-cast extrusion provided a time- and cost-saving solution compared to other ceramic production techniques that involved more artisanal forms of labor (Bender and Böger 2009; Stratton 1993). Die-cast clay extrusion remains a dominant form of architectural ceramic manufacturing used in buildings today as can be seen in the design of the Jewish Community Center in Mainz, Germany, by Manuel Herz Architects; the Holburne Museum in Bath, England, by Eric Parry Architects; the Spanish Pavilion in Zaragoza, Spain, by Francisco Mangado; and Steinway Tower in New York, USA, by SHoP Architects.

Current extruded ceramic building materials, including those used in the aforementioned projects, are made as modular units in industrial mass-production lines by pushing clay through a die over a conveyor belt. Having evolved over 400 years, die-cast extrusion is the most productive and cost-efficient manufacturing method for architectural ceramic façade panels compared to alternative production methods such as additive manufacturing (AM) or dry pressing techniques. Despite its economical advantages, current extrusion techniques fail to provide comparable geometric variability to AM methods (Händle 2019), which offers advantages for building design due to the differentiating factors revolving around site, climate, context, user requirements, and architectural design interests. While clay AM might be considered a form of micro-scale extrusion that supports designers and fabricators with new avenues for geometric variability, it is more time and energy intensive than industrial extrusion practices (Bechthold 2016; Händle 2019). Although recent developments from the University of Buffalo and Boston Valley Terra Cotta's Architectural Ceramic Assemblies Workshops (Garófalo and Khan 2017, 2019, 2021), SabinLab, MaP+S Group, and architectural built works demonstrate that architectural ceramics continue to be an area engaged in exciting research and design possibilities, little research has been undertaken into the exploration of robotic extrusion.

Historically, ceramic extrusion production has benefited from inventions in other disciplines, such as the employment of the Archimedes screw providing a step-change in the productivity of early hand-operated extruding machines and, more recently, through the use of extrusion simulation software (Bender and Böger 2009). In this light, present barriers to producing geometric variability within the ceramic extrusion process could be addressed by introducing robotic fabrication methods within the extrusion process. Presently, industrial robot use in the ceramic industry is primarily centered on packaging (pick and place) and glazing activities (Bechthold 2016). In this research, an industrial 6-axis robot is outfitted with an extrusion die and clay material supply, and tasked with extruding clay while varying its motion trajectory. The research explores the control parameters and feasibility of developing robotic die-extrusion variable forming, and evaluates its utility as an industrial manufacturing process. Experiments were conducted using custom extrusion dies coupled to a World's Advanced Saving Project (WASP) compressed-air-actuated plunger material reservoir mounted to a 6-axis articulated robot arm. Within each manufacturing run, a constant flow of compressed air pushed clay through the die while the robot moved on a pre-programmed trajectory. We ran several experiments exploring different values for contributing parameters, including the clay water content, extrusion-die profile geometry, material reservoir air pressure, and robot velocity and trajectory, to evaluate best practices. To demonstrate proof-of-concept, we designed and fabricated a partial, full-scale façade screen prototype comprised of multiple, variably extruded, glazed, ceramic parts. We also developed a computational method incorporating the observed design constraints and applied it to the design of a speculative façade screen.

STATE OF THE ART

While architects seek to design bespoke buildings with geometrically varied parts, (Bechthold 2016), this competes with other core objectives, such as material, cost, and environmental efficiency metrics (Piroozfar and Piller 2013). These opposing objectives can compromise on the ideal of mass-customization (Bechthold 2016; Piroozfar and Piller 2013; Kusiak 2018): "… the idea that digital machines could produce every object differently, at no additional cost" (Restin 2019, 40). However, implementing this ideal still poses significant challenges; in practice, the architectural ceramic industry still relies on conventional production techniques for producing identical modular components because of their cost and time efficiency (Händle 2019; Andreani and Bechthold 2017). In academia, AM-Technologies (AMT) has been designers' preferred manufacturing approach to the production of complex geometrical parts for at least two decades. The use of clay AM is still an ongoing field of research (Lange and Holohan 2019) that has been broadened through developments, including the ability to print over non-planar surfaces (Bechthold 2016; Ko et al. 2019), printing in choreographed paths (Bilotti et al. 2018; Im, AlOthman, and García del Castillo y López 2018; Lange and Holohan 2019), inventing ad-hoc end-effectors (Yu, Luo, and Xu 2019), and multi-material printing (Seibold et al. 2019).

Despite these innovative developments, production time and cost of AMT is not competitive to industry prevalent die-cast extrusion methods. However, research is limited into die-cast extrusion's capability to incorporate the production of geometrically differentiated parts. To date, architectural ceramic extrusion research has included the design of profile dies, extrusion over non-planar formwork, and variable cutting (by hand, CNC machines, or robotic arms) (Andreani et al. 2012; Andreani and Bechthold 2017; Ugarte-Urzúa et al. 2020), or a combination of these (Garófalo and Khan 2017, 2019, 2021). While robots have been employed for cutting, glazing, and packaging, research into variable robotic extrusion has not been explored.

METHODS

To take advantage of industrial robotic arms for extruding variable clay parts, we mounted a cylindrical reservoir to an industrial robot. We supplied the reservoir at one end with a hose to an air compressor, and at the other end with a custom-designed, and 3D-printed, die. Several extrusion experiments were undertaken exploring variations in geometry, material, robot velocity, robot trajectory, and air pressure. Following these, a series of extruded parts were manufactured, bone-dried, bisque-fired, and glaze-fired, assembled into a 1.5-meter-high prototype. Since the ceramic parts are not modular, the system requires detailed instructions for assembly. To reduce the assembly time and create assembly instructions efficiently, we employed a human-robot collaboration approach.

Robotic Extrusion, Step-by-Step

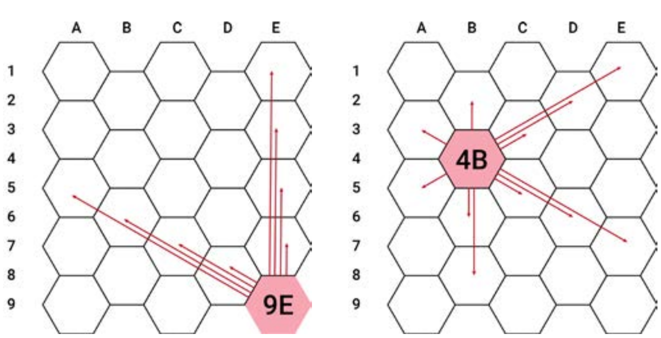
All robotic extrusions were executed by an ABB IRB 4600-60 6-axis industrial robotic arm attached to a linear axis track. A 5L WASP extruder tank (as material supply) was attached to the robot's flange plate. One end of the tank was connected to a pneumatic plunger connected to an air compressor via a hose, and the other end was equipped with a polylactic acid (PLA) 3D-printed, extrusion die.

For each run of extrusion, 10-pound of clay (EM-101 Miller #10-G Cone 06) was mixed with water in a pug mill (VPM-60 Vacuum Power Wedger) for two hours. Loaded with the clay mixture, the tank was attached to the robot for extrusion. The robot's trajectory was designed and modified in Rhino3D 7, and its visual programming environment Grasshopper. Using Grasshopper's Visose Robots plugin 1.6, a RAPID code was exported to ABB's RobotStudio software 22.3 for connecting to the robot's controller.

Developing an effective clay die-extrusion method is challenging due to the mutual interdependency of several control parameters, including the geometry of the die, the viscosity of the clay, the air pressure of extrusion, the speed of the robot, and the trajectory of the robot (AlOthman et al. 2019; Bilotti et al. 2018). To deal with this multi-dimensional problem, we made a set of experiments. In each experiment, one parameter was addressed.

We started by designing multiple die profiles that are all circumscribed inside the sectional circle of the tank, which was a constraint within the whole project. To design these profiles, we considered the thickness of the walls, the outline of the geometry (considering elements such as tongues and grooves to support multi-part assembly), and filleted corners (that was later discovered to reduce friction and help the clay be extruded more evenly).

Multiple clay mixtures of different clay/water ratios were then made to achieve even and stiff extrusions. All mixtures were mixed in the pug mill for 60 minutes before insertion in the extruder tank.



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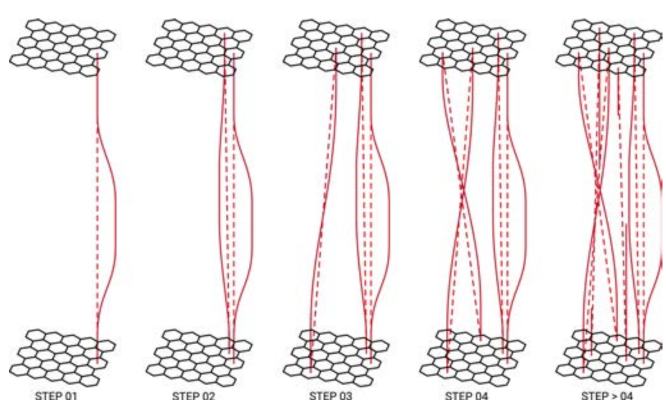

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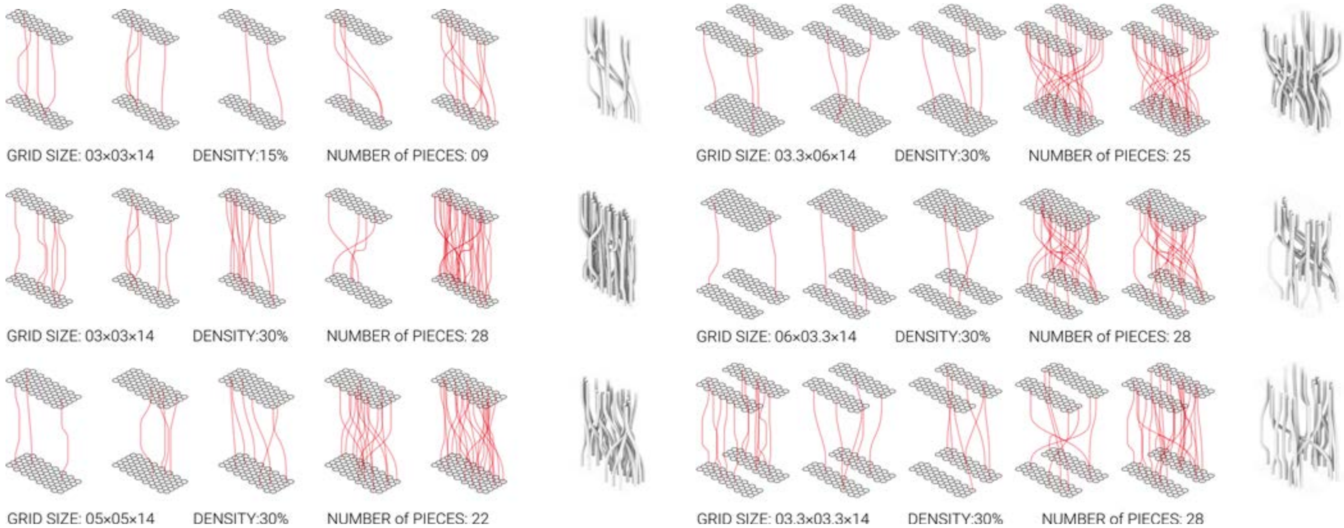

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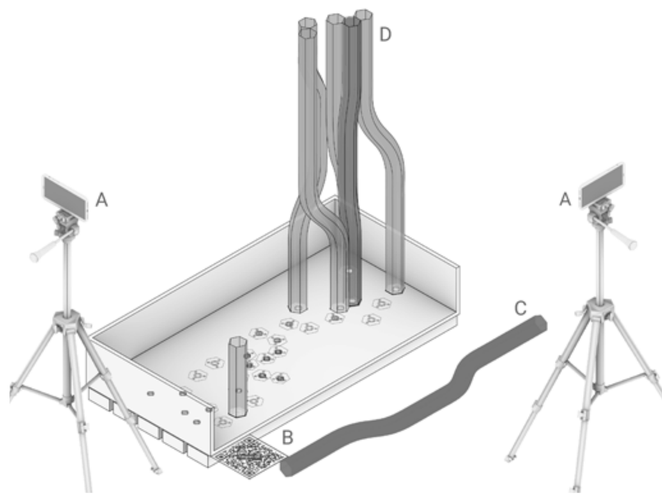
In the next step, we executed several extrusions to figure out the limitations of path design. The contributing parameters in this experiment were the degree of curvature, fillet radius of curvature, and rotation of the robot's tool center point (TCP).

All extrusions were executed over off-the-shelf drywall boards. Then they were left aside for 48 hours to be bone-dried. All parts were fired twice, once for bisque-firing and again for glaze-firing, in an electric kiln (Olympic Kiln FL53E with inside dimensions of 70" W 75" D 72" H) under cone 04 with a temperature of 1,830 °F and under cone 06 with a temperature of 1,945 °F, respectively.

To showcase how these extrusions can be part of a design language, we parametrized the aggregation constraints observed through the experiments. The façade design aggregates hundreds of variably extruded ceramic tubes. The organizational logic of the network of tubes is based on a hexagonal grid (Figure 2). On a hexagonally tessellated plane, different growth patterns for the tubes are executed according to the step number between the part's startpoint and endpoint. When the step size is 0 or 1, the pattern "loop" is executed. When the step size is 2 or 3, a smooth curve is generated. When the step size is too large, a discontinuous short tube is generated (Figure 3).

We only need to input the startpoint grid and the endpoint grid, so we can generate density-controlled, free-standing forms (Figure 4).

To assemble the prototype, customized hexagonal base mounts were designed and 3D-printed out of PLA. Industrial applications would likely involve the fabrication of steel parts. The base mounts were fixed to a 3/4-inch plywood sheet by wood screws.



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2 Two examples showing all possible ending hexagons that are in the decision pool of a specific starting hexagon. Hexagon (9E) has nine possible ending hexagons, including itself. Hexagon (4B) has twelve possible ending hexagons, including itself.

3 The number of steps changes the curve connecting the starting and ending hexagons.

4 Aggregations differing in grid size, ending-starting hexagons, and density.

5 Prototype installation setup: Multiple mobile devices (A) confirm the size and location relationship of the virtual and the real worlds by scanning a QR code (B). The UI's virtual model designator shows the model's specific orientation and angle where it should be installed (D). A duplicate version of the model (C) is laid down next to the QR code to facilitate secondary confirmation.

To assist in visually setting out the assembly locations and sequence, the Fologram plugin, a mixed-reality interface connecting Rhino3D to mobile devices, was employed (Figure 5).

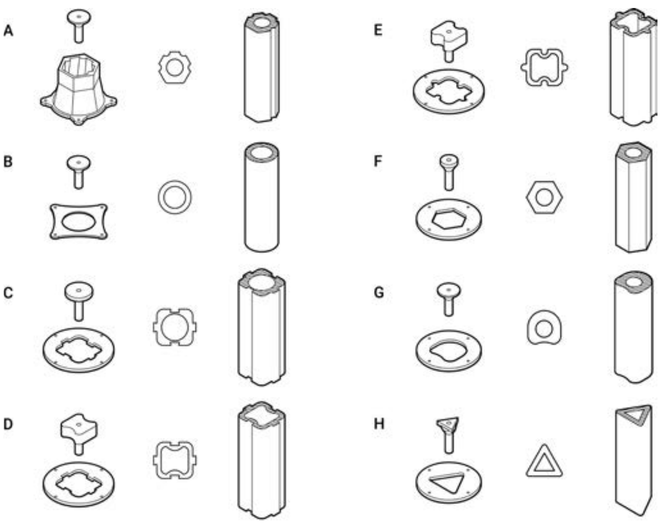
RESULTS AND DISCUSSIONS

EXPERIMENT 01: Extrusion Die

We 3D-printed multiple extrusion dies out of PLA on 40 percent material density (some examples displayed in Figure 07), and extruded clay out of these dies. These dies are varied in outline geometry (circular, rectangular, hexagonal, triangular, uniform, non-uniform, grooved, and non-grooved). Industrially extrusion dies usually have outer walls of 8 to 10-millimeter thickness, and a central hollow core of about the same width (Bechthold 2016). We figured out that a specific wall thickness helps the extruded part keep its shape during the bone-drying period, and prevents warping. In Figure 6, the extrusions out of profiles B and F had the best outcomes.

In an industrial production line, because the clay body lands on a conveyor belt that is moving at a constant speed relative to the extrusion speed, the need for friction between the clay and the belt is not a fundamental consideration. In our extrusion set-up, in contrast to an industrial one, a minimum friction amount between clay and a paper-faced drywall board is needed to prevent the robot from dragging the clay with itself during the extrusion process. To provide this friction, we picked the die with a hexagonal outline. The clay that is extruded out of this hexagonal die has a flat surface area in contact with the drywall board so that it sticks to the board (Figure 8). Another advantage of the hexagonal die is that its products can be more easily tessellated and bundled alongside each other in a rhombille pattern (Ugarte-Urzúa et al. 2020).

Later, to reduce the cracks during bone drying, we modified the geometry of the die and replaced the straight lines of three sides with wriggled curves (Figure 9). These wriggles add tiny texture to the surfaces when the clay is extruding out of the die. This texture helps inevitable hairline cracks grow alongside the pattern. Moreover, they increase the surface area which, itself, leads to more



	A	B	C	D	E	F	G	H
CLAY DROOPING								
SECTIONAL AREA (cm²)	18.6	15.7	23.9	21.0	20.8	21.1	24.3	16.5
AIR PRESSURE (PSI)	36	44	43	49	48	33	33	51

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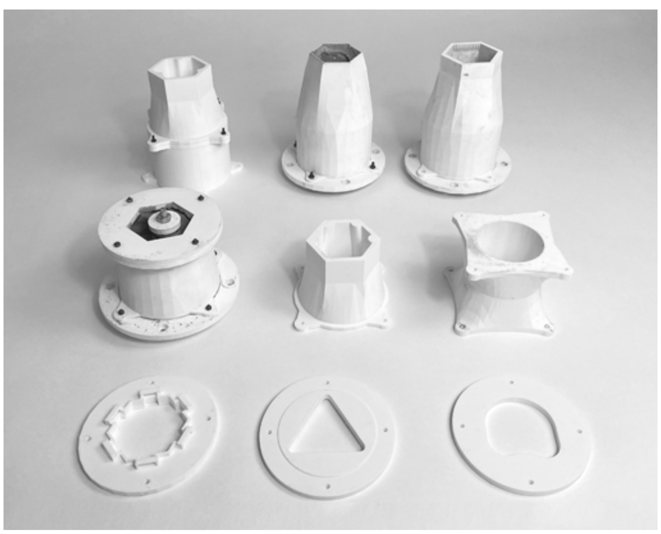

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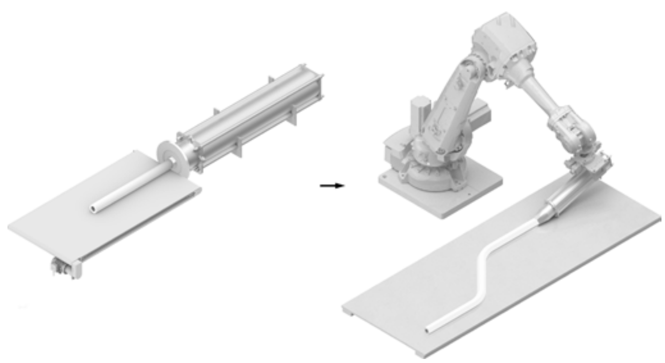

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6 Different die profiles, shape of the extruded parts, sectional area of each die, and air pressure needed for extrusion.

7 PLA 3D-printed dies. The upper right one was chosen for the subsequent experiments we are discussing.

8 Illustrating an industrial extruder extruding on a moving conveyor belt and a robot extruding on a nonmoving drywall board.

9 Left: Straight lines of three sides replaced with wriggled curves. Right: Assembly of WASP extruder tank, PLA 3D-printed die, and pneumatic plunger with air regulator.

consistent drying.

EXPERIMENT 02: Water-to-Clay Ratio for Extrusion
Proceeding to the next step, we made multiple clay mixtures to achieve even and stiff extrusions. In comparison to our set-up, industrial clay extruders work with higher air pressures, so they can extrude drier clay bodies (Bechthold 2016). To make a successful, stiff, and consistent extrusion, we started testing different mixtures of clay and water. All mixtures were mixed in a pug mill for 60 minutes before insertion in the tank. Figures 10 and 11 show the relation of clay, water, deformation, and the needed air pressure for extrusion. As previously stated, many interrelating parameters contribute to a successful extrusion. In our set-up, and for our selected die, we figured out that adding 18 ml of water to 200 grams of ball clay can make a clay mixture suitable for extruding with 50 psi air pressure. We observed that mixtures with higher water content ratios caused more slumping in extruded parts, while mixtures with low water content ratios caused the clay to get stuck in the tank, even with the highest

	CLAY (g)	WATER (ml)	RATIO	AIR PRESSURE (psi)
[01]	200	00		NA
[02]	200	12	06 %	NA
[03]	200	18	09 %	50
[04]	200	24	12 %	35
[05]	200	30	15 %	30
[06]	200	36	18 %	25
[07]	200	42	210 %	20

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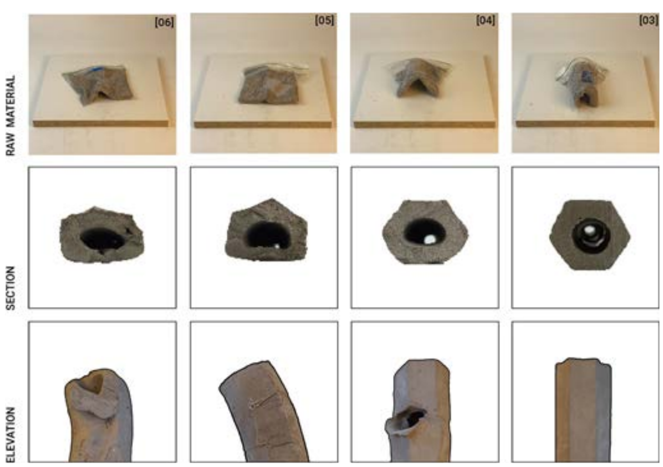

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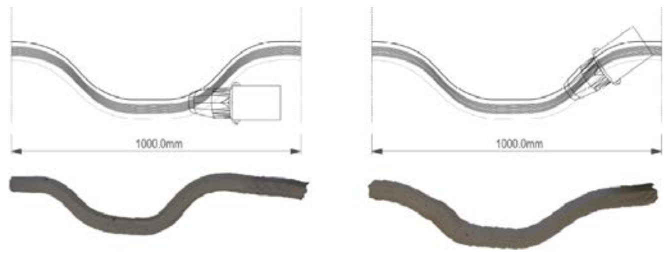
10 Relation of the clay moisture and needed air pressure for extrusion.

11 Performance and deformation of different clay mixtures: Each column is allotted to the corresponding row in Figure 10. The clay mixed with a water content of 0.9% (as shown in the right column) exhibited the best performance. It had a viscosity low enough to extrude with 50 psi air pressure, yet high enough to maintain the shape of the extruded part.

tested air pressure.

EXPERIMENT 03: Extrusion Path and Speed Control
Taking the die profile (F) from Experiment 01 and clay mixture (03) from Experiment 02, we executed several extrusions to figure out the limitations of path design. The contributing parameters in this experiment were the degree of curvature, fillet radius of curvature, and rotation of the robot's TCP. Forty-five-degree rotation and 225-mm curvature radius were the best results that we



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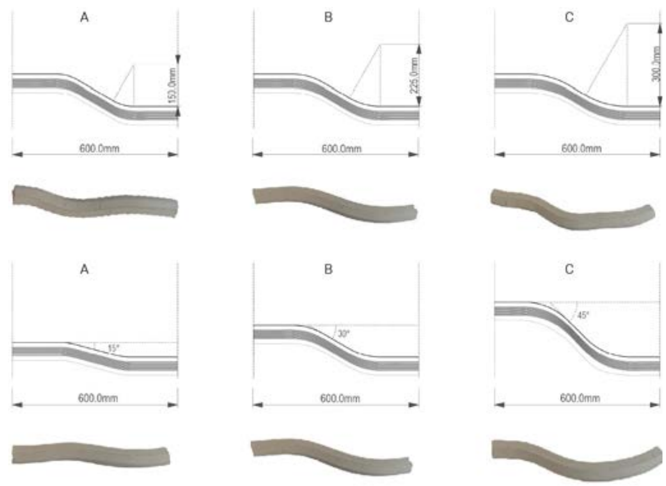

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TEST	ANGLE	RADIUS (mm)	LENGTH (mm)	TCP ROTATION
A	45°	225	1000	×
B	30°	150	600	×
C	30°	225	600	×
D	30°	300	600	×
E	45°	225	1000	✓
F	15°	225	1000	✓
G	30°	225	1000	✓
H	45°	225	1000	✓

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12 Performance of robotic extrusion. Left: TCP Rotation Off. Right: TCP Rotation On.

13 Performance of robotic extrusion according to the curvature radius and angle in the top and bottom rows, respectively.

14 Relation of angle, radius, and TCP rotation for proper extrusion.

could achieve in this experiment while the robot's TCP was constant (Figures 12, 13, and 14).

EXPERIMENT 04: Extrusion Speed and Robot Speed

In EXPERMENT 03, we observed that the robot automatically reduces its speed when its trajectory changes from a straight line to a curved one. Since the speeds of the robot and extrusion must be a constant parity, this feature resulted in noticeable fractures at locations of bends in the extrusion (Figure 15).

To avoid these fractures during the robot extrusion, it is necessary to strike a balance between the robot's velocity and the extrusion speed to achieve neatly curved extrusion bends. The actual robot speed during extrusion can be controlled by the pendant manually, adjusting the speed from 0 to 100 mm/s. The extrusion speed is controlled by a manual pneumatic plunger (in psi). To make a connection between the robot's speed and extrusion speed (translated to the air pressure of the pneumatic plunger), we added a certain length of lead-in and lead-out paths, before and after the preset path. This specific operation requires two people to cooperate, one controlling the pneumatic regulator and the other controlling the robot's speed on the pendant (Figures 16, 17, and 18).

This workflow is defined in six steps: a) the robot is located at the starting point, and the pneumatic regulator is switched on; b) run the lead-in path when the extrusion speed is relatively stable, and the operator adjusts the

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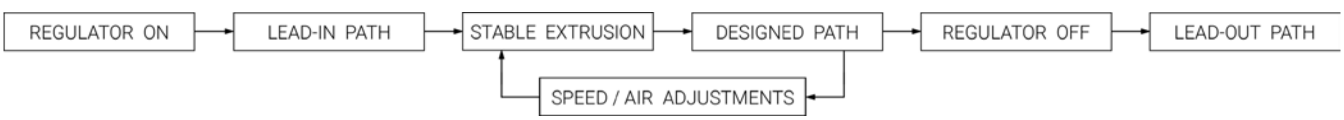
15 Imparity of robot speed and extrusion speed resulted in fracture at bends in the extrusion.

16 Controlling extrusion with collaboration of two operators.

17 Sequence of a proper robotic extrusion: It is needed to change the air pressure and robot's speed accordingly, based on the curvature of the designed path for proper robotic extrusion.

18 Left: Two operators holding (A) robot's flexpendant and (B) pneumatic air regulator (Right) for a smooth extrusion.



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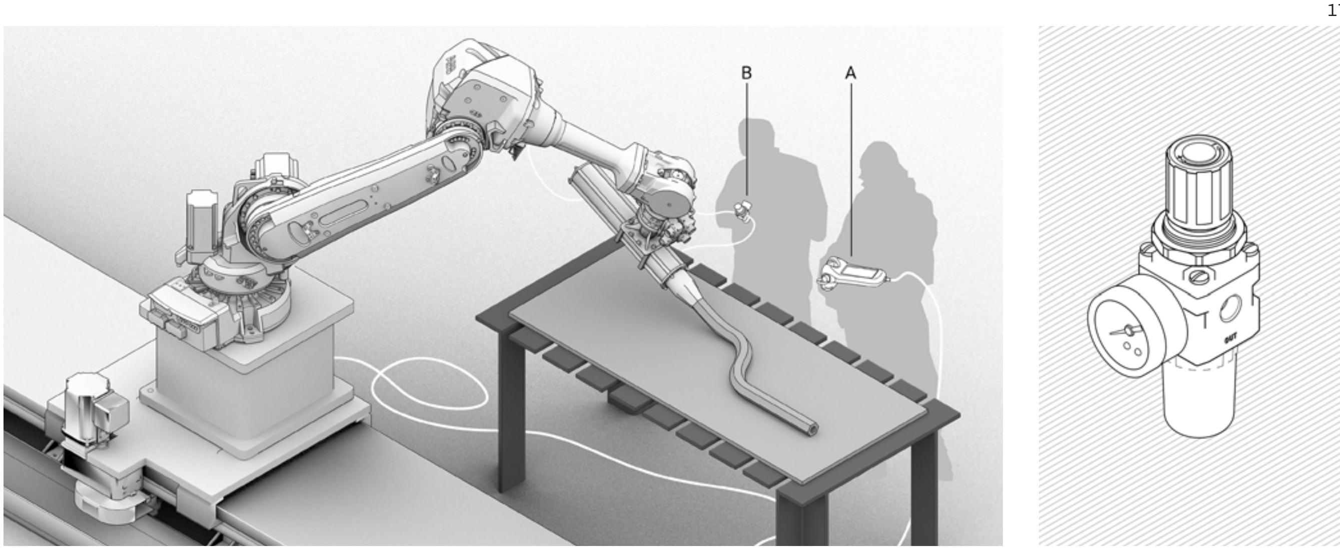

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TEST	ROBOT VELOCITY (mm/s)	AIR PRESSURE (psi)	OBSERVATION	RESULT IMAGE
A	6	30	• OBVIOUSLY DRAGGED • UNCLEAR BENDING	
B	6	40	• DRAGGED • UNCLEAR BENDING	
C	3	30	• MATERIAL ACCUMULATION	
D	3	40	• EVEN DISTRIBUTION • SMOOTH BENDING5	

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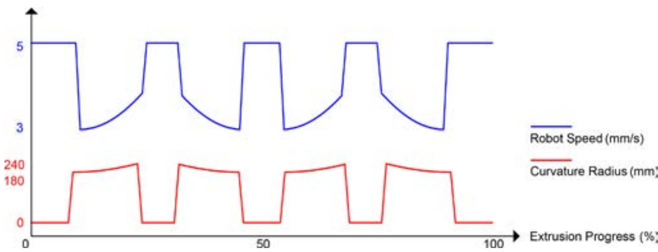

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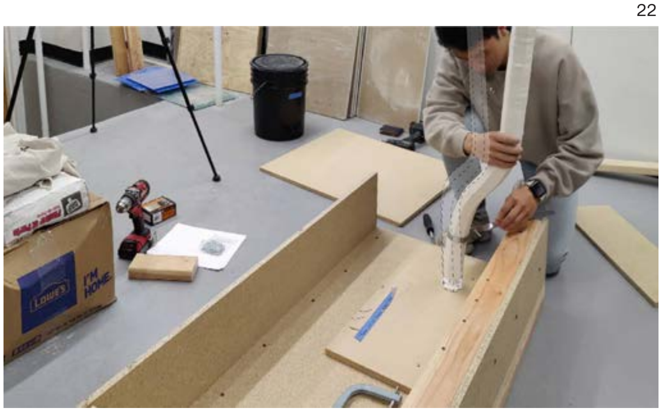

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extrusion air pressure to balance with the robot's speed; c) run the lead-in path until a smooth extrusion is acquired; d) start extruding the designed path, during which the air pressure remains unchanged, and the robot speed will make adaptive adjustments according to the curvature change, while the operator ensures the extrusion is happening evenly; e) switch off the pneumatic regulator; and f) run the lead-out path.

We conducted this experiment to investigate the relation of robot speed and the extrusion speed translated, by air pressure in psi, with a constant clay mixture. We discovered that when the extrusion speed is less than the robot's speed, the extruded clay is noticeably dragged by the robot over the drywall board. When the extrusion speed is less than the robot's speed, excessive clay accumulation occurs. Only when the robot speed and the extrusion air pressure are relatively balanced, the extruded piece is closest to the favorable designed shape (Figures 19, 20, and 21).

To portray how the robotic extrusion technique can be employed in architectural design, we proposed and prototyped an architectural, ceramic, façade screen, aggregated of multiple variably extruded ceramic parts, by using an algorithmic design approach (Figure 22).

Unlike modular bricks, assembling a set of differentiated parts in a pre-defined design requires a comprehensive sequence of instructions, and involves substantial manual work. To test how these ceramic parts can be assembled more precisely and faster, we employed software-assisted assembly. We looked for a concept that "... alternate-reality devices are used to train and assist humans in completing technical tasks more efficiently (i.e., by augmenting human physical strength, increasing precision during manual manipulation, or providing contextualized knowledge in situ)" (Johns, Anderson, and Kilian 2020, 672). This technique can be easily used because of the ever presence of mobile devices as a mixed-reality interface (Jahn et al. 2018). We designed an installation in Grasshopper from

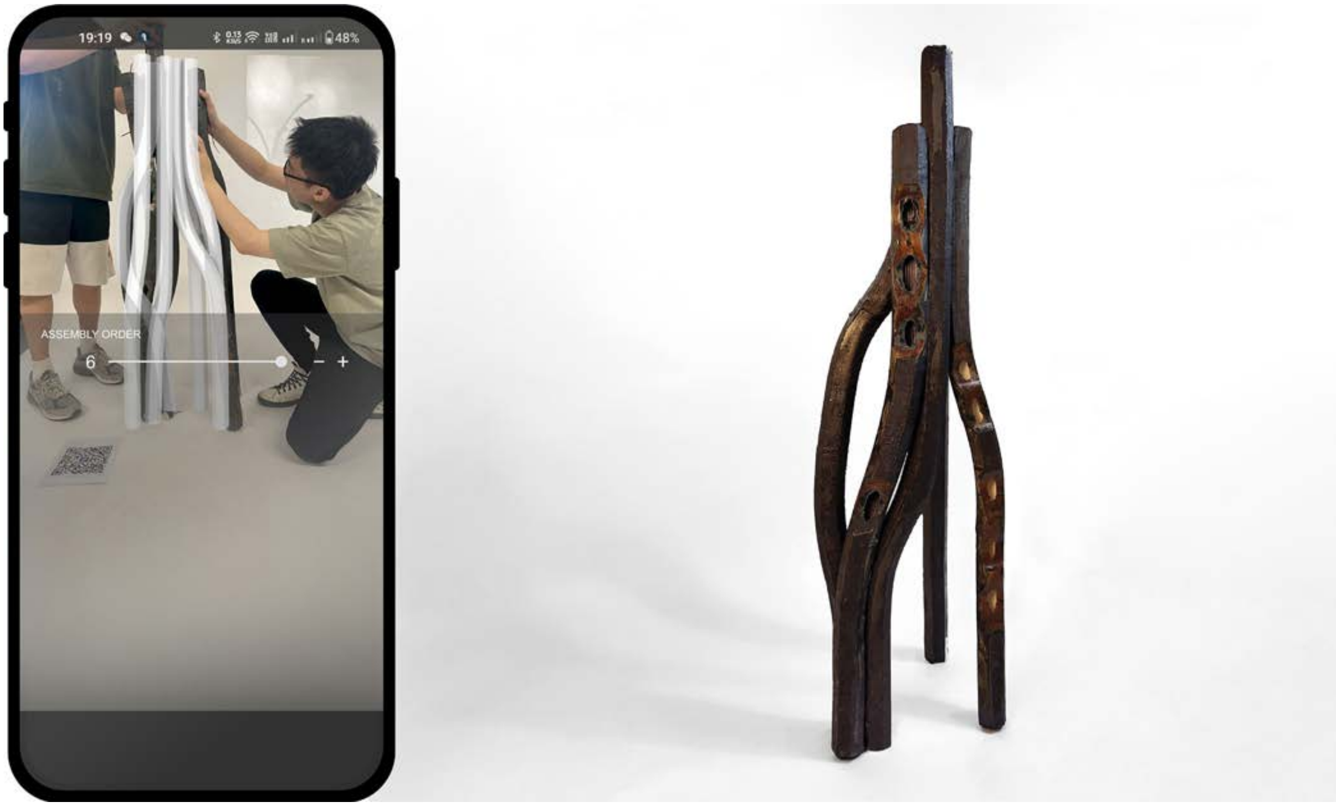
19 Experiments on robot velocity and extrusion speed (air pressure) relation.

20 Relation of curvature radius and robot velocity.

21 Extrusions of same path. Left: Robot velocity was adjusted adaptively, Right: Robot velocity was kept constant.

22 Portraying an architectural design of robotic extruded ceramic façade.

23 Illustrating how the mixed reality can help to find the correct angle and position of parts.



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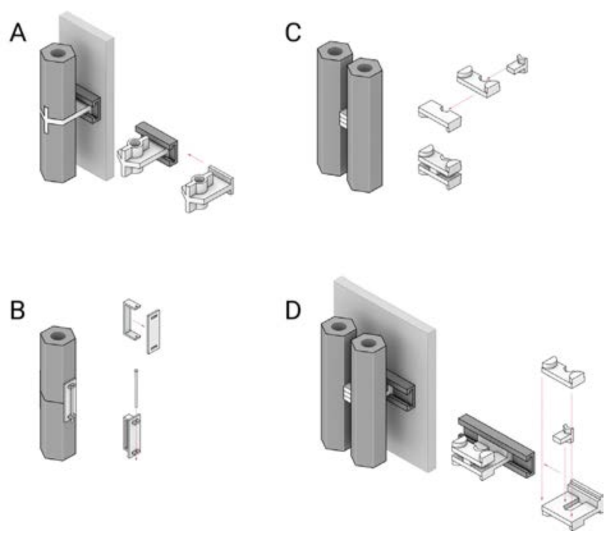

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24 Left: The interface of Fologram on a mobile device. Right: The prototype assembled with the help of mixed reality.

25 Designed joints for connecting tubes to themselves, to each other, and to supporting wall.

26 Designs A,B, and D from Figure 25 were 3D-printed and physically tested.

27 Illustrating the idea of how utilizing the extrusion die with a simple mechanism can add more degrees of variability.

28 Installation steps of a mechanism comprised of a stepper motor, multiple involute spur gears, and linear racks. By the help of such a mechanism, the cross-section profile of the die can be continuously expanded and contracted during extrusion.

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several variably extruded ceramic parts. Parts were input into the Fologram plugin as sequences of assemblies, and operated through real-time streaming connections with mobile devices (Figures 23 and 24). A close-up picture of the assembled prototype is found in Figure 29.

CONCLUSION

We proposed a method for enhancing die-cast clay extrusion by leveraging a 6-axis industrial robot arm's motion to create variable clay extrusion paths. Following experiments in die profile design, clay composition, robot choreography and speed, extrusion speed, and mixed-reality assist, we are highly encouraged that the method demonstrated a suitably varied and rapid manufacturing process, offering potential as a mass-customization method for the architectural ceramics industry. Beyond the micro-scale extrusion of clay by time-intensive AMT methods, die-cast clay extrusion has not been explored using robotic manufacturing methods, suggesting that there are many open avenues still to investigate. These

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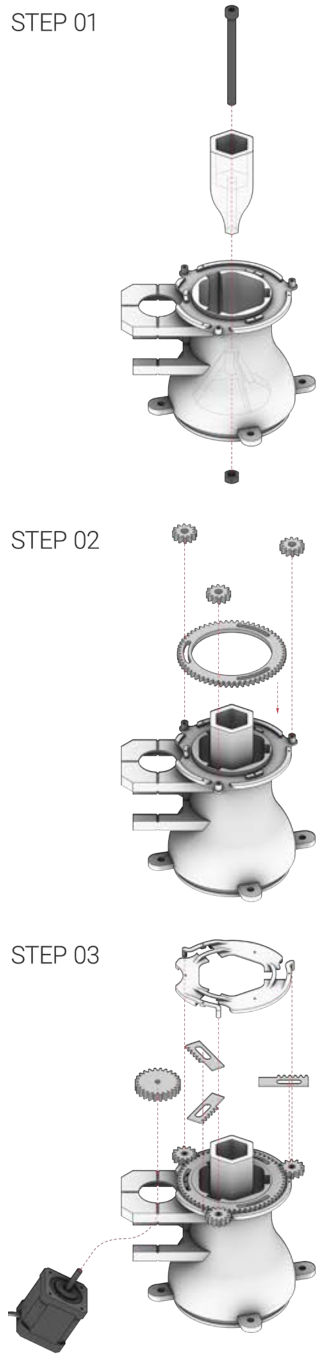

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experiments indicate this area of research holds great promise in offering a cost-effective, mass-customization method.

This research was carried out in a period of four months. The constraints, including time, and access to materials, tools, and machines, greatly impacted the results of the research, leaving some areas under-explored. For further investigation, we are interested in a) designing a more architecturally suitable system of assembly joints (Figures 25 and 26); b) designing and developing a mechanical end-effector that can add more degrees of variability to extrusion (Figures 27 and 28); c) addressing environmental performance considerations in the computational design method; d) decreasing the weight and material volume of extruded parts; and e) improving manufacturing precision.

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