Dynamic Slip Casting

An Efficient Robotic Approach to Geometrically Variable Ceramic Part Production

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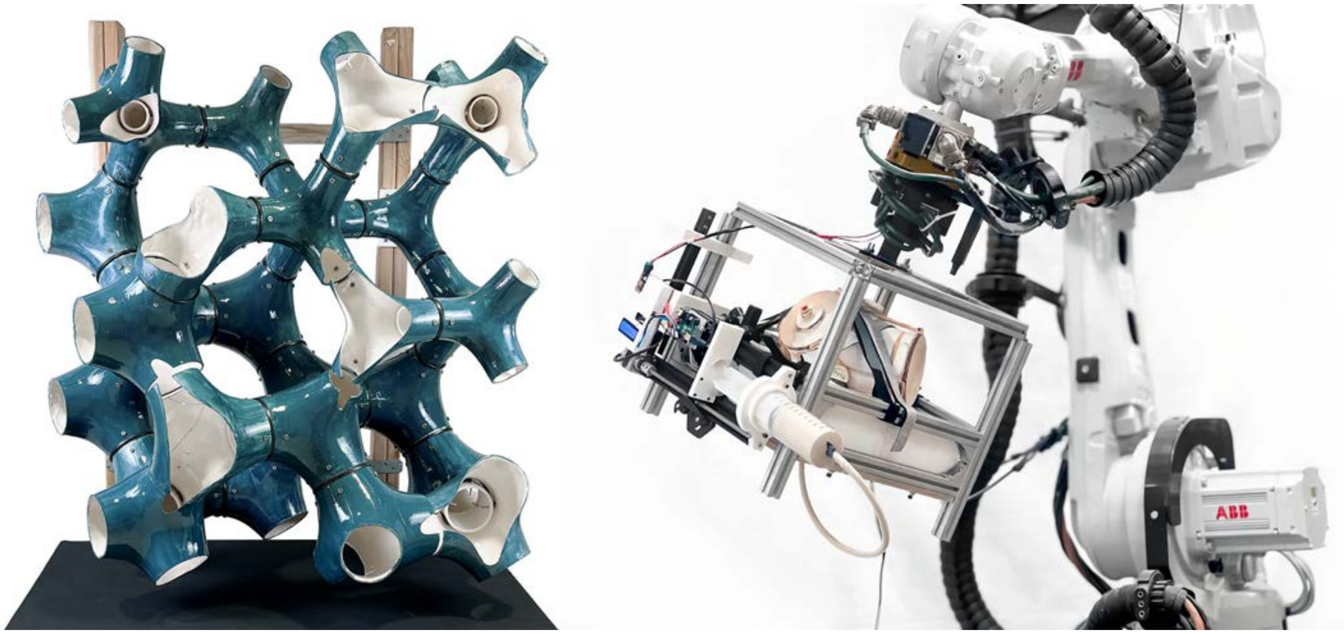


1 Final fabricated prototype and custom-fabricated end effector

ABSTRACT

Clay slip is renowned for its versatility, enabling seamless molding, casting, and firing processes that facilitate the production of precisely-shaped and diverse products with varied sizes. However, its limitation in producing variable components without new molds presents challenges for integration into architectural practices where variability is often advantageous. This paper introduces an innovative slip casting approach that allows for the production of diverse clay forms using a single mold by employing a 6-axis articulated robot to rotate the mold during the solidification process. A simulation program predicts the solidified slip's shape in realtime, and a customized end effector attaches the mold to a robotic arm and periodically injects additional slip for precise edge control. The proposed method combines traditional slip casting with industrial robotics, offering greater control over geometric qualities without increasing mold demands. This study offers a potential solution for advancing ceramic manufacturing by overcoming conventional limitations, which could offer opportunities for increased innovation and creativity in architecture and beyond.

INTRODUCTION

This research revolved around the process of slip casting. Slip casting is a technique where liquid clay is poured into a mold, allowed to dry and consolidate on the mold's inner surface, before excess clay is drained, resulting in a hollow part. This process is commonly used in the industrial production of sanitary ware and in craft-based settings for creating different parts (Bechthold et al. 2015). Slip casting allows for the economic mass production of geometrically complex ceramic parts (Dawson 1964).

In today's modern settings of industrial production of sanitary ware, slip casting has experienced further enhancements in process efficiency. During the process of plaster mold making, researchers have introduced an additional step involving compression and vibration to effectively enhance the mechanical strength of the gypsum mold (Lin et al. 2018). Moreover, as gypsum molds have a limited lifespan and are deemed disposable industrial waste after use, alternative materials like Alumina(Aluminum Oxide) molds are currently under investigation as potential substitutes (Kondo et al. 2010). These advancements enabled consistent, high-quality slip-cast elements, meeting mass production demands with precision and effectiveness.

However, slip casting does come with certain limitations. It requires the creation of plaster molds for each desired shape, each with a minimum of two mold parts per geometry, with complex parts often requiring larger numbers of parts (Bechthold et al. 2015). As a result, application in architecture has been primarily limited to mass-produced parts, as the creation of individual molds for each geometry can be time-consuming and expensive. Consequently, architectural façades, in particular, have often relied on alternative materials and manufacturing techniques to achieve variation. For instance, water jet cutting has emerged as a versatile technique for precisely cutting metals often used in creating variations in architectural applications (Górka and Kotarska 2018). Alternatively, digital fabrication technologies, such as 3D printing, enable the creation of intricate and customized designs without the requirement of individual molds (Chan et al. 2020), but are not able to achieve comparable precision and finish quality to slip casting, setting slip casting apart from alternative materials and manufacturing techniques.

BACKGROUND AND STATE OF ART

Architectural ceramics have recently seen a resurgence, evident in projects like the 111 West 57th Tower in New York City designed by SHoP Architects whose 1,428-foot-high exterior is clad in terracotta tiles (Dreith 2022) and Disney's New York City headquarters that features a green terracotta paneled façade designed by Skidmore, Owings & Merrill (SOM) (SOM 2020). These projects integrate advanced technology and traditional craftsmanship, demonstrating the widespread use of ceramic façade solutions. Notably, however, none of these projects utilised slip cast manufacturing due to its limitation in producing components with geometric variation without the need for additional molds for each geometrically unique part. The inability to easily introduce geometric variation makes it challenging to integrate slip casting into architectural practices, where the ability to create differentiated geometric conditions is often preferred.

Four established methods for introducing variation in slip-cast parts from the same mold include: (1) adjusting the waiting time before draining the slip to vary the internal thickness of the cast's walls which is not visually apparent (Özkal et al. 2004); (2) altering the composition of the slip to control the overall color, which often requires unique clay bodies for each variation (Özkal et al. 2004); (3) utilizing a 6-axis articulated robot to incrementally inject multiple colors of slip into a rotating mold in a similar manner to plastic rotational molding in order to produce multi-colored marbling effects on parts of identical geometry (Dunaway, et al. 2022); or (4) in precast concrete, variable parts have been produced from the one cylindrical mold using jigs actuated by an articulated robot arm, setting a partially filled mold at different angles for a number of iterations. While each part is geometrically distinct, the parts are constrained to planar profiling due to gravity that limits their geometric possibilities (Tessmer et al. 2019). These methods each provide distinct means of introducing variation, however, do not offer a solution to the geometric variation of hollow slip cast parts using a single mold.

This research expands on the approach introduced by Dunaway et al. to fabricate slip cast parts using a 6-axis articulated robot to perform rotational molding. While Dunaway et al. produced color marbling pattern variation on geometrically identical parts, this research develops capabilities to produce geometrically varied parts, demonstrating a method that could support the mass-customisation of slip casting for architectural ceramics applications.

To address unpredictability, we developed a slip casting simulation software to estimate the shape and thickness distribution of the cake (solidified slip) after intricate robotic motion, and designed a specialized tool to inject additional slip and counterbalance water loss, enhancing cast part quality. Additionally, we developed a method for generating robotic trajectories to produce desired shapes. The feasibility of the research approach is also demonstrated through the production of a full-scale partial façade-screen assemblage prototype. Our proposed approach involves a robotic approach to the rotational molding of slip, the micro-dosing of slip on a custom robot end-effector tool, and the development of simulation software. Together these developments enable different geometrical outcomes from slip casting with the same mold and hold the potential to enable the unprecedented mass-customisation of slip cast architectural elements.

METHOD

Overview

This research presents a dynamic slip casting method that employs variable rotation of the slip mold using an industrial 6-axis articulated robot and micro-dosing of slip into the mold during the slip casting process. The objective is to produce various geometries with a controlled edge thickness from a single mold. In this process, a Robotic Trajectory refers to one cycle of robotic motion done to lay a layer of slip. The whole cycle of robotic motion workflow, including the pickup and unloading of the mold, and casting using several robotic trajectory cycles, is termed as Robotic Routine.

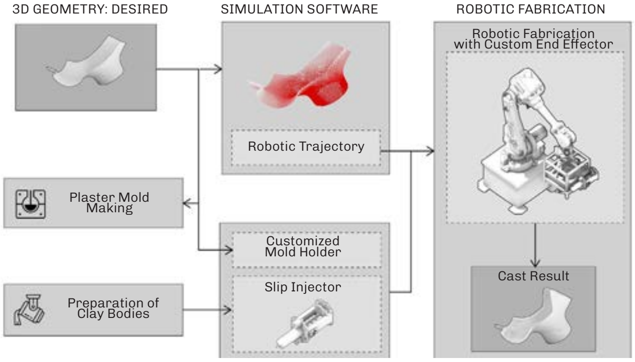
Beginning with selecting the clay body and the plaster mold design, the method was developed through a sequence of rotation experiments, along with the parallel development of a simulation modeling method and custom robotic end effector. Conclusively, a robotic fabrication workflow was proposed, encompassing the trajectory design and manufacturing procedures (Figure 2).

Clay Body

The chosen clay body, Miller Slip NS1 by Laguna for slip casting low-fire hobby ceramics, was a crucial variable in our experiments. To increase liquidity and meet experimental requirements, we added 250 ml of water to each 2.5-gallon bucket of clay body before use. Reused slip required additional water due to water absorption by the plaster mold during casting. To assess liquidity consistency, we conducted dripping tests for the reused slip, using the first-used slip as a control group. Two drops of slip were dropped onto a flat plate, and the plate was tilted to a specific angle. The distance the slip traveled over 60 seconds was measured. Although this manual method lacked precision, it allowed us to control slip fluidity.

Plaster Mold

Three different-sized molds (small, medium, and large) were fabricated for different steps of experiments (Figure



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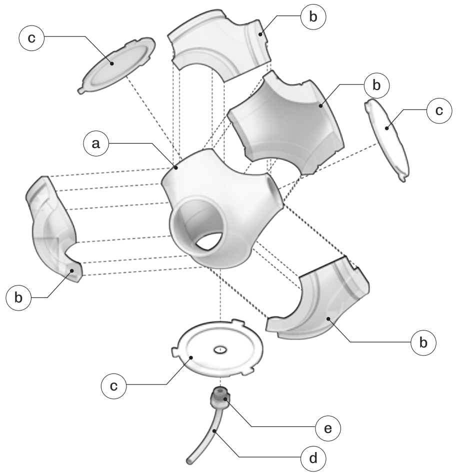

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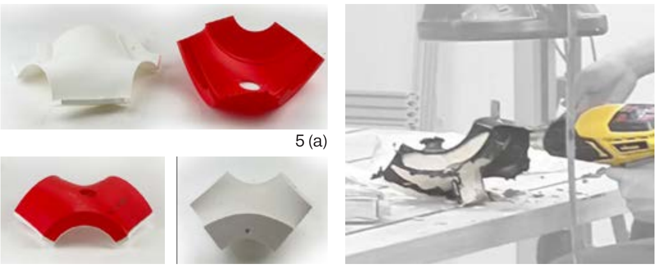


5 (a)

5 (b)

5 (c)

5 (d)

2 Fabrication workflow.

3 Three molds in small, medium, and large sizes for different experiments.

4 Exploded view of plaster mold:
(a) Resulting casted piece (b) Four-part plaster mold
(c) 1/8-inch laser-cut MDF laminate end caps (d) 1/2-inch tubing
(e) Push-to-connect tube fitting

5 (a) 3D printed pattern apart (b) 3D printed pattern assembled
(c) Resulting plaster mold piece (d) Extraction of plaster mold using a

3). For the largest mold used in our final experiment, a four-part shell core design was utilized (Figure 4). To achieve high accuracy and high surface quality for the project's complex shapes, we fabricated the mold using a two-part Polylactic Acid (PLA) 3D printed shell pattern that we hot-glued together. The mold geometry incorporated a shell core design that was one-inch offset (minimum thickness required for a slip cast mold) of the desired geometry. The shell core design minimized wasted space and reduced overall weight, compared to traditional cube-shaped molds which was ideal for use on an ABB IRB 4600 robot with a 60 kg payload. No. 1 Pottery Plaster with a 10:7 plaster-to-water ratio for slip casting was used, and after pouring the liquid plaster into the PLA 3D printed shell pattern, it was allowed to cure before being removed with a heat gun. We chose PLA due to its lower decomposition temperature of 300°C. A fume extractor ensured proper ventilation during the melting process (Wojtyła, Klama, & Baran, 2017) (Figure 5).

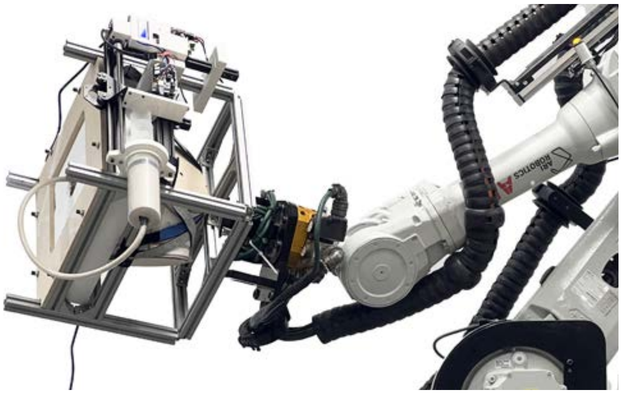
Each node of the four-part plaster mold had an interchangeable lid, enabling the choice of an injection point, based on the desired cast piece and the robot's initial position. The external interface between the lid and plaster mold was hot-glue-sealed to prevent slip leakage during casting. The adhesive properties facilitated easy removal of the hot glue from the plaster after casting.

Robot End Effector

We have developed a robotic end effector with two parts: a mold holder that allows a robotic arm to hold and manipulate plaster molds freely, and a slip injector (Figure 6).

The mold holder was fabricated from a series of aluminum extrusions, highly adaptable to various mold geometries. It incorporates computer numerical control (CNC) foam inserts to securely hold different mold types in different starting orientations during the robotic routine. Efficient loading and unloading of the molds were heavily considered, requiring the release and re-screwing of just four bolts (Figure 7). VELCRO® straps were employed for quick and efficient strapping and unstrapping of the mold in each robotic routine. After completing a routine and draining the slip, the foam insert and mold can be easily removed and set aside to dry, allowing the next routine with a different mold to commence.

To account for the issue of reducing slip inside the plaster mold (explained in the results section), we designed a slip injector using 20mmx20mm aluminum extrusions (Figure 8a). The slip injector incorporates a 500ml syringe, ensuring sufficient slip volume for each routine based on the scale of the mold used in our experiments. Custom 3D printed parts were developed to mount the slip injector to the end effector (mold holder) and integrate the 500ml syringe into the design. For accurate control of the slip injection amount, we opted for a mechanical linear actuated system powered by an Arduino-controlled stepper motor over a pneumatic-powered system. To ensure the accuracy of movement and to minimize friction, series bearings, and metal parts for 3D printing, such as lead screws, were utilized. As each robotic routine required a different amount of slip to be injected, we also programmed and fabricated a custom control box for the Arduino, which is a programmable microcontroller built onto a single printed circuit board and commonly used for electronics



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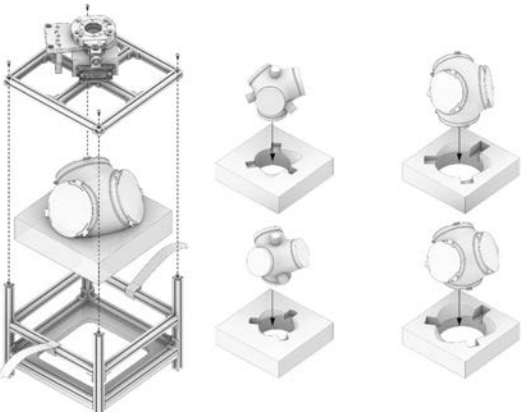

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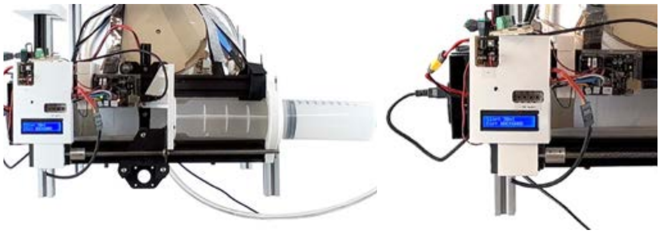


8 (a)

8 (b)

6 Mold holder fabricated attached to the robot.

7 Corner bolts released for mold unloading and series of foam inserts fabricated

8 (a) Custom fabricated slip injector (b) Slip injector control box for injection amount control.

projects, to enhance the efficiency of the workflow (Figure 8b). The control box features an LCD screen displaying the current setting, along with four buttons serving different functions: (1) decreasing the slip injection amount by 1ml, (2) increasing the slip injection amount by 1ml, (3) selecting the direction of syringe movement, and (4) manually actuating the injector with the current setting. Additionally, the control box allows for connection to the digital output of the robot, enabling synchronization of slip injection timing during the robotic routine. An Arduino script was developed to receive the signal from the robot, converting the desired slip volume into the precise number of rotations needed to actuate the syringe plunger.

Simulation Software

To address the unpredictability of our proposed dynamic casting technique for robots, where continuous mold rotation is employed for complex shapes, we have designed simulation software. The software needs to produce precise forecasts of slip casting outcomes based on certain input parameters, including mold shape, infill percentage, trajectories, etc.

One key aspect of this simulation is to determine a suitable method to simulate the slip behavior inside the mold. Given the relatively stable conditions within the mold, such as temperature, humidity, and the speed of robotic motion, the slip progresses slowly throughout the process. Therefore, we treated the slip as static in very brief time intervals for simulation purposes.

Another key aspect is estimating the thickness distribution of the cake in the cast part. Based on prior research findings (Banno et al. 1999, 2001) that indicate cake thickness grows with time, we chose to determine the thickness of the cake based on the coverage time for each mesh vertex. By tracking the coverage time for each vertex, the program can estimate the thickness distribution of the solidified slip in the cast part, further enhancing the optimization of the dynamic casting proces (Figure 9).

This software advances future research by predicting casting outcomes using specific parameters like mold shape, slip infill, and robot trajectory. Moreover, the simulation software allows us to design the required robotic trajectories for creating specific, partially cast shapes, providing essential support in fostering our research progress and enhancing production methodologies.

Robotic Fabrication

Robotic Trajectories: The robotic trajectory involved a series of rotational mold-orienting motions to lay layers of slip inside the mold. The dynamic casting procedure this paper proposed is slow-paced and consistent, indicating that the mold's orientation is the primary determinant of the result. Ideally, the robot should pick up the mold and revolve it around a set point.

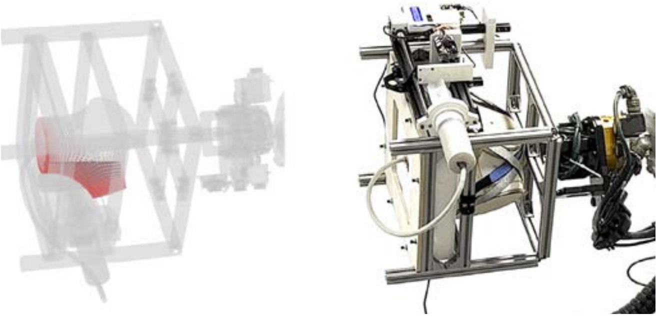
The robotic casting trajectories are generated using genetic algorithms, assessing 1,000 to 17,000 mesh vertices per part based on specified criteria. With an initial set of 20 numbers, corresponding to 10 different orientations, a continuous trajectory is created by using these orientations as pivotal points. By comparing the simulated and target geometries, we assessed mesh vertices based on specific criteria. Points were awarded to vertices on the target geometry, while deductions occurred for vertices outside or missing the target vertices. By iterating through generations and selecting the best performers, we refined the casting process and achieved more accurate casting trajectories.

Robotic Fabrication Workflow: The workflow followed predefined toolpaths for the pick-up and unloading of the end effector, and simulation-generated robotic trajectories. The plaster mold was loaded with a foam base and strapped into the mold-holder cage. The robot executed the mold pick-up toolpath at the pick-up point, fastening the end effector with screws. The slip injector incrementally injected slip into the mold during the robotic routines, repeating the trajectory until the desired slip layer was achieved. After completion, the robot returned to its initial position for slip drainage, followed by the unloading tool path. The mold and foam mold holder were then removed for drying, and the process was repeated with another mold. The pieces remained in their molds for an additional 20 minutes before removing the lids. To ensure smooth edges at the nodes, a blade was inserted between the lids and molds to cut and separate them.

RESULTS AND DISCUSSION

Results from Dynamic Slip Casting Feasibility Test

Before operating on the robot, a series of small-scale, manual, partial-cast experiments were performed using a custom-orienting jig on a single type of mold to test the feasibility of proposed partial cast methodologies (Figure 10). These small-scale partial cast tests showed the possibility and promise of creating varied geometries. However, we found the manual method’s limitations, as the resulting openings were always flat due to the slip’s liquid properties' tendency to level out under gravity. This further showed the need for us to integrate robotic motion into the workflow (Table 1). In addition, to study the potential of dynamic change of angle, a small number of initial manual



9 Custom-developed simulation software predicting slip motion and wall coverage inside the mold

10 Mold orienting jig with two axes of tilt fabricated for manual feasibility

tests of gradually changing the angle of the mold from one angle to another were conducted. This showed potential for integrating the gradual change in angle to produce partial cast pieces that have non-planar cuts through the piece (Table 2).

Results from Slip Consistency Test

To further evaluate the proposed partial cast methodologies, and to transition to performing dynamic casting using a 6-DOF (Degree of Freedom) robotic arm, we had the robot repeatedly execute the same trajectories to create an evenly distributed cake. The test was conducted using a medium-sized mold, with the same trajectory and total time, while varying the robot speeds and slip consistencies.

For slip consistency assessment, we conducted dripping tests after each robotic routine, which is further described in the method section. Initially, using low-consistency slip

Table 1: Results of Feasibility Test by Manually Tilting Single Mold

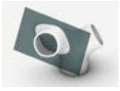
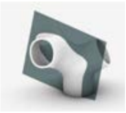
Jig Angle Bottom (degree)	Jig Angle Top (degree)	Slip Stay Time (minute)	Slip Dry Time (minute)	Jig	Cast Piece	Section
5	25	15	25			
20	25	15	25			
20	25	15	25			
5	20	15	25			

Table 2: Results of Feasibility Test by Manually Tilting Single Mold Incrementally

Jig Angle Bottom (degree)	Jig Angle Top (degree)	Slip Stay Time (minute)	Slip Dry Time (minute)	Jig	Cast Piece	Section
5	20~45	15	25			
20	20~30	15	25			

Table 3: Two Results of Slip Consistency Test

Injection Amount (ml)	Viscosity	Slip Dry Time (min)	Slip Dry Time (hr)	Motion Repetition	Robot Speed	Result	Photo
400	High	60	8	25	100%	All Cast	
400	Low	60	8	25	50%	Not Full Cast Sticky Slip	

and slower robot speed yielded unsatisfactory results. Thick slip lacked fluidity, hindering movement within the mold and causing uneven thickness distribution and increased cracking risk. In contrast, slips with higher water content produced a more even thickness distribution (Table 3).

The results highlighted the importance of controlling slip consistency for optimizing the dynamic casting process. Precise control of water content will be crucial for future applications, especially in mass production, to ensure consistent quality and efficient processes. Moreover, the tests revealed limitations in robot speed. Moving too fast or too slow resulted in non-uniform slip distribution.

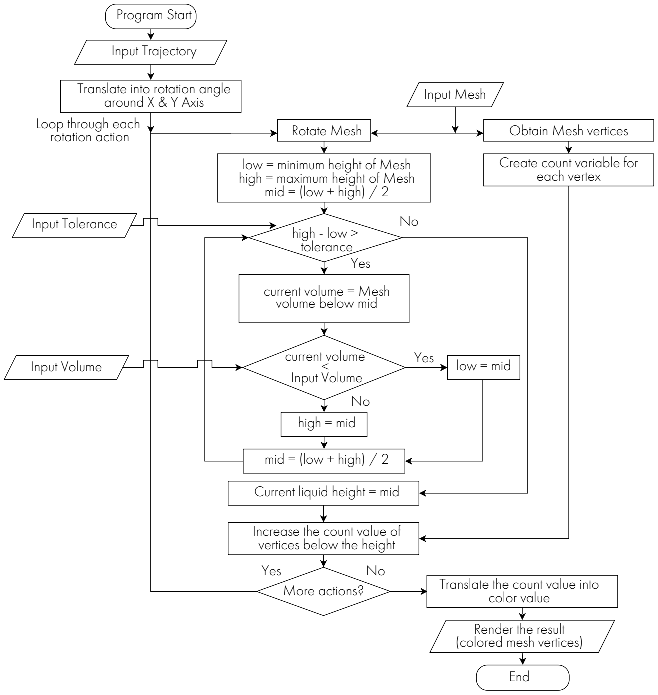
Simulation Software Development

The simulation software is built upon our prior feasibility research. Our approach involves recording the mold orientation at regular time intervals, calculating the slip level for each orientation, and determining the coverage time for each mesh vertex. Finally, the program generates a mesh representing the resulting cast part with a specific thickness distribution based on the coverage times.

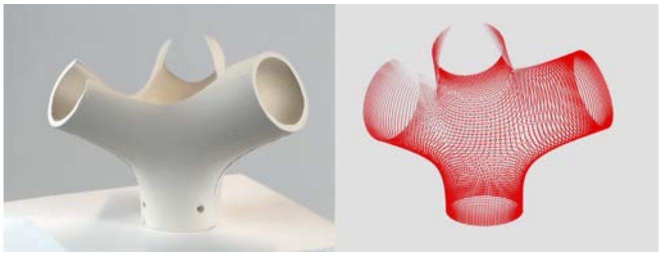
The process is as follows:

- Recording Mold Orientation: The simulation software converts the mold's orientation along the X and Y axes into x and y coordinates. This conversion enables users to manipulate the orientation via a slider control, and the software continuously logs the mold's orientation. By tracking the orientation, we can effectively control the mold's ongoing rotation throughout the dynamic casting process.
- Calculating Slip Level and Mesh Vertex Coverage: For each recorded mold orientation, the program calculates the current slip level within the mold using the binary search algorithm (Figure 11). All mesh vertices below the slip level plane are considered to be covered by the slip. The program keeps track of the time each vertex remains covered by the slip throughout the entire casting trajectory.
- Generating Output Mesh Vertices and Coverage Times: The program simulates the entire casting trajectory and then outputs the mesh vertices with non-zero coverage times and their durations. These elements contribute to the creation of the final mesh for the cast part, showing a specific thickness distribution (Figure 12), based on varied coverage times, providing an accurate representation of dynamic casting results.

Although the developed simulation was a simplification of the dynamic slip casting process, our experiments showed its effectiveness in reverse engineering the robot's trajectory from desired user input geometry. We evaluated it using a 3D scan of a successful cast piece made with less consistent slip (Figure 13). Simulated mesh vertices, depicted as red dots, represent thickness - deeper red



11 Flowchart of the simulation software employing binary search algorithm.



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12 Colored mesh vertices output from the simulation according to their coverage times, and resulting casted piece.

13 Trajectory used to cast the piece, and comparison of 3D scan and simulated

means greater thickness. While the overall geometry exhibits a good match, some misalignments persist. For instance, the bottom of the piece, thicker due to gravity's effect during drying, shrinks less than the thinner upper parts, indicating that the simulation predicts shapes from dynamic slip casting, but neglects shrinkage during solidification and drying, causing potential discrepancies and necessitating further research.

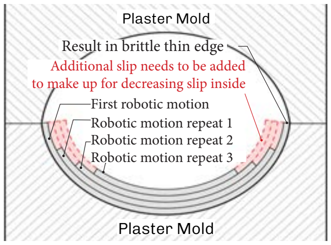
Looking forward, the software's performance would be substantially boosted by incorporating central processing unit (CPU) parallel programming or exploiting graphics processing unit (GPU) acceleration. These approaches could pave the way for high-performance computing applications, including real-time simulations or machine learning.

Results from Integration of Slip Injector and Simulation into Workflow

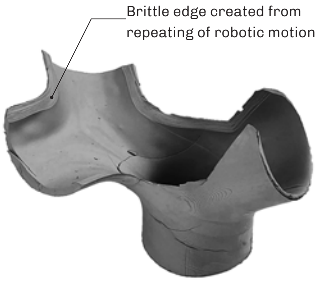
Initial tests on the robot, which utilized the mid-size mold to evaluate the simulation's effectiveness in reverse engineering, and generating the robot's trajectory from desired geometry, also exposed challenges linked to the edge condition of the resulting cast part. As the cake formed inside the plaster mold, the moisture in the slip was absorbed, causing a direct reduction of movable slip over time (Figure 14). In our workflow, each robotic trajectory laid a slip layer inside the mold, repeating until achieving the desired cake thickness. However, as these trajectories were repeated, we discovered a decrease in the height of the movable slip inside the mold due to the slip's moisture absorption by the plaster mold. This resulted in a brittle edge condition that was less ideal, as the layered edge was chamfered, thin, and fragile, increasing the likelihood of cracks (Figure 15). While the water was lost as the cake formed on the mold's inner walls, direct water injection was not ideal because thorough mixing with the existing slip during fabrication was nearly impossible.

To overcome this, we designed a custom slip injector end effector to compensate for lost water by adding extra slip at the beginning of each robotic trajectory repetition. A series of injection tests were performed (Table 4). Although this series of tests showed the potential for this solution, it resulted in different edge conditions. Further tests were needed to improve the consistency of the results. We also conducted an analysis to determine slip volume within the mold for each robotic trajectory repetition, aiding in determining the appropriate amount of added slip.

This analysis involved photo matching the resulting piece with the 3D model. Since each repeated robotic trajectory

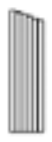
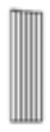
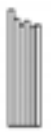


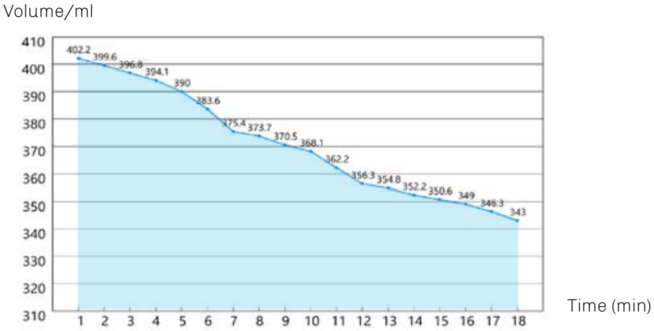
14 Diagram showing loss of slip within mold as robotic motion is repeated.



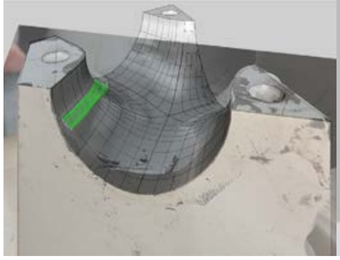
15 Layering of slip and edge condition created.

Table 4: Results of Injection Test

Geometry	Surface Area (sq	Time (min)	Injection Amount Each time (ml)	Injection Times	Total Injection Amount	Amount Evaluation	Edge Condition	Edge Section
	6987	90	0	0	0	No Injection		
	10594	90	20	18	360	Insufficient		
	89750	90	20	18	360	Proper Amount		
	81575	90	<=20	18	<=450	Insufficient		



16 (a)



16 (b)

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16 (a) Plotted graph to determine the rate of decrease (b) photo match with 3D model.

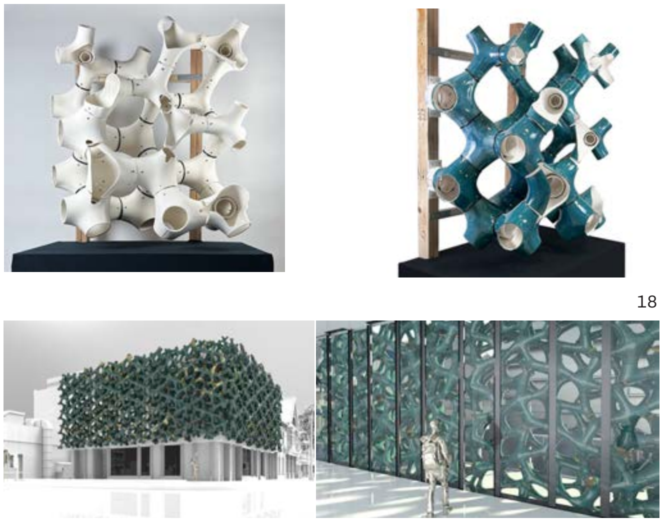
to build cake thickness, and the orientation of the mold for each trajectory were identical, we analyzed the level of the slip by selecting the layer line created from each robotic trajectory. Taking this level of slip within the mold, we calculated the volume of slip at that selected time of the routine. This data was then plotted on a graph to determine the rate of decrease over time (Figure 16). Based on this rate and the initial slip volume, we determined the required injection amount for each robotic routine.

Although further research and data collection are needed to refine the precise rate of slip decrease, tests utilizing the determined injection amount during the robotic routine demonstrated improved edge conditions of the cast piece (Figure 17).

Demonstration of the Approach in Architectural Application

To further explore our method and to inform potential applications in architecture, such as façade screen assemblages, we designed and fabricated a full-scale mock-up of a section of a façade. Although our proposed workflow allows the creation of various geometric variations from a single mold, we used multiple molds to decrease production time and to explore a wider range of variations for larger areas. The full-scale prototype of the 1.3m-by-0.6m-by-1.3m façade consisted of 28 dynamic casted pieces (Figure 1). Fabricated using only four different plaster molds, the prototype embodies 15 geometric variations (12 partial casts and 3 full casts) (Figures 18, top).

The prototype demonstrates the effectiveness of our proposed workflow and showcases the high degree of accuracy the simulation and slip injection workflow had in reproducing designed 3D geometry. To further the research and evaluate its architectural implications, a design proposal of a larger façade was developed using the same limited number of molds. This allowed us to assess the effectiveness of part variability in the architectural façade design across a larger number of parts (Figure 18, bottom).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18 (Top) Images of assembled bisque-fired prototype. (Bottom) Renderings of proposed façade.

CONCLUSION

This research demonstrated the production of geometrically varied slip cast parts from a single mold, through employment of robotic motion during the casting process in combination with a custom end effector tool that enabled the incremental addition of slip throughout production to control slip cake thickness and edge detailing. The developed material simulation software also enabled unprecedented insight into slip material behaviour inside the mold that is otherwise unseen. Experiments demonstrated our ability to improve the quality of casts and edge conditions validating the coupling of the simulation model to the robotic manufacturing process.

Although the simulation was successfully used to reverse engineer robot manufacturing instructions from a 3D design model to improve edge conditions in fabricated parts, it cannot currently account for shrinkage during the entire manufacturing process that could cause misalignments between simulated results and the geometry of fabricated parts. Further testing and development are necessary to improve the speed and accuracy of the simulation to account for clay bone-drying and bisque firing processes. Similarly, slip injection amounts were constant for each repeated robotic routine, based on the rate of decrease of slip within the mold derived from our initial experiments. To further fine-tune the accuracy of workflow, further testing to determine ideal quantities and timing of slip injections for each repeated routine would be beneficial.

The capacity to produce geometric variation within an automated slip cast process was first demonstrated using a single mold in experiments before being applied to a 28-part prototype that used 4 molds before being explored in a facade screen with thousands of components arising from the same 4 molds. Together these outcomes demonstrate the research's merits in being applied to architectural ceramic facades where high-volume production is potentially achievable with reduced quantities of mold compared to alternative slip-casting approaches.

This research contributes to a growing interest in robotic slip casting and focuses on a casting method that can efficiently create geometrically varied custom ceramic parts from a single mold. With further development such capabilities could potentialy enable slip casting to be mass-customised at high volumes of production and offer possibilties for use in architectural ceramic facades.

ACKNOWLEDGEMENTS

This research was conducted through the Spring 2023 curriculum for the Master of Science in Design: Robotics and Autonomous Systems Program in the Weitzman School of Design, University of Pennsylvania. Thank you to instructor Billie Faircloth for guidance provided through the course Scientific Research & Writing. And, thank you Nicholas Sideropoulos and Sophia O'Neill for contributing to this work through your management of the ARI Robotics Lab.

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