Introducing Bespoke Properties to Slip-Cast Elements

Designing a Process for Robotically Controlled Rotational Casting

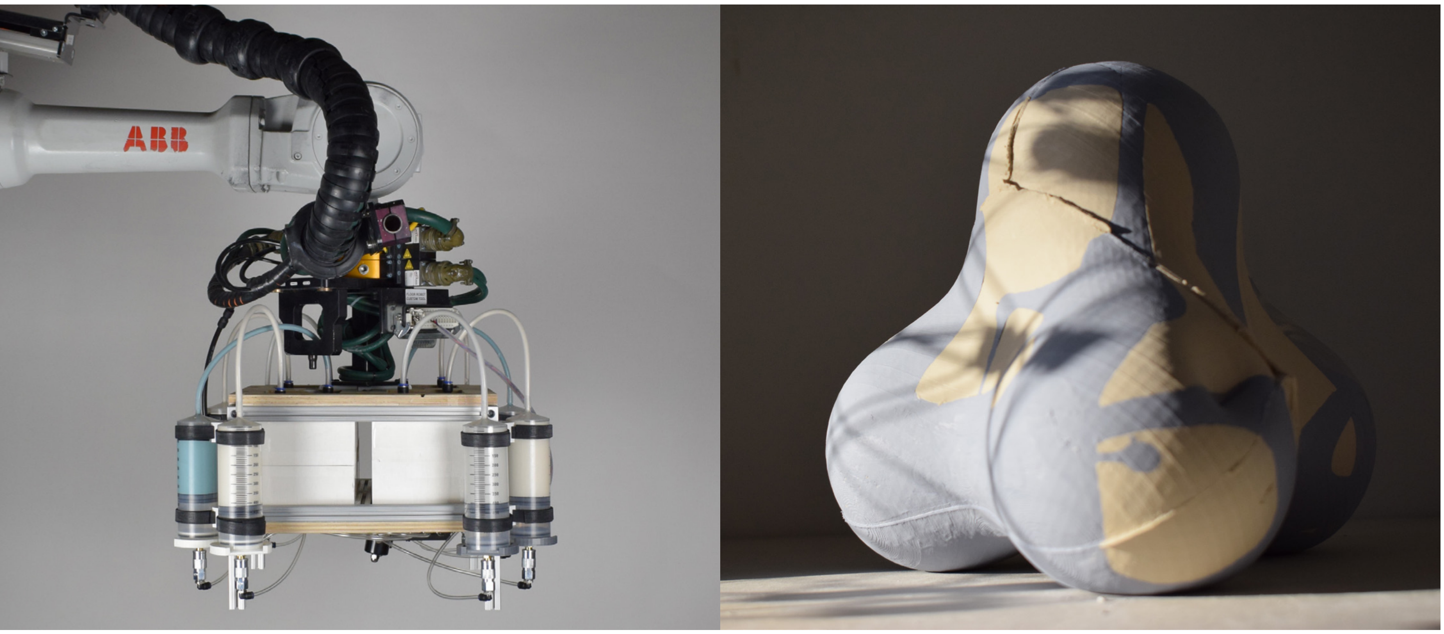
Davis Dunaway
University of Pennsylvania

Dan Rothbart
University of Pennsylvania

Layton Gwinn
University of Pennsylvania

Dr. Nathan King
University of Pennsylvania/Virginia Tech Center for Design Research

Robert Stuart-Smith
University of Pennsylvania/UCL



1A

ABSTRACT

The industrial use of slip casting is niche but highly recognizable. The phase-changing nature of the clay slip makes the process ideal for the production of complex, standalone geometries, such as those needed by the sanitary ware and fine porcelain industries. Slip casting, however, currently lacks the ability to produce meaningful visual variation between components without the need for an entirely new mold. This research explores a novel technique for creating bespoke, slip-cast artifacts through the use of 6-axis robotic motion. By incrementally injecting different amounts of colored slip into the mold while it is rotated, we are able to achieve variable color, pattern, and structure. Because of the highly precise nature of the robotic motion, this variation can be repeated with a high degree of accuracy. In addition, the incremental injection of slip also allows us to achieve a full cast with a minimal amount of slip, removing the draining process of traditional slip casting entirely. The level of control this process might give a designer is explored through a series of tetrahedral components that demonstrate the types of marbling that can be achieved. This work borrows heavily from the field of plastic rotational molding, as numerous parallels can be made between the two processes' flexibility and parametrization. By drawing on this neighboring field, we hope to bring new variables into the world of mass-manufactured slip-cast ceramics in the form of controllable color and pattern.

1A (left) The completed end effector for preforming robotically controlled slip casting, allowing the robot to control the injection of slip into the mold and for the molds to be held in virtually any orientation; (right) An example of a slip cast part that demonstrates a desirable marbling pattern

INTRODUCTION

At its core, slip casting is a simple and elegant process. The process consists of two parts, a liquid clay body often referred to as slip and a plaster negative of the desired geometry to serve as a mold. To create an artifact, slip is poured into the mold until it is completely filled. Over a short period of time, the plaster draws moisture out of the slip causing it to harden into a leather like shell, completely taking the form of the interior of the mold. The remaining slip is then drained and the mold is removed, creating a hollow version of the desired part. The slip's ability to go from liquid to solid is what makes it unique as a clay body. It is this phase-changing nature that makes slip casting a go-to process for the production of complex ceramic geometries by both artisans and industry (Bechtold, Kane and King 2015).

There are currently two basic ways of producing variation between slip-cast parts that come from the same mold. The first is to increase the wait time before drainage. This allows the plaster mold to absorb more moisture from the slip resulting in a final part that has thicker walls. While this does provide critical control over the structure of the part, the variation is not at all externally visible. The second way to control variation is to change the composition of the slip. This can provide control over the overall color of the final part but requires every variation to have its own unique clay body which often makes it unsuitable for providing a wide degree of variation. Because the amount of control over the visual qualities of a slip-cast part is minimal, we often see the process used to create identical artifacts, both structurally and visually, in mass quantity. We, however, believe that through the use of industrial robotics, an augmented version of the slip casting process can produce results with a near infinite number of visual variations. More specifically, we propose that by incrementally injecting different amounts of colored slip into a mold that is rotated by a 6-axis robotic arm, we can achieve variable color, pattern, and in some cases controllable aperture on the surface of the part.

This hypothesis was evaluated rigorously using both human and robotic tests to ensure that the proposed process is both functional and feasible to perform (Figure 1B). These tests took the form of casting a series of tetrahedral components. We successfully found that we were able to achieve a wide range of constantly repeatable patterns, demonstrating that this process does, in fact, give a new level of control to the designer of slip-cast parts.

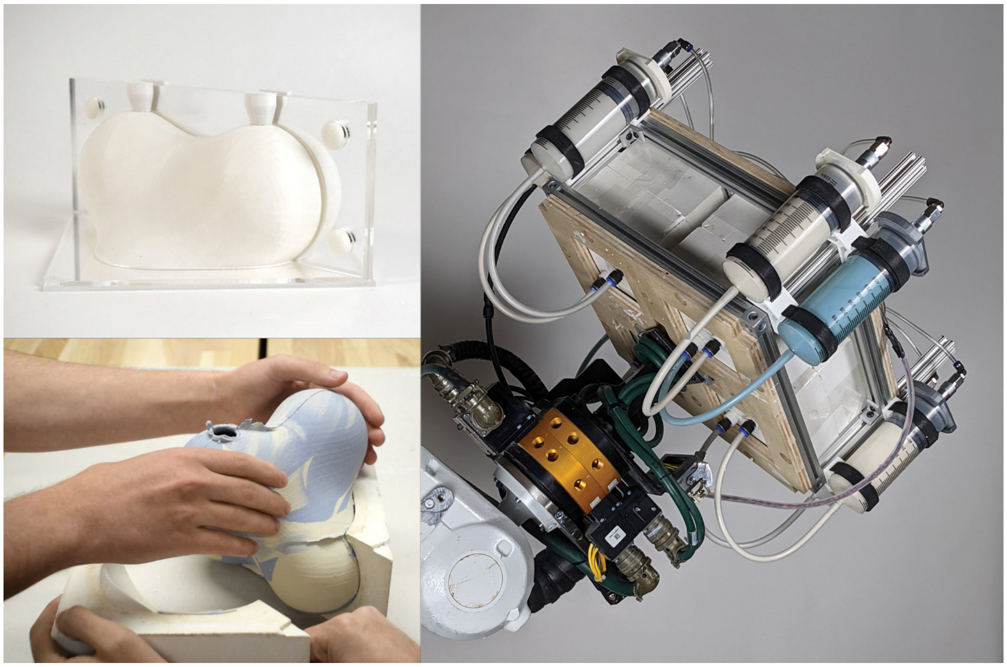
Additionally, we found that an auxiliary benefit of the process is that we can drastically reduce the amount of slip needed to produce a successful part. Because the mold is being rotated while slip is injected, the interior of the surface can become coated with slip without needing to fill it entirely. This removes the need for a drainage step as we can fill the mold with the minimum amount of slip needed to get a full coating. This means that no slip is wasted in the process.

BACKGROUND

Overview of Traditional Slip Casting

Slip casting's use is both widespread and time tested. It can be seen used in European ceramics dating back to the 18th century, and its use in Chinese ceramics even earlier (Paxton and Fairfield 1980). Industrial use of slip casting can be traced back to mid-14th century China during the Ming Dynasty, where the town of Jingdezhen used the process to mass produce the iconic blue-and-white porcelain pottery that is still common today (Canby 2009).

1B A manual test of the robotically-assisted rotational casting process: two colors of liquid slip were poured into a plaster mold and rotated intermittently in order to bring about a controlled marbling effect in the slip cast artifact



2 Composite image of the major parts of the robotically-assisted rotational casting process: (top left) A 3D-printed PLA and laser cut acrylic positive for the production of a plaster mold; (right) Custom end-effector for injecting multiple colors of slip into a series of plaster molds while the robot is changing their position and orientation; (bottom left) A completed slip cast being removed from the plaster mold, a process that often requires a delicate touch

In the modern industrial context, the efficiency of the process has been increased. The plaster molds have a relatively short lifespan, and creating those negatives can often be the most arduous part of the slip casting process. Because of this, larger operations now use stainless steel formworks to produce plaster molds quickly and efficiently. Given a large enough number of plaster molds, identical slip-cast elements can be produced virtually continuously making it ideal for mass production.

Slip casting is also commonly used by artisans due to its simplicity and cheap material costs. In fact, while the core of the slip casting process has remained relatively untouched by mass manufacturers, artisans have been able to explore more experimental changes. While not exactly slip casting, we can see the use of colored slip to achieve decorative surface marbling as early as the mid-19th century (Erickson 2003). Artists such as Peter Pincus and Jenny Rijke have taken this idea of using multiple colors of clay body and have applied it to slip casting. We took note of Jenny Rijke's work in particular, as it achieves the marbling effect by using a pre-swirled multi-colored slip in the casting process. This technique can create variation in color and pattern, but the result is always different as it is not repeatable from part to part.

Current Research of Casting Compatible Materials

Slip casting has largely been unexplored within the field of architectural robotics. Because of this, our research primarily builds off of work that uses other casting materials such as concrete, plaster, and plastics. Concrete, in particular, is the material of choice for a number of projects that explore methods for generating bespoke results through robotic fabrication. We have seen the use of flexible fabric formworks in pre-cast and on-site concrete, the use of robotic manipulation to produce thin shell structures via rotational molding, and the use of 6-axis robotic arms to manipulate a formwork over the length of column-like elements, varying their sectional geometry serially with a high degree of control (Hawkins et al. 2016; Tessmann and Mehdizadeh 2019; Lloret-Fritschi et al. 2020). When analyzing the last of these examples in particular, we can begin to see a direct relationship between robotic motion and fabricated artifact. This relationship gives credence to the use of robotics, specifically the use of a 6-axis industrial arm, in low volume settings.

This specific type of relationship between robot and artifact has been given the name of Design Robotics and is formally defined as an argument for the use of robotics that "bridges the gap between primarily artistic endeavors and the construction automation research of the building industry" (Bechtold and King 2013). While exploring this idea in the field of architecture is not new, applying these design principles to casting-based processes is still in its infancy, as overcoming the overwhelming influence the mold has on the final part has proved challenging. The research previously mentioned attempts to overcome the mold in different ways, most notably through the use of flexible formwork that can be manipulated robotically (Lloret-Fritschi et al. 2020); however, this is currently not an option for the production of ceramics as the material characteristics of the plaster mold are essential in facilitating the phase change of the slip (Bechtold, Kane and King 2015). For inspiration on how to tackle this problem, we looked to existing processes that existed outside of both the field of architectural robotics as well as ceramic production as a whole. This led us to a practice commonly used in the production of plastic components called rotational molding. Recent increased parametrization and automation of material add-ins to rotational-molded plastic parts started to show glimpses of how mold-based production methods might be made more bespoke (Gupta and Sangani 2020).

METHODS

Plaster Molds

While the creation of plaster molds in low volume settings is incredibly well documented, our specific geometry and need for highly accurate dimensions forced us to be creative in how we produced our molds. We created custom formwork out of 3D-printed PLA and laser cut acrylic that would then be used to produce our four-part plaster mold (Figure 2). In order for the formwork to be reusable, it was critical that all of the materials be resistant to water. When casting the plaster molds, we used the typical plaster-to-water ratio of slip casting using USG number 1 plaster; however, some of the casts took an extended period of time to dry before being usable. Batches of molds were put either into an oven at 150° or in direct sunlight for extended periods of time in order to aid the drying process; however, neither process significantly decreased the overall drying time during our testing period.

Robotic End Effector

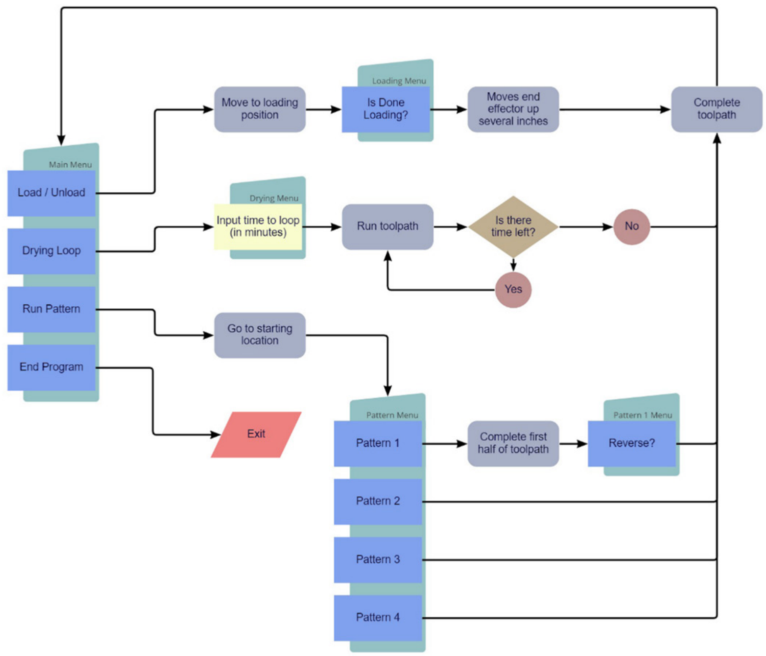
We developed an end effector that would allow for a robotic arm to manipulate the molds freely as well as fully automate the injection of slip into each mold (Figure 2). The end effector was designed to carry four molds simultaneously. The loading and unloading of the carriage was heavily considered. A human operator only has to release four bolts, unload and load the plaster molds, and rescrew the same four bolts before the robot can begin another round of casting. For automatic slip injection, we opted for the use of a pneumatically powered system of plungers to feed slip into the molds.

A custom 3D printed backing was designed for a 500 ml syringe that allowed the syringe to be connected to compressed air via an industrial quick connect fitting. The optimal pressure for operating these syringes was 30 psi. The end effector was fitted with eight of these syringes, one for each color of slip for each mold, and were connected in groups of four to allow independent actuation of each color of slip when injecting. Because these backings were a semi-permanent addition to the syringes, we had to devise a way to refill the syringes with slip after use. We used a small venturi module to generate a vacuum that could pull the plunger back down causing the syringe to refill. While this pneumatic loading method did show promise as a relatively low cost solution, we found that the optimal pressure was not achievable in our lab setting, as we were limited to 80 psi total (20 per syringe) and even at optimal pressure the flow rate of slip was inconsistent. Ideally, the system would be designed for use with a pneumatic cylinder or a linear actuator to more accurately control the slip. For our final tests, we manually loaded slip into each mold in order to ensure the quantity of slip was accurate.

Robotic Toolpaths

We also developed and tested a series of robotic toolpaths. These aim to consistently coat the entirety of the mold with slip when run in combination. The order in which the toolpaths are layered define the creation of unique patterns that are always replicable (Figure 3). Each of these toolpaths used different methods to coat the molds. Some focused on moving quickly from corner to corner, while others focused on

3 Composite image describing the face classification of plaster molds when rotating them by hand alongside two separate casts which produced the same marbling patterns using the same rotational motion while casting. Both of these casts introduce one mason stain of slip into the plaster mold, moving the mold such that sides 0, 1, 2, and 3 faced downward, and repeating with the second color. When side 5 is faced downward after 400 ml of slip is introduced and swirled in that rotation, the pictured effect is achieved.



4 Flowchart depicting the organizational structure of the RAPID code script that allows the user to select from a number of different toolpaths necessary for performing the rotomolding process. This includes the four swirling patterns, a repetitive drying loop, and the loading and unloading routine.

slow and continuous rotation. In addition to the coating toolpaths, we also produced toolpaths for loading and unloading the end effector, as well as a looping drying cycle that could be run continuously after the coating process. Because of the large number of different procedures that we needed to execute in a given production run, it was important to create a master program that allowed us to trigger manually the desired function quickly and efficiently from the robot's teach pendant. We created a small RAPID program that prompts the user with the different possible toolpaths and ensures that nothing can be run in an order that would cause issues for the robot (Figure 4).

Preparation for Experiments

One of the most important variables to control was our clay body. Early tests were conducted with Leuders Casting Slip—a stoneware casting slip that comes pre-mixed in a two-gallon bucket—due to its availability from a local ceramics shop. The majority of our tests, however, were instead conducted using Laguna Fine Porcelain NS-125 Very White Liquid Slip. The clay body was mildly altered before use by the addition of mason stain in order to achieve the different colors of slip necessary for our process. The mason stains we used were Mason Color Works colors—Peacock 6266, Robin's Egg 6376, and Gunmetal 6591—all in a ratio of 1/4 lb mason stain to 1 gallon of slip. For manual tests where an exact quantity of slip was needed, a 500 ml food-grade syringe was used that allowed us to accurately add slip in increments of 10 ml. When casting, the plaster molds were fastened together using standard packing tape. We opted for tape over large rubber bands or other common fastening methods due to the fact that our molds consisted of four parts. The tape allowed the assembled molds to have a small amount of play until we were confident in the mold's alignment. To precisely track the motion in the initial manual tests, such that we could translate them to robotic motion and ensure repeatability of the results, we restricted most of the rotations of the plaster molds to the six faces of the molds' cubic bounding boxes. After casting, pieces were left in their molds for an additional 30 minutes before removal. Once removed, the seams on the cast would be trimmed by hand, and the mold would be placed on a sheet of drywall to dry. Each mold was limited to two casts per day in order to prevent over-saturating the plaster with moisture.

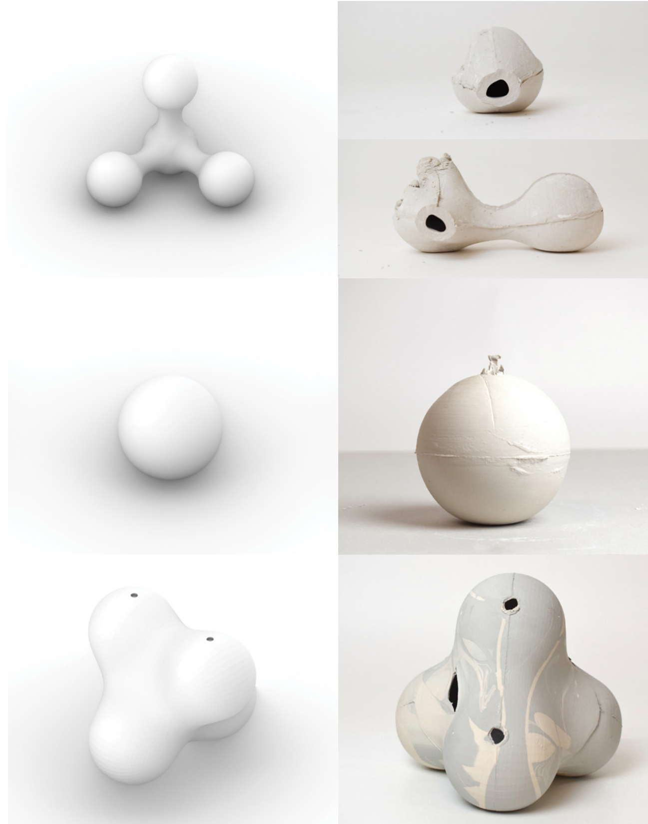
RESULTS AND DISCUSSION

Results from Early Experimentation

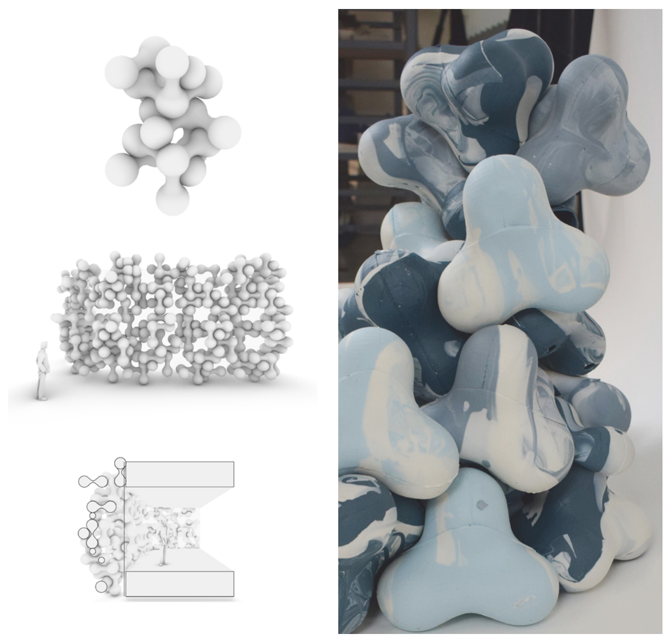
Three different geometries were explored during the initial hand tests before choosing a final geometry. The tested geometries were a regular sphere, a metaballed cubic corner (referred to as cornerpod), and a metaballed tetrahedron (referred to as tetrapod) (Figure 5). These three different geometries were designed with varying spatial packing and interlocking capabilities in mind. This was done with the aim of potentially informing future research into architectural applications such as facade screen assemblages (Figure 6).

The cornerpod was explicitly modeled to allow for the interlocking of two or more pieces while maintaining an open aperture in some areas. The tetrapod serves as the counterpart to this, as it was modeled without a specific organizational packing structure in mind. All three of these molds were first subjected to the traditional method of slip casting. Each mold was filled entirely with stoneware casting slip and left for varying amounts of time before drainage. When waiting longer than 30 minutes before draining, all molds produced highly unstable results, often collapsing under their own weight. At shorter wait times, both the sphere and tetrapod proved feasible, while the cornerpod often failed. This was because the mold would trap air inside itself leaving uncoated surfaces. Additionally, slip often became trapped in the thin neck between nodes resulting in an almost solid barrier. This prevented the cast from draining fully and often resulted in partial collapse of the cast after being removed from the mold. While this particular geometry did not result in any successful casts, it seemed to support our motivation for wanting to rotate the mold during the casting process as adding slip in small increments rather than all at once allowed for all surfaces of the mold to become coated in slip without needing to worry about the release of trapped air. While we believe we could now cast this geometry successfully using our new production method, it proved too difficult to explore via hand tests and was dropped in favor of the other two molds.

Our next series of tests involved filling the molds with a fraction of their interior volume's worth of slip and proceeding to rotate the mold in a regular fashion. We sought to determine a sufficient relationship of interior volume, volume of slip used, and rotational motion used to achieve a full coat of the mold shape. For these tests we switched over to a porcelain-based slip as it is the standard for most industrial slip casting processes. Our original motivation for this test was to achieve varying thickness in different parts of the cast; however, this proved exceedingly difficult to control with any sort of reliability in both molds. We did, however, make two unexpected discoveries. The first was that while we were unable to consistently control thickness, we were able to constantly control which parts of the mold were coated in slip and which parts were not. This led to the creation of apertures within the individual pieces that warrant further research. The second was that we were occasionally able to coat the entirety of the mold without the need for draining excess slip. This was achieved by adding a specific volume of slip relative to the part's overall volume to the mold and rotating it onto all six sides. It is worth noting that the percent volume of slip that the sphere and the tetrapod molds required in order to achieve this result varied, as the sphere mold required about 50% slip volume to the tetrapod's 15%. This relationship requires more research, as we were unable to derive a formula for the ratio due to the relatively small sample size of our tests.



5



6

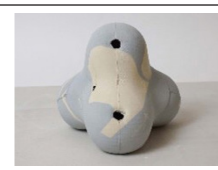
5 Renderings of the component shapes selected for the robotically-assisted slip casting experiments: a form with a cubic shape that resulted in failure due to the difference in weight between its spherical and its connecting elements, a spherical form used to test a casting process using only a fraction of the amount of slip, and a form with a tetrahedral base for use in a robotic cast

6 Renderings of facade screen application of cornerpod, physical aggregation of components displaying color and formal opportunities of the tetrahedral component

Table 1: Notable tests of volume ratios - spherical component (550ml volume)

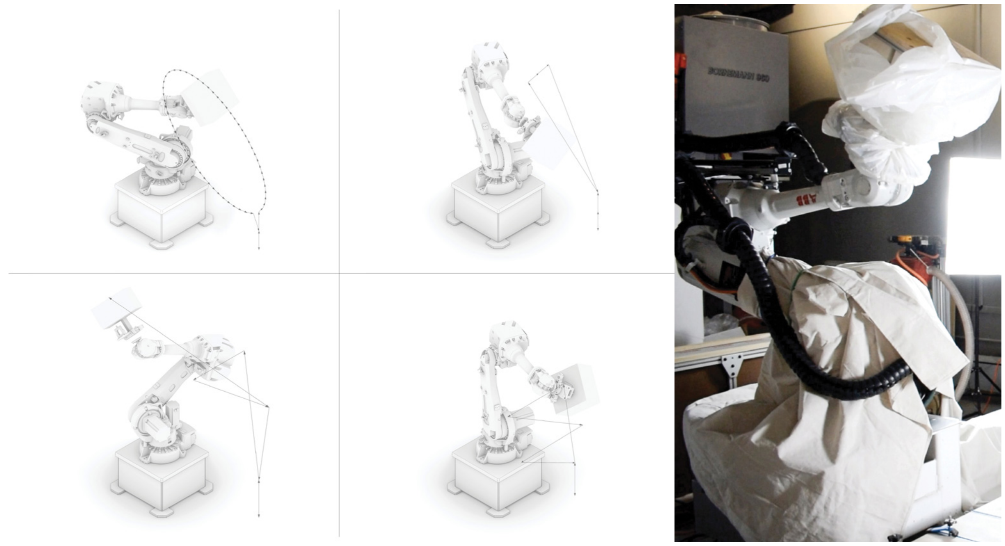
Test Number	Volume of Slip Injected (ml)	Rotation Specification	Notes	Image of Result
1	550	Sides 1,2,3,4,5,6: 2.5 minutes ea.	Unstable, high drainage, collapsed under own weight	
2	225	Sides 1,2,3,4,5,6: 1.5 minutes ea.	Stable, full coat achieved, fairly delicate	
3	112	Sides 1,2,3,4,5,6: 1.5 minutes ea.	Stable, does not achieve a full coat	

Table 2: Notable tests of volume ratios – tetrahedral component (2543ml volume)

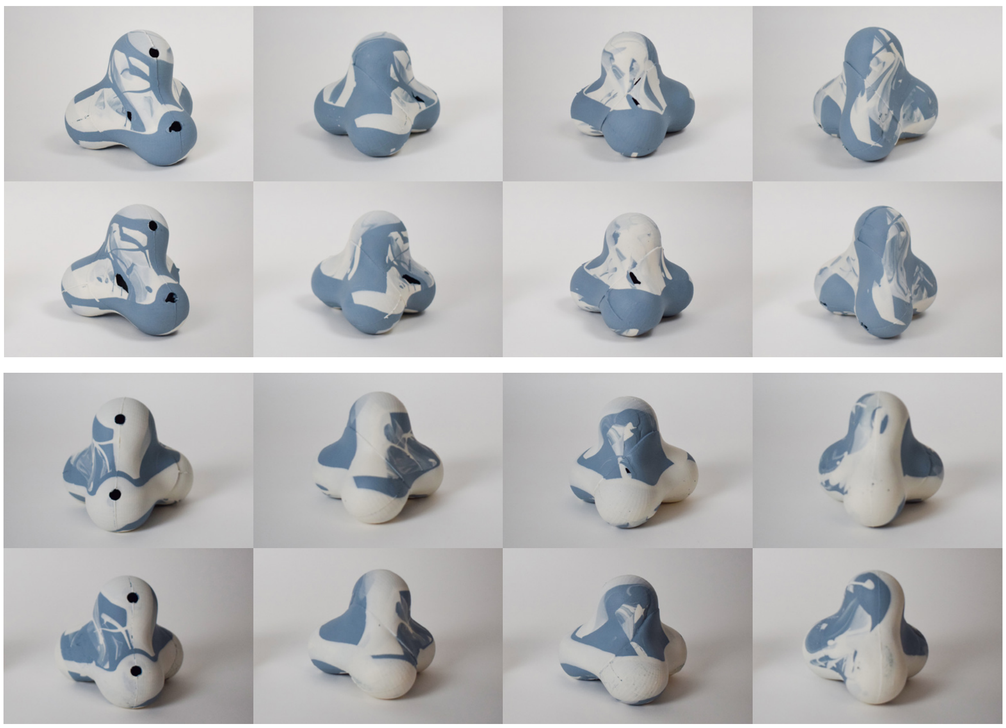
Test Number	Volume of Slip Injected (ml)	Rotation Specification	Notes	Image of Result
10	532	Color 1, 0-1-2-3, Color 2, 0-1-2-3, repeat. Then 1 minute on each side, then 30 minutes of drying	Good result, some drainage	
12	355	Color 1, 0-1-2-3, Color 2, 0-1-2-3, repeat. Then 1 minute on each side, then 30 minutes of drying	Not a full coating	
14	400	Color 1, 0-1-2-3, Color 2, 0-1-2-3, repeat. Then 1 minute on each side, then 25 minutes of drying	Most successful; ready for replication on robot	

In current industrial practice, the step to remove the drainage in the slip casting process would not be incredibly impactful, as slip is entirely recyclable; however, this newfound lack of drainage does open the doors to several new methods of creating bespoke artifacts from a single mold that were previously not feasible. In our research, this took the form of the simultaneous use of multiple colors of slip. Normally, this would be impractical as the drained slip would be an unknown mixed color and, therefore, be unable to be recycled, but the lack of a drainage step mitigates this entirely. Additionally, the marbling effect that results from swirling two different colors of slip is a perfect design characteristic to directly showcase the robotic movement that lead to its creation.

Our last series of hand tests focused on achieving a uniformly coated cast that consistently produced no excess slip. For these tests, we decided to focus purely on the tetrapod as its form lent itself to the injection of two different colors of slip without immediate mixing. A new mold was designed that allowed for two separate injection sites at the top of the mold, one for each color. Unlike the previous tests, slip was injected incrementally between rotational movements rather than all at once. For the tetrapod mold, we found that injecting 400 ml of slip in 50 ml increments consistently resulted in a uniform coating without the need for drainage. We achieved different patterns of swirling by changing the order in which we rotated the mold between injections.



7 A composite image depicting four toolpaths used in the robotically-assisted rotational casting process: four plaster molds are rotated 90, 180, or 270 degrees while moving along the lines notated by the arrows. In the image, the IRB 4600 industrial robot arm is covered by canvas and construction bags as a safeguard against leaking slip.



8 Two composite images comparing separate robotically-assisted slip-cast marbling patterns. Examples of repeatability inherent to our process, the components with the same coloration were cast completely separate from one another. The placement of all major color blocks is almost identical and some more intricate features have striking similarities.

Results from Robotic Tests

For these tests, we attempted to keep as many variables as possible constant in order to look solely at the effects that the toolpaths had on the marbling and see to what degree it was repeatable. To do this, the molds were loaded identically to our most successful hand test, 200 ml of each color loaded alternating 50 ml increments via syringe between each toolpath. Despite the ability for our end effector to carry four molds, we opted to only test with two as this would reduce the time that the mold remained stationary for the filling process.

Like the rotational motion tests done by hand, we were able to see a direct relationship between the robotic toolpath and the achieved artifact through the created marbling pattern. Each test ran a series of eight toolpaths constructed from the four present in our RAPID interface. As mentioned previously, the four toolpaths use different techniques to systematically coat the mold (Figure 7).

In order to determine if the marbling patterns were repeatable, we ran the same combination of toolpaths multiple times across multiple days. While not identical, the relationships in the marbling show a high degree of similarity (Figure 8).

We believe that at least a portion of the remaining variation comes from the varying injection angle of the slip when loading manually. This is something that could easily be minimized in a more industrial context. In theory, any number of feasible toolpaths could be designed and run in any sequence in order to generate new patterns, giving the designer almost complete control over the marbling effect that occurs on the surface of the part.

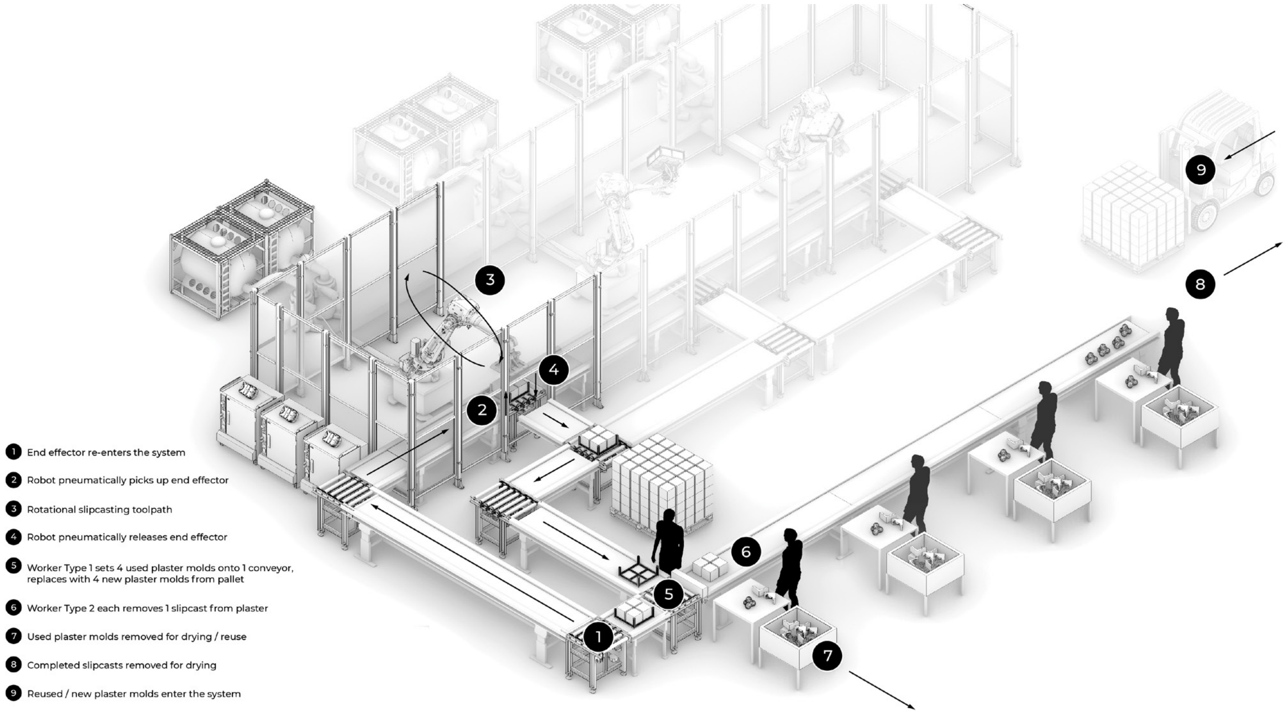
9 Photograph of an aggregation of robotically-assisted rotational cast components, fused to one another during the firing process

CONCLUSION

In this paper, we have proposed a method for augmenting the traditional slip casting process with industrial robotics in order to afford a designer more control over the visual qualities of the final artifact. We have developed this process with the principles of Design Robotics in mind in order to ensure that what we are creating truly warrants the use of robotics. Marbling effects are achievable by hand; however, the addition of the robotic motion makes the process repeatable and significantly less wasteful. Both of these qualities are a necessity in bringing the practice of marbling to high volume production settings.

In parallel with our research, we began to explore potential architectural applications that would necessitate the need for a large quantity of parts produced in this way. Attempts were made to explore the aggregation potential of our tetrapod components by pressing them into each other before firing (Figure 9).

Almost all of these attempts resulted in tearing, cracking, slumping or other critical failures in the components that prevented more than a small number of pieces from being joined together. While our research into this particular aspect was not thorough enough to completely rule out the possibility of pre-firing aggregation, the process was clearly telling us that it was better suited for the creation of individual artifacts. Architects are often the ones driving Design Robotics style research, and the current lack of an immediately clear architectural use that would not be better achieved with concrete or other castable materials likely contributes to the fact that slip casting is an underexplored process. All this said, slip casting still excels at the creation of stand alone artifacts, which is why, despite not commonly seeing it used in an architectural setting, it is still a valuable process that deserves the attention that other materials and processes are getting in Design Robotics research. The technique proposed in this paper only further enhances its abilities, as it now introduces controllable variables of color and pattern into a process that typically only produces exact copies of an artifact. One can begin to imagine the implications that this process could have on an assembly line as controlled marbling could be added to any number of ceramic artifacts without any increase in time (Figure 10).

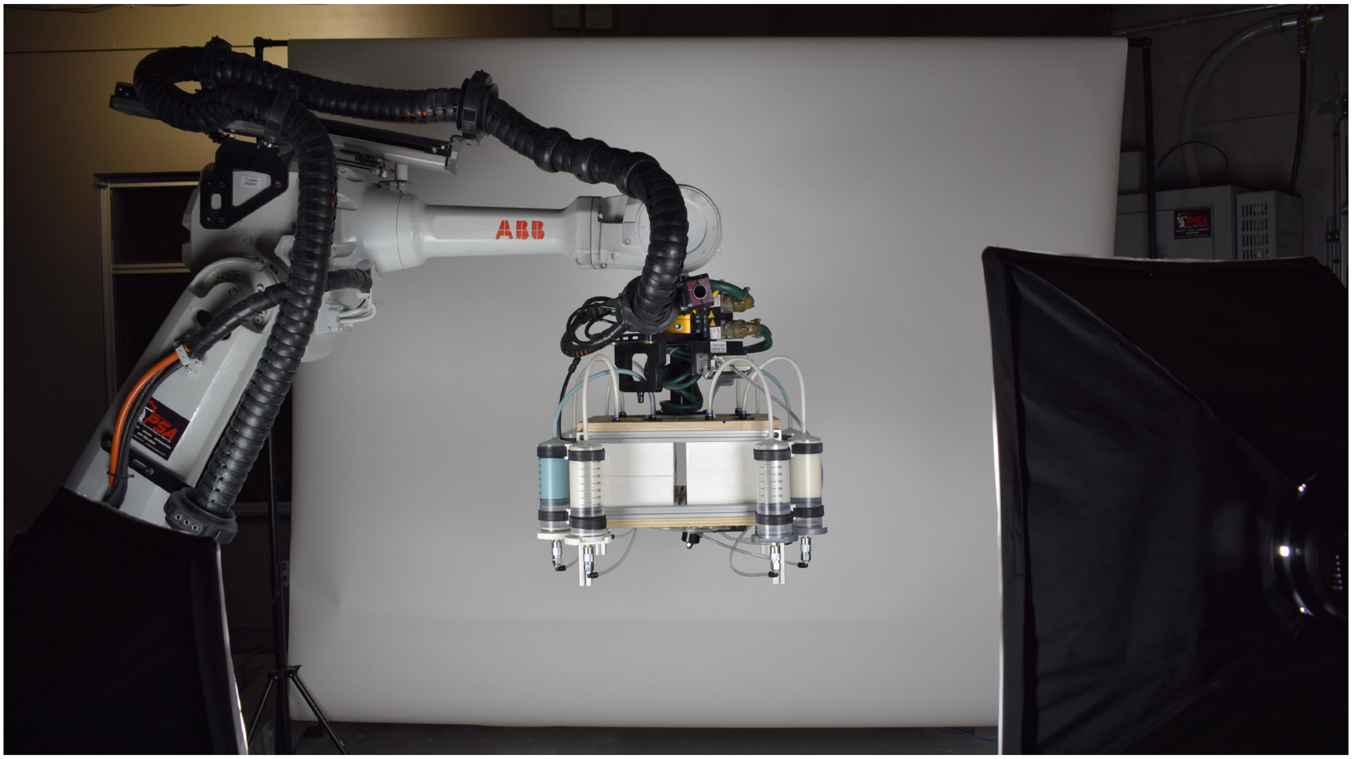


10 Diagram of a hypothetical proposal to industrialize this ceramic rotomolding process: changes to the end effector such as a system for automatic attachment to the robot and locating the slip off the robot for easier refilling would allow it to run continuously. Humans are stationed to perform the delicate task of removing the slipcast part from the mold.

While this process has proved highly promising in the initial stages of research, there is still much to be done. More variations of robotic toolpaths must be explored in order to gain a better understanding of how different types of motion contribute to different types of visual effects. A catalog of these relationships must be created in order to allow a designer to effectively utilize them in the design process. Additionally, a strict equation or, at the very least, methodology must be developed for determining how much slip should be used in a given mold. This is needed in order to allow new molds to be quickly implemented into the process without the need for trial and error.

While not critical to its cementing as a process, the possibility of creating aperture on the surface of a part is also something that should be further explored. This would allow for control over the actual geometry of the part which could open up brand new possibilities for designers using the process. We believe that with this additional research, this process has the potential to become a serious method for the production of ceramic artifacts. It adds the ability to create meaningful and repeatable visual variation in parts that come from the same mold, something that current slip casting techniques, both industrial and artisan, are unable to do. In a world where the bespoke is becoming ever more sought after, that ability makes the process valuable and worth future research endeavors.

10 A series of robotically-assisted rotational cast components with varying degrees of aperture, as a result of an incomplete coat of the plaster surface



11 Photo of the completed end effector being tested for the first time

ACKNOWLEDGMENTS

This research was primarily performed in the Master of Science in Design: Robotics and Autonomous Systems program, at the Stuart Weitzman School of Design, University of Pennsylvania. A 16-week project integrated across four courses, this work owes a lot to the input of Jeffrey Anderson, Billie Faircloth, Nathan King, and Robert Stuart-Smith in their courses Advanced RAS Programming, Scientific Research & Writing, Experimental Tooling, and Material Agencies, respectively. Each of these faculty, as well as David Forero, had valuable contributions to the work. This paper was written as a part of the Scientific Research & Writing course and the pneumatic end-effector was developed for the Experimental Tooling and Material Agencies courses.

REFERENCES

Bechthold, Martin, Anthony Kane, and Nathan King. *Ceramic Material Systems: in Architecture and Interior Design*. Berlin, München, Boston: Birkhäuser, 2015.

Canby, Sheila R. *Shah 'abbas: The Remaking of Iran*. London: British Museum Press, 2009.

Erickson, Michelle. 2003. *Swirls and Whirls: English Agateware Technology. Ceramics in America*. Milwaukee, WI and Hanover, NH: Chipstone Foundation.

Bechthold, Martin, and Nathan King. 2012. "Design Robotics." In *Rob | Arch 2012*, edited by S. Brell-Çokcan and J. Braumann. 118–30.

Gupta, Nikita, P. L. Ramkumar, and Vrushang Sangani. 2020. "An Approach toward Augmenting Materials, Additives, Processability and Parameterization in Rotational Molding: A Review." *Materials and Manufacturing Processes* 35 (14): 1539–56.

Hawkins, Will J., Michael Herrmann, Tim J. Ibell, Benjamin Kromoser, Alexander Michaelski, John J. Orr, Remo Pedreschi, et al. 2016. "Flexible Formwork Technologies; A State of the Art Review." *Structural Concrete* 17 (6): 911–35.

Lloret-Fritschi, Ena, Timothy Wangler, Lukas Gebhard, Jaime Mata-Falcón, Sara Mantellato, Fabio Scotto, Joris Burger, et al. 2020. "From Smart Dynamic Casting to a Growing Family of Digital Casting Systems." *Cement and Concrete Research* 134 (August): 106–17.

Paxton, John, and Sheila Fairfield. 1980. *Calendar of Creative Man*. London and Basingstoke: Macmillan.

Tessmann, Oliver, and Samim Mehdizadeh. 2020. "Hollow-Crete." In *DMSB 2019, Impact: Design With All Senses*, edited by C. Gengnagel, O. Baverel, J. Burry, M. Ramsgaard Thomsen, and S. Weinzierl. Cham: Springer. 474–86.

Valenstein, Suzanne G. 1989. *A Handbook of Chinese Ceramics*, rev. and enl. ed. New York: The Metropolitan Museum of Art.

IMAGE CREDITS

All drawings and images by the authors.

Davis Dunaway received his Bachelor of Design from Carnegie Mellon University and is a recent graduate of the Master of Science in Design, Robotics and Autonomous Systems from the University of Pennsylvania.

Dan Rothbart holds a Master of Science in Design, Robotics and Autonomous Systems from the University of Pennsylvania and a Bachelor of Architecture from Rensselaer Polytechnic Institute. He currently works as a Project Engineer at A. Zahner Company, Kansas City, Missouri.

Layton Gwinn received his Bachelor of Arts in Architecture from Clemson University and is a recent graduate of the Master of Science in Design, Robotics and Autonomous Systems from the University of Pennsylvania. He is currently employed at Quarra Stone Company LLC as a Design Engineer in their QLAB.

Dr. Nathan King is the Co-Director of the Center for Design Research at Virginia Tech, an Instructor at the University of Pennsylvania and Harvard University, and leads the Autodesk Research organization focusing on the Industrialization of Construction.

Robert Stuart-Smith is Director of the Master of Science in Design, Robotics and Autonomous Systems program at the University of Pennsylvania, Director of the Autonomous Manufacturing Lab (AML) at the University of Pennsylvania (Architecture), and Co-Director of the AML at University College London (Computer Science).