An Exploration of Collaborative Vision-Augmented Robotic Slip Cast Fabrication

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Abstract

Slip casting is a traditional ceramics technique capable of producing complex shapes efficiently by pouring liquid clay into molds. However, conventional slip casting requires a dedicated mold for each design, limiting flexibility and increasing cost. This thesis proposes a vision-augmented robotic slip casting system that enables the fabrication of varied ceramic forms from a single mold. A 6-degree-of-freedom industrial robot arm is integrated with a camera-based sensing system and human oversight to adapt the casting process in real time. The robot dynamically tilts and rotates a plaster mold during the casting and initial drying phases, guided by computer vision feedback, to control the deposition of clay slip and achieve distinct geometries. A human operator works collaboratively by initiating the clay pour and handling post-casting operations, leveraging human intuition for material handling and decision-making. The objective is to demonstrate that such a collaborative robotic system can manipulate liquid clay to produce different shapes from a single mold, thereby greatly increasing the versatility of slip casting. The methodology combines an eye-in-hand monocular camera for slip monitoring with known mold geometry, ArUco marker tracking for feature detection, and a control pipeline that adjusts mold orientation based on the slip's observed state. Experiments confirm the feasibility of the approach: the vision system successfully tracks the clay slip's evolving profile, and the robot achieves shape variations according to target patterns. This work lays the groundwork for more adaptive ceramic fabrication, illustrating how merging robotics, computer vision, and human interaction can overcome material unpredictability and reduce the need for custom molds. The results indicate that relatively straightforward sensing and control strategies can handle a material problem that otherwise might require complex simulation. The proposed vision-guided, human-assisted robotic slip casting system could significantly broaden design possibilities in ceramic production and serves as a foundation for future research in collaborative human-robot fabrication.

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1. Introduction

Clay is an abundant and economical material with a wealth of desirable properties and applications. Slip casting (SC) is a ceramics fabrication method in which a liquid clay suspension (called *slip*) is poured into a mold and partly solidifies to form a shell before the excess slip is drained. This process can efficiently produce intricate geometries with fine details. Unlike other ceramic forming techniques, SC can capture complex internal and external features without expensive machining.[3] Traditional SC is used for mass production of pottery and ceramic components due to its simplicity and precision. However, a major drawback is that a new plaster mold must be made for each distinct design, which is labor-intensive and generates waste.[2] This constraint limits the versatility and viability of traditional SC for custom designs and low volume production.

Recent advances in robotic fabrication (RF) of clay have focused mostly on solid or plastic forms of clay. These methods have achieved complex shapes but often require carefully tuned material mixtures and control parameters for each design.[6-10] In contrast, applying robotics to the SC process remains largely unexplored—to date, there has been only a single known investigation into robotic SC. That pioneering work demonstrated the production of varied shapes from one closed mold using heavy physics-based simulation of the slip's behavior. While successful, the reliance on detailed material simulation had limitations, such as difficulty modeling slip shrinkage during drying.[13] This gap in the literature indicates an opportunity to develop an alternative approach to robotic SC that relies on *sensing and adaptation* rather than solely on upfront simulation.

This thesis aims to lay groundwork in the development of a collaborative vision-augmented robotic SC method to enhance classic manual methods and improve upon prior robotic attempts. The overarching research objective is to develop a system where a robot manipulator, enhanced with real-time feedback and human assistance, can dynamically control the SC process to produce various desired geometries from a single mold. The foundational aspects of the fabrication method include SC (for its efficient molding capability), robotics (to handle and move the mold with high precision), computer vision (to monitor the state of the liquid clay in the mold), and human–robot interaction (HRI) (to leverage human intuition and adaptability in the loop). The aim of this work is to first answer lower-level questions that serve as prerequisites for achieving the broader goal.

This work seeks to demonstrate that a six-degree-of-freedom robotic manipulator, equipped with visual sensing capabilities, can achieve rudimentary manipulation of slip within a single mold to generate varied clay geometries. The robot should be able to cast multiple shapes from one mold by changing how the mold is oriented and moved during the casting process. To achieve this, several supporting questions are addressed, such as how to sense the slip's distribution in real time and how to adjust the mold's motion accordingly. Ultimately, this project is laying the groundwork for more adaptive and versatile ceramic fabrication by providing the robot with a basic level of "slip control" that future work can build upon.

At this early, proof-of-concept stage, the scope of experimentation is intentionally narrow to manage complexity. The system is demonstrated using a single simple mold geometry (a sphere-shaped cavity) and focuses on one mode of slip manipulation: controlled tilting and swirling of the mold around its axes to redistribute the slip. The robot's motions are relatively simple but are sufficient to investigate the concept of dynamic SC. The human's role is also constrained to key manual steps: pouring the initial slip into the mold and handling the piece after casting. No additional actuators or sensors (beyond one camera) are used. Furthermore, this work concerns only the formation of slip profiles. Subsequent steps like drying, kiln firing and glazing are beyond the scope and are not addressed. By clearly limiting the problem in this way, fundamental challenges such as real-time slip monitoring and manipulation of geometry can be tackled and understood before scaling up to more complex scenarios.

2. Background and Literature Review

This section provides the necessary background and prior work to inform the development of the vision-augmented robotic SC system. It begins with an overview of clay and SC fundamentals, then examines the state of robotic clay fabrication to date. Next, it discusses the motivation for combining SC with robotics and human assistance. The role of computer vision in fabrication processes is reviewed, and finally the specific advantages of a robotic approach to SC are outlined. Together, these topics establish the context and significance of the presented research.

2.1. Context of Clay and Slip Casting

Clay has been used as a versatile material since ancient times.[1] It is valued for being widely available and for its favorable properties, including plasticity when wet and strength and durability after firing. Objects made of clay can range dramatically in size and shape, from delicate porcelain figurines to large structural components. Notably, clay-based ceramics are found in applications as diverse as art sculpture, dishware, sanitary ware, industrial filters, biomedical implants, aerospace components, and building materials. These diverse uses are possible because clay in various formulations can be porous, workable, insulating, and capable of taking on fine detail once hardened. Fields of study in ceramics engineering and material science have long investigated clay's behavior to optimize it for different purposes.

SC is a fabrication technique in ceramics where a liquid clay slurry (slip) is poured into a plaster mold to form a hollow ceramic piece. In a typical SC process, clay powder is mixed with water, deflocculants, and other additives to create the slip. This slip is poured into a porous mold, usually made of plaster of Paris, and left to sit. The plaster mold absorbs water from the slip at the mold interface, drawing clay into small crevices, and causing particles to deposit and consolidate against the mold walls. Over time, a layer of clay of the desired thickness builds up on the mold's interior surface. Once this happens, the remaining liquid slip is drained out, leaving a clay "shell" conforming to the mold's shape. The piece is then allowed to dry further, first within the mold until it is stiff enough to handle, and then outside the mold until it becomes a hardened piece. It undergoes firing in a kiln to produce a rigid ceramic, and is possibly glazed for finish.[2]

SC is favored in industry because it allows economic yet precise mass production of complex shapes.[3] Forms with fine details and intricacies that would be difficult to achieve by sculpting or machining can be easily generated. It requires no expensive CNC machines or heavy presses, and circumvents the maintenance and upkeep associated with this equipment. Once a mold is available, the process of filling it with slip and letting it form is straightforward and low cost. The main limitation, as noted, is the need for a unique mold for each shape.[4] Creating these molds is time-consuming, can be costly, and molds only have a finite lifespan. As a result, traditional SC is economical only if one plans to make many identical copies from the same mold. It is inefficient for custom applications where a large range of shapes are required because the mold itself must be laboriously fabricated and cannot be reused for a different design. The waste generated from mold-making and discarded molds also detracts from the sustainability of the process.[5] These drawbacks motivate research into more flexible approaches to SC where the need for new molds is reduced.

Another relevant point is that in conventional SC, gravity is essentially the only force shaping how the slip coats the mold aside from capillary action in the plaster.[2] The mold remains stationary as the slip sets, which limits the geometry to what that particular mold can produce. If one could actively manipulate the mold (e.g. by tilting or rotating it during the casting process), it would be possible to influence the thickness distribution or surface features of the casting. In manual pottery, artisans sometimes tilt molds or use rotational casting to achieve certain effects[22], but these techniques are difficult to control precisely and not widely used in production. This observation hints that introducing robotic motion control into SC could unlock new capabilities, which is a key idea behind the proposed work.

2.2. State of Robotic Clay Fabrication

In recent years, there has been growing interest in bringing robotic automation to the realm of clay fabrication. Most of this work, however, deals with solid or plastic clay forms rather than liquid slip. A number of teams have investigated robotic additive manufacturing (3D printing) of clay. For example, Afsari and Sanguinetti developed a robotic clay 3D printing process using cement-like clay mixtures for construction applications.[6] Ko *et al.* demonstrated a multi-axis clay printing system where a robotic arm extrudes clay onto freeform foam molds, using additional tools like hot-wire cutters to trim the prints.[7] Ming *et al.* introduced an “impact printing” method in which small lumps of clay are shot out by a robot and stick together via plastic deformation upon impact.[8] All of these methods work with a malleable but solid form of clay rather than liquid slip. They typically require the clay to have a certain viscosity and cohesiveness to maintain shape during printing, which often involves careful tuning of the clay mixture and significant trial-and-error to calibrate parameters. As a result, these approaches can lack robustness: if the clay's properties deviate from expected (e.g. slightly different moisture content or consistency), the print quality may suffer. In general, purely additive clay printing methods must balance complexity of shapes with the need for the material to support itself during fabrication, which remains an ongoing challenge.[8,9]

Robotic subtractive techniques for clay have also been explored. Ma *et al.* developed a system for stylized robotic clay sculpting, where a robot carves a solid clay block to achieve a desired form. This approach treats clay like a soft machining material, removing material with tools. While effective for creating one-of-a-kind artistic pieces, subtractive methods are inferior to SC in terms of reproducibility, efficiency at scale, and in creating complex or hollow forms.[9]

While there have been notable successes in RF with clay, these efforts have predominantly focused on solid or semi-solid forms, where material behavior is more predictable and easier to control. In contrast, applying robotic methods to SC presents a compelling opportunity. The liquid nature of slip enables the generation of distinct and complex geometries, but it also introduces significant challenges. Unlike solid clay, slip is highly sensitive to flow dynamics, timing, and environmental factors, all of which add layers of complexity to the fabrication process. As a result, this approach requires managing a greater number of parameters and developing sophisticated sensing and control strategies to ensure reliable and precise outcomes.

To date, robotic SC is almost uncharted territory. The only reported study of a robotic SC technique is by Wu *et al.* (2023), who demonstrated a proof-of-concept system. In their setup, a robot arm dynamically reoriented a closed mold while cementitious slip cured inside it, producing varied concrete bricks from a single mold. This approach, termed *"dynamic slip casting,"* used an extensive computational model of the slip's behavior to plan the mold movements. By simulating how the liquid would flow and solidify, they could program the robot to move in ways that yielded different thickness distributions. The outcome showed that different shapes could indeed be achieved from one mold, confirming the potential of the idea. However, the authors noted that their simulation struggled to account for certain real-world effects, such as the shrinkage of the clay as water evaporated during curing, which affected the accuracy of the results.[13] This suggests that a *fully predictive* model for liquid clay behavior is very difficult to perfect due to the material's complexity.

Given the challenges of purely additive or purely simulated approaches, some researchers have started incorporating feedback and adaptation into clay fabrication. Im *et al.* (2018) expanded clay 3D printing capabilities by adding a closed-loop feedback system. In their work, as a 3D printed clay lattice was being built, a camera system monitored the print in real time. If the actual geometry deviated from the digital model, the system would adjust the remaining toolpath to compensate.[10] This adaptive approach significantly improved print quality over open-loop methods, highlighting that *real-time sensing* can overcome uncertainties in material behavior. Such feedback-driven methods represent a bridge toward more robust robotic clay fabrication, where the robot can respond to the material rather than just executing a pre-computed plan.

Research in analogous domains also provides inspiration. For instance, in concrete construction, robots have been used to manipulate molds or formwork dynamically. Tessmer *et al.* (2019) demonstrated a robotic system that tilts a mold while concrete sets to create customizable architectural blocks from one mold design.[11] This is conceptually similar to dynamic slip casting, though with concrete. In woodworking, Brugnaro and Hanna (2019) integrated sensors and machine learning into robotic carving of wood, showing the value of combining human craftsmanship knowledge with robotic precision. In their project, data from skilled human actions and autonomous trials were used to inform the robot, enabling it to handle irregularities in the material and avoid waste.[12] These examples highlight a trend in RF: moving away from treating the material as uniform and predictable, and instead embracing variability by sensing and adjusting to it.

Key lessons from the above studies are that adaptability to material variation is crucial for success in clay fabrication and similar processes. Working with clay in a solid form is easier to predict than in a liquid form, as a solid shape will not suddenly flow or change under its own weight. Liquid slip, on the other hand, introduces significant uncertainty: its behavior changes over time as it dries and its properties can be affected by subtle environmental factors like humidity or temperature. Therefore, to reliably automate SC, one must consider strategies that can handle this dynamism, which is where real-time monitoring and human expertise can play important roles.

2.3. Combining Slip Casting, Robotics, and Human-Robot Interaction

Automating SC with a robot presents unique challenges due to the fluid and time-varying nature of the material. Unlike a solid clay extrudate that retains shape momentarily, liquid slip continuously redistributes itself until it begins to solidify. Its viscosity decreases as water is absorbed and evaporates, changing how it flows over time. This means that a fixed robotic motion that worked at the start of a cast will not yield the same result if applied later, because the slip's consistency and volume have changed. Small differences in environmental conditions (temperature, humidity) or slip preparation can lead to different outcomes, making the process stochastic and difficult to model fully. This complexity motivates the incorporation of feedback and adaptability into the system.

One way to introduce adaptability is through sensor perception—specifically, using the robot's camera to observe the state of the clay in the mold and adjust accordingly. By continuously surveying the slip's shape (for example, its silhouette or the thickness of the forming layer), the system can detect when and where the slip is building up or draining away. This information can guide the robot to alter the mold's orientation in real time. This sensor-driven adjustment is a core principle of the present work, reducing reliance on perfect physics models.

Another powerful strategy is to leverage human intuition and skill alongside automation. HRI in fabrication allows a human operator to handle aspects that are difficult to fully automate, making the overall system more robust.[18] Humans have centuries of collective knowledge in working with clay. They can sense subtle material cues and make judgments on the fly, such as knowing by eye if the slip is at the right consistency or deciding when to stop a pour.[19] By integrating a human in the loop, we can utilize human strengths like creativity, adaptability, and problem-solving, while the robot provides precision, strength, and repeatability. This collaborative approach draws on the concept of collective systems, where multiple agents (human and machine) work together and compensate for each other's weaknesses.[20]

In the context of SC, the human might perform tasks such as mixing and pouring the slip (where tactile judgment is valuable), and intervening if something unexpected happens outside the domain of the robot's competency. For example, if the slip behaviour deviates significantly from what the robot is used to, the human can decide to adjust the extent of robot's motion. The robot, on the other hand, excels at holding the heavy mold in precise orientations and following a controlled motion trajectory that would be fatiguing or impossible for a person to do steadily. By dividing the responsibilities appropriately, the human and robot together can achieve results neither could alone.

Research in human-robot collaborative fabrication supports this approach. Han *et al.* (2021) reviewed numerous projects where human workers and robots jointly perform construction and fabrication tasks, and found that such collaborations greatly increase flexibility and robustness in unpredictable environments. Fully autonomous solutions in complex tasks like building or fabrication are still extremely challenging and resource-intensive to develop. Robots often struggle with generalizing to new situations that weren't explicitly programmed or trained for. By contrast, if a human is present to handle novel situations or make high-level decisions, the system can overcome many of those limitations. In practical terms, a semi-autonomous system can often be deployed sooner and more cost-effectively than waiting for a completely autonomous system to be perfected.[14] This insight is directly applied in our project: rather than attempting a fully autonomous adaptive SC robot, we incorporate the human as a critical component of the system's intelligence.

To summarize, combining SC with robotics and HRI yields a collaborative fabrication method that plays to the strengths of each element. The robot provides controlled motion and strength, the computer vision provides real-time material awareness, and the human provides oversight and adaptability. Such a system is well-suited to tackle the dynamic behavior of liquid clay slip, ensuring that as conditions change, there is either a sensor-driven or human-driven response to maintain the desired outcome. This collaborative, adaptive philosophy underpins the design of the system described in this thesis.

2.4. Computer Vision in Robotic Fabrication

Computer vision has become an increasingly powerful tool in RF, enabling robots to perceive and react to complex, unstructured environments.[15] In the context of this project, CV is the primary sensing modality used to monitor the SC process. The rationale behind this choice will be outlined along with insights from prior studies on effective application.

A recent literature survey by Çapunaman and Gürsoy shows that the integration of vision systems into RF has expanded greatly over the past decade. Vision-based feedback is now employed in a wide range of materials and processes, especially where traditional sensors (like encoders or load cells) cannot easily capture the state of a deformable material. In many novel fabrication scenarios, predicting the outcome purely by computation is infeasible due to material complexity, and that is where real-time visual sensing can step in. By observing the actual state of the workpiece and feeding that information back into the process, a robot can adjust its actions on the fly, shifting away from the rigid pre-planned approach of classical manufacturing.[17] This is a paradigm shift: instead of forcing materials to conform to ideal behavior, the process can accommodate the material's natural variations and attempts to work in harmony with them

Cameras offer several key benefits that make them well-suited for monitoring a process like SC. They provide high-resolution, rich information about the scene. From a single camera image, one can derive multiple types of data—the shape of the slip's surface, its motion, its color/texture (which might indicate moisture content), etc. Few other sensors are as versatile. Unlike contact sensors, vision is non-intrusive and does not disturb the clay by touching it. This is crucial when dealing with a soft or liquid material that could be easily perturbed. Vision can detect fine details such as the thin edges or small surface ripples that might signify flow, which would be hard to measure with any alternative sensor. Cameras have the additional asset of being accessible and cost effective, as they are a mature technology produced at economies of scale for consumer purchase. This makes a vision system cost-effective to implement. With their unique combination of precision, adaptability, and affordability, vision-based sensors stand out as a powerful and practical choice for modern fabrication processes.[15] For our purposes, being able to capture the *silhouette* and surface details of the clay slip in the mold is essential, and a camera is ideal for this.

Of course, vision is not without limitations. Common challenges include sensitivity to lighting conditions, occlusions, and the computational load of processing images in real time.[17] However, in a controlled manufacturing workcell, many of these issues can be mitigated. Consistent lighting can be ensured by using lamps or enclosing the area to block external light. The strict environmental control in manufacturing limits the presence of dust and debris, and it can be reasonably assured that the camera's visibility will remain unobstructed. Additionally, because it is known *where* in the image the action takes place (inside the mold), we can focus our processing on that region of interest, reducing computational demands. By exploiting the structured nature of the task, we can overcome many generic vision problems. As a result, the controlled nature of the manufacturing setting maximizes the effectiveness of vision-based sensing, making it a reliable choice.

Another consideration is the type of vision system. There are 3D imaging options like stereo vision or depth cameras (e.g. structured light or time-of-flight sensors), which provide explicit depth information. These have been used to resolve the ambiguity of monocular vision, but they come with trade-offs. Stereo vision requires multiple cameras and careful calibration to compute depth via triangulation. Depth cameras (RGB-D sensors) actively project light to measure distance, but they can struggle with certain surfaces (like specular or textureless liquids) and typically produce lower resolution data. They also add computational overhead and can be costly to integrate.[17] In our case, the slip's surface might not have a lot of texture for stereo matching, and a shiny wet clay surface can confuse depth sensors. Instead, we adopt a monocular vision approach—essentially using a single standard camera—combined with known references (markers) to infer the slip geometry. Monocular vision is the simplest setup and avoids potential failure modes of more complex sensors. While a single camera cannot directly give full 3D data, we can leverage *a priori* knowledge of the mold's shape and position, and we can place visual markers (ArUco markers) in the scene as reference points. By doing so, we constrain the problem enough that the 2D image can be translated into meaningful 3D information about the slip's extent.

Computer vision is a cornerstone of the proposed system, providing the real-time eyes that guide the robot. The approach capitalizes on the structured environment to make monocular vision viable for monitoring the workspace. By using vision, we aim to capture the state of the SC process in a way that can be quantitatively analyzed rather than relying on subjective judgment. This data-driven awareness is what enables the robot to make informed adjustments and ultimately achieve the adaptive control necessary for successful robotic SC.

2.5. Merits of Collaborative Robotic Slip Casting

Bringing together the threads of the previous sections, the specific advantages offered by a collaborative vision-guided robotic approach to SC can now be effectively articulated:

- **Enhanced Mold Versatility:** By dynamically moving the mold (swirling, tilting, reorienting) during the casting and drying phases, a single mold can produce a wider variety of shapes. The robot can, for example, cause clay to deposit more on one side of the mold than the other, resulting in asymmetry or varying wall thickness in the final piece—something impossible to achieve if the mold remains static. This capability bypasses the need to create a new mold for each variation, as the robot's motions introduce new degrees of freedom in shaping the outcome. Over a production run, this could save significant time and resources by reducing mold fabrication.

- **Humanly Difficult Motions Made Easy:** Certain motions required of dynamic SC, such as holding a heavy mold at an awkward angle for several minutes, or performing a complex, repetitive rocking sequence, are impractical for a human to do with precision. A robotic arm excels at such tasks—it can hold a mold perfectly still or move it along a precise path without fatigue. This not only expands the creative possibilities (allowing complex motion profiles that a human caster wouldn't attempt), but also raises the upper bound of achievable consistency due to the robot's incredible ability to actuate within tight tolerances.

- **Precision Sensing and Evaluation:** The integration of visual sensing enables objective, metric-based observation of the fabrication process. Through the camera, the robot can capture key visual features—such as the silhouette and texture of the forming clay—allowing for rigorous, quantitative assessment. This evaluation is critical for developing task-specific competency and, over time, supports learning and performance optimization. Moreover, real-time feedback enhances adaptability, enabling the system to respond to variations in material behavior or environmental conditions with appropriate adjustments.

- **Exploiting Human Expertise:** The collaborative nature of the system means it can leverage the strengths of both human and robot. The human can handle tasks like preparing the slip to the right consistency, judging by experience if the slip needs more water or deflocculant (something that is hard distinguish with machine sensors). The robot then handles the physically demanding and precision tasks of moving the mold. If the slip behaves in a manner beyond the range of the robot's expertise, the human can intervene. This synergy increases the robustness of the process. It also means the system can be adjusted on the fly by the operator—if a certain motion sequence isn't yielding the desired result, the human can perceive that and modify the procedure, which the robot can then repeat exactly. In essence, it forms a platform for material-centric exploration, where human intuition guides the robot's capable execution.

Collaborative vision-augmented robotic SC as the overarching research objective offers a way to push beyond the static limitations of conventional SC. It unlocks new design possibilities (multiple outcomes from one mold), improves the precision and repeatability of the process, and increases adaptability to material variability. By doing so, it promises to make ceramic fabrication more flexible—bridging the gap between mass production and custom craft.

3. System Design and Methodology

This section describes the design and implementation of the collaborative vision-augmented robotic SC system during initial exploratory stages. The methodology spans the physical workcell design, the computer vision-based sensing algorithm, and the control strategy to manipulate the state of the slip. The guiding principle in development was to start with a simple, robust setup that can be incrementally advanced.

3.1 Workcell Setup and Hardware

The experimental workcell consists of a 6-DoF industrial robot (KUKA KR 90-270 on a linear rail) equipped with a custom end-effector to hold a plaster mold. The mold used is a plaster bowl attached securely to the robot's end-effector so that it can be manipulated in orientation. The robot's size and payload capacity are larger than strictly required for the mold, but this setup was chosen for convenience with available equipment. In principle, a smaller robotic arm could also perform the task, as the motions and forces involved in tilting a bowl of liquid are modest. A standard webcam is mounted rigidly to the end-effector, looking down into the mold. This eye-in-hand camera moves with the mold and provides a continuous view of the slip inside. The camera was calibrated (using a Charuco board calibration method) to obtain its intrinsic parameters and to enable mapping of image coordinates to real-world coordinates on the mold. In addition to the robot and camera, a human operator is an integral part of the system's hardware setup. The human is responsible for tasks that are difficult to automate or require a tactile touch: **(1)** pouring a measured amount of liquid clay slip into the mold at the start of the process, and **(2)** handling the mold after casting, removing the formed piece once the clay has solidified sufficiently. This human-robot collaboration is designed such that the robot handles precise, repetitive movements and holding of the mold, while the human performs the nuanced operations of material handling.

Figure 1: Workcell setup with robot and end effector

3.2 Computer Vision Sensing Pipeline

The computer vision system is the primary sensing modality used to monitor the state of the slip. The goal of the vision system is to observe the silhouette of the clay slip inside the mold and extract key measurements that indicate how far the slip has spread up the mold walls at various locations. To achieve this, an image processing pipeline operates on keyframes captured by the camera. The mold interior is white plaster and the clay slip is a darker muddy color, so there is natural contrast between the two. We enhance this contrast by preprocessing and applying edge detection to clearly identify the boundary between clay and plaster. Fiducial markers placed around the rim provide matched keypoints between the image plane and the world that simplify processing and computer vision.

1. **Image Capture and Preprocessing:** The eye-in-hand camera continuously captures images of the inside of the mold as the robot moves. Each frame first undergoes lens undistortion using the camera's calibration parameters. The image is then converted to grayscale, as light intensity is sufficient for distinguishing clay vs. plaster. Next, a Gaussian blur is applied to reduce high-frequency noise that could interfere with edge detection. This yields a clean image where the primary intensity changes are due to the slip's outline.

2. **Region of Interest Masking:** Using the known geometry of the mold and the placement of fiducial markers, the region of interest (ROI) in the image that corresponds to the inside of the mold can be isolated. Eight ArUco markers are placed around the rim of the mold as shown in Figure 2. These high-contrast square markers can be robustly detected in the image and serve two purposes: **(1)** They provide fixed reference points in the real world that the vision system can recognize, and **(2)** from their known arrangement, we compute a homography (projective transform) to map image coordinates to the mold's top-plane coordinate system. In practice, once the camera sees the markers, the system can continuously recalibrate the perspective of each frame. This allows us to identify which pixels lie inside the bowl of the mold versus outside. All image areas outside the mold's interior are masked out, focusing the vision algorithm on the slip region only. This masking not only improves processing speed by limiting the area for analysis, but also prevents any external objects or edges from confusing the slip detection logic. As the robot moves the mold and camera, the homography is updated in real time, making the method robust to the moving camera viewpoint. We work around the imposed depth ambiguity by projecting everything onto the top plane of the mold. While this simplification ignores some 3D effects, it is sufficient for tracking the slip's spread across the mold surface.

3. **Edge Detection:** Within the ROI (the interior of the mold), we apply the Canny edge detection algorithm to identify the boundary of the slip. The clay slip appears as a contiguous dark region against the bright plaster, so the outline of this region shows up as a strong edge in the grayscale image. The Canny edge detector is tuned so that it reliably

captures the slip-plaster boundary while ignoring noise or faint edges from lighting gradients. The result of this step is a binary edge map highlighting the silhouette of the slip, essentially a line along the slip's perimeter inside the mold.

4. **Key Point Extraction:** We distill the slip's silhouette into eight key points that succinctly describe the slip coverage. We chose eight points corresponding to eight evenly spaced radial directions (every 45°) around the center of the mold. The center of the mold opening (pole) is known from the ArUco marker configuration—specifically, we compute it as the intersection of lines drawn between opposite marker positions on the rim. For each of the eight predefined line segments, we cast a radial line (ray) from the perimeter keypoint towards the pole in the edge map. Along each ray, the system searches for the first edge pixel that indicates the presence of clay slip. Because the slip always starts at the bottom-center of the mold and extends upward and outward as the mold is tilted, this first encountered edge along a ray corresponds to the furthest extent of slip in that direction (effectively the height of the slip along that wall direction). We record the pixel coordinates of these eight edge points.

5. **Coordinate Transformation:** The pixel coordinates of the slip edge key points are then transformed into the real-world reference frame of the mold. Using the homography computed from the ArUco markers, each key point's image coordinate is mapped to a coordinate on the mold's top plane (i.e. the rim plane). This yields eight points in a consistent 2D coordinate system tied to the physical mold. In this frame, if the slip has evenly coated the mold, the eight points would form a roughly circular pattern near the mold's edges; if the slip is uneven, the points will deviate outward or inward in certain directions. These transformed key points are used both for evaluating the current state against a desired target and (potentially) for feedback control. While we could further project these points onto the 3D curved surface of the mold (since the mold's shape is known), for our control purposes the 2D planar projection is sufficient as an indicator of slip coverage. Essentially, the distance of each key point from the mold center on the top-plane correlates with how high up the wall the slip has reached in that direction.

Through this pipeline, every frame yields a set of eight numeric values that succinctly describe the slip's state. This representation is highly efficient compared to processing the full image—reducing the problem to just eight critical measurements. It proved advantageous in our system by cutting down computation time significantly (the alternative was to analyze entire edge profiles or regions, which was slower). With this vision system, the robot (or the human operator monitoring the data) can tell in real time how well the slip distribution is matching the desired outcome.

3.3 Control Strategy and Software Integration

The control strategy for the robot is based on adjusting the mold's orientation to guide the flow of slip toward a target silhouette shape defined by eight goal key points. In the current implementation, we approached this as a sequence of preset motions informed by the target, rather than a continuous real-time feedback loop—mainly due to time and hardware constraints. However, the system architecture is designed to support closed-loop control in the future by leveraging the vision data. The general approach is: tilt the mold in various directions so that the liquid slip runs outward and coats the walls up to the desired height at each of the eight key points. Because the slip is a fluid, achieving a particular distribution often involves moving in a coordinated, smooth manner rather than point-to-point motions. We developed a mold tilting trajectory that moves through a series of waypoints corresponding to the key point positions and orientations. In effect, the robot "pours" the slip toward each compass direction in turn. Concretely, if the target shape is a uniform height around the bowl, the robot executes a gentle continuous rotation, or an alternating tilt, to evenly distribute slip. If the target shape has specific high points, the robot will increase the extent of its tilting toward those directions.

Time and hardware constraints limited capabilities to implement a feedback system within this project as intended for the larger research objective. The current system does not yet incorporate automatic, feedback-driven iteration. Once a motion pass is completed, the run terminates. However, the necessary components are already in place to enable such a closed-loop process. Vision data can be analyzed after each segment of motion, and if deviations from the target are detected, the robot could autonomously adjust its end-effector trajectory for subsequent passes before continuing. This would allow the system to refine its performance in real time, improving accuracy and adaptability.

From a software and implementation standpoint, we utilized a mix of tools to program and coordinate the system. The robot was controlled using a high-level interface through Rhino Grasshopper, a visual programming environment commonly used in design and architecture, with the KUKA|PRC plugin for robot motion planning. The eight target key point coordinates (in the mold's reference frame) were fed into Grasshopper, which allowed us to visualize the target silhouette on a 3D model of the mold and plan the robot's tilting trajectory accordingly. We employed the Open Sound Control (OSC) protocol to communicate the detected slip key point data from the vision program (running in Python with OpenCV) to the Grasshopper environment. Grasshopper, with its parametric design tools, made it easy to tweak geometric parameters and control logic on the fly before committing them to the robot's code. Once the trajectory was finalized, the motion commands were uploaded to the robot's controller to execute the physical movements. This somewhat unconventional integration of design software (Rhino/Grasshopper) with robotic control proved convenient in our development process, allowing rapid prototyping of the control strategy. In a more traditional setup, one could use a robotics framework like ROS to handle vision and motion together; in our case, the OSC-to-Grasshopper approach provided a quick solution given the team's familiarity with those tools.

3.4 Operational Workflow

Bringing together the hardware, vision, and control, the overall operation workflow of the experimental and explorational system can be described. The process consists of multiple steps with coordinated human and robot actions:

- The process begins with the mold in an upright level position. The human operator pours a measured amount of liquid clay slip into the mold. Once the slip is poured and this initial settled state of the material is sensed, the toolpath is generated based on the data. The robot is programmed with only eight discrete waypoints and orientations, which it cycles through repeatedly. This setup enables systematic observation of how the material behaves under motion, providing data to refine understanding and inform future strategies.

- The operator initiates robot motion, and the tilting routine is undertaken. Guided by the planned trajectory based on implemented feedback rules, the robot dynamically tilts and rotates the mold about its center, effectively "swirling" the slip around. The goal in this phase is to coat the interior walls of the mold according to the target pattern.
- Once the trajectory is completed, an image of the resulting material state is captured for data inference. The robot returns the home position so that the operator can remove the mold from the end effector and oversee subsequent manual stages of production.

The methodology involves a human-robot team: the robot manipulates the mold to shape the slip, guided by vision sensing, and the human assists at the beginning and end. With the system design and method described above, the results of applying this method to create various cast shapes are presented, and the system's performance is examined.

4. Experimentation and Discussion

To evaluate the effectiveness of the vision-augmented SC system, we conducted a series of tests spanning from preliminary trials with simulated materials to full trials with actual clay slip. The primary goals of the experiments were to (a) verify that the robot could achieve different slip distribution patterns as intended, (b) assess the accuracy of the vision sensing (i.e. how well the slip's actual coverage matched the target silhouette), and (c) observe the system's general behavior during exploration.

Two representative target shapes were chosen for demonstration: a "circle" profile (a relatively uniform distribution up the mold, representing a cup-like shape) and a "star" profile (an intentionally non-uniform distribution where slip reaches higher on the wall in four lobes, creating a star-like edge pattern). Each target silhouette is defined by eight radial key point positions on the mold, which were visualized to the operator and used to plan the robot's motions. Initial runs were done using a *slip simulant* for practicality, followed by trials with real ceramic slip to validate the actual casting outcomes.

In early testing, resource and time constraints motivated the use of simulants. Waiting for clay slip to dry in the mold and cleaning the mold between trials is time-intensive, which limits how rapidly one can iterate experiments. To expedite development, we used a stand-in material: whipping cream that mimics the fluidity of slip. To avoid damaging the plaster mold during these tests, we 3D-printed a waterproof plastic liner that fits inside the mold, so the dairy would not soak into the plaster. This allowed quick repetition of trials—after each test, the liner could be removed, cleaned, and reused without needing the plaster to dry out. We also performed some extremely simplified trials with a small marble rolling inside the mold to simulate how a point mass might move, though those served more to verify our understanding of the kinematics than to produce meaningful "coverage" patterns. The most informative tests were with the cream simulant and the real slip, which are discussed below.

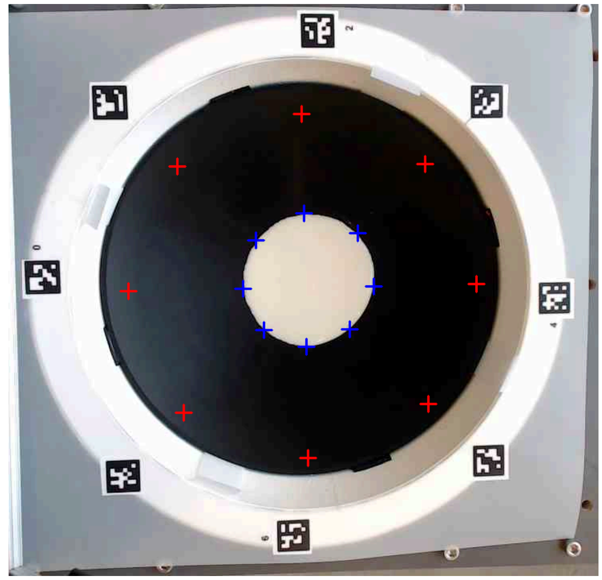

Figure 2: Initial slip state kepoints (blue) before any robot motion, compared to the desired target profile (red).

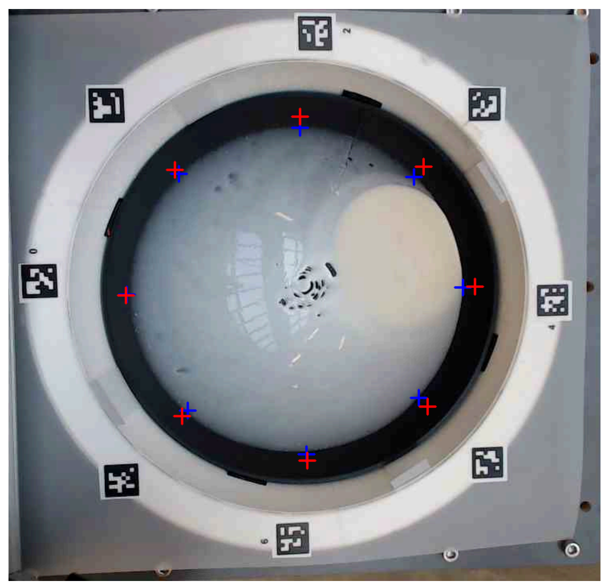

Figure 3 : Final slip state keypoints (blue) after the robot's tilting motion using the simulant, compared against the target "circle" keypoints (red).

Using the dairy-filled liner, the robot executed the casting routine for the circle. The vision system recorded the resultant material silhouette, and we compared the outcome to the target. These trials demonstrated the system's basic functionality without the complications of clay. The cream's flow properties are slightly different from clay slip (lower viscosity, so it flows faster and doesn't build up a thick layer), but it provided a clear visual of coverage.

Real Slip Tests: With the process flow and motion plan refined using simulant, limited trials were conducted with actual clay slip for both target shapes. Each slip trial required allowing the cast to set and then cleaning/drying the mold, so we performed a small number of runs and focused on evaluating the outcome of each in detail rather than doing many repeats. In the circle target case with real slip, we poured the clay, then ran the same tilting program as used with the simulant. The presence of the camera and vision system allowed us to monitor progress, but the robot executed the motion open-loop (we did not intervene mid-run). The clay slip has higher viscosity than the cream, so it flows more slowly and is able to build up a thicker layer without immediately running back down. This had the advantage that it more faithfully *stayed* where it was guided, but it also brought to light the central challenge previously anticipated: the material properties of the slip changed rapidly due to water loss, even over short durations of robotic motion. This highlights the inherent complexity of working with such a dynamic material.

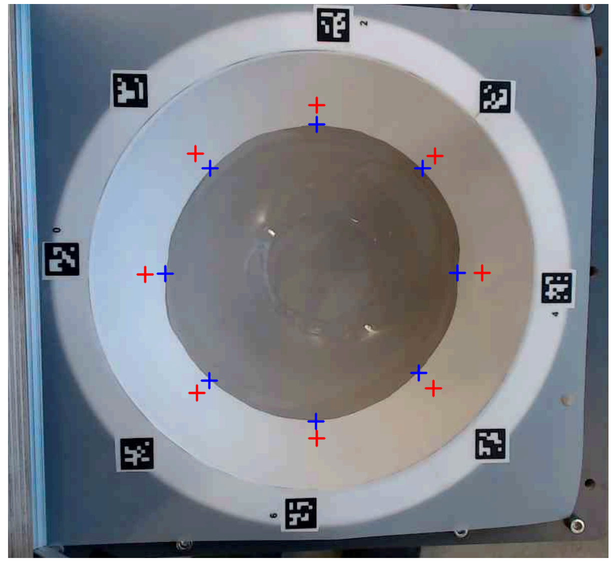

Figure 4: Final casting result using clay slip for the "circle" target. he overlay illustrates the target points (red) and the actual slip state points (blue).

For a more complex shape, we tested the star pattern target. This target had alternating high and low points around the rim—essentially four "high" lobes and four "low" recesses (eight points in total). Both the simulant and the slip tests for the star shape showed the concept working, as material could be piled up more in the lobe directions.

The system successfully created raised lobes of slip in the four intended directions (top, bottom, left, right in this view), with the sharpness of the star points dependent on the bead size of the fluid. The comparison of key points shows that the robot met the high points closely, while the intended low points still received some slip (though less than the high points), resulting in a softened star shape. As shown in Figure 4, the final slip shape in the mold clearly reflects the star pattern. The slip reached higher in the four principal directions, creating a wavy rim. The red target outline versus blue actual outline indicates that while the general shape was achieved, the contrast between high and low was less extreme than intended—the "valley" directions had clay extended farther than the ideal target.

This outcome is not surprising, as liquid will always seek a level and completely emptying out certain directions is nearly impossible without active measures like absorbing material or extremely slow tilting. Nonetheless, the star experiment demonstrated that our system can go beyond uniform coatings to intentionally heterogeneous shapes. These variations of profile were achieved using the same mold—a testament to the system's versatility compared to traditional SC where each of those shapes would typically require a differently shaped mold.

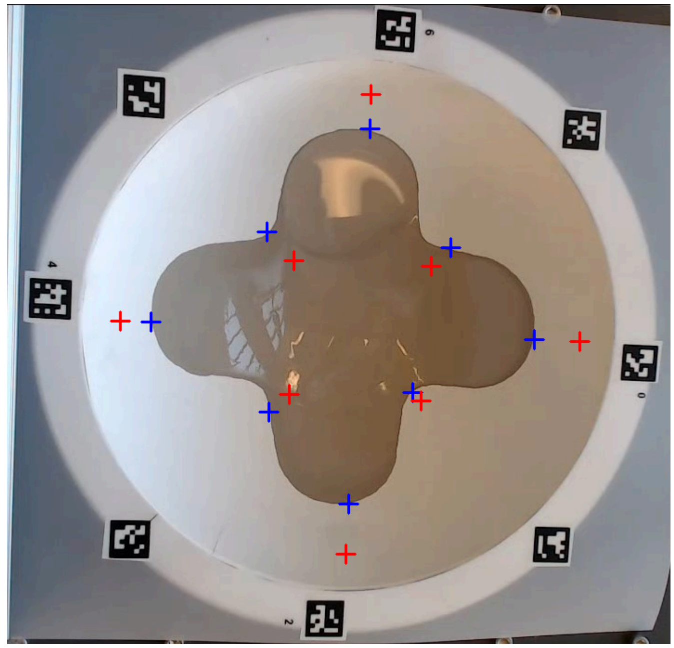

Figure 5: Achieved slip distribution for the "star" target pattern using real clay slip. The overlay illustrates the target points (red) and the actual slip state points (blue).

4.1 Performance Analysis and Observations:

Across the tests, we noted several important aspects of system performance:

- ***Accuracy to Target:*** The vision-based measurements enabled us to quantify how close each trial came to the desired shape. For the uniform target with simulant material, the average error in key point radius was 5.3% of the target radius. For uniform target testing with slip, an average error of 11.9% was observed. The star target resulted in larger deviations overall, with errors at 22.5% of targets on average. This decrease in accuracy could be attributed to the increased complexity of the target in addition to material behaviour applying constraints on achievable silhouettes that had not previously been considered. These results indicate the robot can achieve the general form and reasonably fine control over slip distribution. Accuracy achieved in this investigation is quite successful for a first demonstration during exploratory stages.

- ***Material Behavior:*** This investigation confirmed and brought to light behaviour of the slip that will need to be considered in further development. We observed that the clay slip's behavior can change even within a single run. On a second tilting pass (or even toward the end of a first pass), the slip becomes thicker as water is absorbed into the plaster and as the mixture dries, making it less responsive to tilting. As a result, subtle layers of receding slip—formed through repeated passes of the same motion—could be observed on the final pieces. This suggests that timing is important: there is a window of fluidity where the robot's motions are most effective, and beyond that the material manipulability diminishes, requiring amplified motions to achieve similar material profiles across time. In future implementations, one could envision the vision system detecting if the slip front is not reaching as expected (e.g. if after a certain tilt the edge is still far from target) and prompting either an additional tilt or informing the user that more slip is needed. Additionally, the physics of the material impose constraints on the range of achievable silhouettes. Surface tension acting on the 'bead' of slip swirling within the mold limits the tightest curvature that can be formed. To avoid depositing slip on specific areas of the mold, certain motion paths must be precisely retraced. Although the robot successfully tilted the mold to achieve the desired angle—guiding the slip to settle low in the bowl—the transition from the previous position caused unintended slip deposition higher up along the surface. Furthermore, under the current control logic, the initial slip volume may result in 'donut holes'—regions where slip is pushed outward to meet the target extent but fails to fully cover the bottom of the mold. This issue will need to be addressed in future development through improved toolpath planning and control logic refinement.

- ***Human-Robot Collaboration:*** The involvement of the human was minimal during the robotic casting action—essentially just monitoring the live video and being ready for the next step. However, the ability for the human to intervene is an advantage in case of anomalies. In none of our automated runs did we need to intervene, but had the slip started to behave unpredictably (say, a large air bubble or clog causing uneven flow), a human could pause the robot and adjust the process. This safety net is part of what makes collaborative operation appealing. After each run, the human's role in demolding was straightforward and the robot's assistance in positioning the mold was helpful. Having the robot support the heavy mold during fabrication process steps saved effort and reduced risk of dropping. These trials reinforced the benefit of the collaborative approach. The robot handled the precise motion and holding tasks, while the human handled the delicate and judgment-based tasks, together achieving results that would be hard to get with either working alone.

Overall, the results demonstrate that the vision-augmented robotic system can successfully execute SC in a dynamic way. We achieved both uniform and patterned castings from one mold, confirming the core hypothesis of increased versatility. The discussion below will tie these findings back to the broader context of RF and outline the implications and potential improvements.

4.2 Discussion of Key Findings

The experiments provided a proof-of-concept validation of our approach. A significant outcome is that a relatively straightforward sensor and motion strategy was able to handle the complex behavior of liquid clay in a mold in a rudimentary manner. Prior approaches to robotic slip casting (notably the one other known study in this area) relied heavily on physics-based simulations of the slip's flow to plan the motion. Our work, by contrast, shows that with sensing, the system can adapt to state conditions during fabrication and reduce the need for advanced modeling. This finding aligns with trends in RF that favor feedback and adaptivity: Han *et al.* (2021) noted that human-robot collaboration and real-time adjustment often yield more robust performance in unpredictable tasks. Likewise, recent surveys of vision-augmented fabrication (Çapunaman and Gürsoy, 2023) emphasize using sensing to deal with material variability, rather than assuming precise models. Our successful casting of varied shapes with minimal prior modeling attests to this philosophy. These results highlight the potential of simple, feedback-aware robotic strategies to begin addressing the nuanced challenges of liquid clay manipulation—laying the groundwork for more refined, adaptive systems in future work.

Another key finding is the versatility gain: using one mold to produce multiple forms. In traditional ceramics production, if you wanted to make a set of pieces with different profiles, you'd need multiple molds. Here, we demonstrated making at least two very different shapes (and in principle many others) from one mold by just changing the robot's program. This suggests a future scenario for manufacturers or designers, where a whole collection of ceramic designs could be created from a single baseline mold, saving considerable time and cost. It also means less waste since plaster molds don't have to be remade for each variant. This ability to *programmatically* alter outcomes merges the repeatability of mold casting with the creativity of hand-shaping, sitting at an intersection of digital fabrication and traditional craft.

There are, of course, limitations to note. Our current system, while adaptive, was only semi-automatic and we did not close the feedback loop in real-time. A fully autonomous system would continuously adjust as the slip moves, perhaps achieving even more accuracy. Additionally, the scale of our experiments was small. Larger or more complex molds would introduce new challenges like needing multi-axis coordination or even multiple cameras. We also dealt with a single type of slip; different clay compositions or colors might have different flow or provide less contrast for the camera, requiring tuning of the vision parameters.

In summary, the results are promising and establish a baseline for what vision-guided robotics can do in the context of SC. The system achieved its technical objectives of monitoring the material and adjusting the robot's trajectory accordingly to produce tangible cast pieces of varying shapes. Furthermore it engaged a human collaborator in a meaningful way for the overall task.

5. Conclusion and Future Work

This thesis presented the development of a novel collaborative robotic SC system enhanced with computer vision feedback. The research was motivated by the desire to increase the versatility of ceramic SC—enabling multiple unique outcomes from a single mold—and to improve adaptability in the face of clay's unpredictable behavior. By integrating a 6-DoF robot arm, a monocular camera, and a human operator in a cooperative workflow, the project demonstrated a proof-of-concept method for dynamic, adaptive SC.

The key contributions of this work include: **(1)** Designing a vision-based sensing algorithm to monitor liquid clay in real time and extract meaningful state information (specifically, the slip's silhouette coverage in the mold captured as eight key points). **(2)** Developing a robotic control strategy that uses this sensory feedback to adjust mold orientation, achieving the desired casting outcome of varied profiles as specified. **(3)** Implementing a collaborative human-robot procedure for SC, wherein the strengths of a human (for material preparation, qualitative judgment, and delicate handling) and a robot (for precision, strength, and repeatability) are effectively combined in the workflow. **(4)** Producing physical cast ceramic samples that validate the approach—showing that complex shapes and variations can be achieved without changing molds, which is something not possible in traditional static mold casting processes. Collectively, these contributions lay down a foundation for a new, more flexible approach to ceramics manufacturing.

The results from our experiments indicate that a relatively straightforward sensor and control loop can address challenges in SC that previously might have required complex simulation or labor-intensive trial and error. This is significant in the context of RF because it emphasizes an alternative to heavy upfront modeling: using real-time perception and simple adaptive rules to handle material uncertainties. The success of this approach underscores how adding sensing and human insight allows robots to tackle messy, real-world processes which are traditionally hard to automate. For the field of ceramics, this work opens the door to more flexible manufacturing techniques. In the future, a ceramics producer could use a single mold design to create a whole family of related products with varying forms or textures by simply altering the robot's motion program—reducing the cost and waste associated with making multiple molds. Designers and artists could likewise exploit this technology to experiment with novel forms that were not achievable before, blending the consistency of mold casting with the variability of hand craft. The project thus contributes to the broader movement of digital fabrication in ceramics, introducing a hybrid technique that merges conventional casting with modern robotic control.

Building on the encouraging results of this thesis, there are several directions for future research and development in the progression towards achieving the overarching research objective:

- **Scaling and Generalization:** Test the system with larger or differently shaped molds, including non-axisymmetric molds or multi-part molds. Larger molds might require robots with higher payload or the use of multiple cameras to cover a bigger area, and complex mold geometries might need more advanced vision processing (for example, 3D depth sensors to fully capture the slip surface). Extending the method to these scenarios will help evaluate the generality and robustness of the approach.

- **Enhanced Sensing and Automation:** Integrate more advanced sensing or intelligence. For instance, a depth camera or a machine learning model could be trained to recognize patterns in the slip's surface (such as the onset of solidification or thinning regions) and predict the optimal mold motions to achieve a target shape faster. Additionally, closing the feedback loop fully in software would allow the robot to continuously adjust its trajectory based on the live camera data. This could improve accuracy and enable the system to respond to disturbances autonomously.

- **Material and Process Variations:** Explore fabrication with different clay slip formulations or even different casting materials. Experiments could be done to intentionally vary the environmental conditions (temperature, humidity) or mold dryness to see how the vision and control system might adapt or need re-tuning.

- **Human-Robot Interaction for Creativity:** Since our approach leverages human input, another avenue is to develop a more interactive interface where a human can intuitively guide the robot's target pattern in real time. Facilitation of more direct communication between human and robot is in line with the intentions of the overarching objective, and allows the strengths of the human to be better leveraged. For example, an artist could draw a desired thickness pattern via a tablet, and the robot could attempt to realize it immediately. The human could also intervene mid-process to adjust the target, creating a live dialog with the material through the robot. This could blend the creative spontaneity of studio pottery with the precision of robotics, leading to interesting artistic outcomes.

In conclusion, the work accomplished in this thesis demonstrates the feasibility and promise of a collaborative vision-augmented robotic SC system. The system achieved its core objectives, successfully manipulating liquid clay to produce different shapes from a single mold, and adapting to state of the material via sensor feedback. These results are preliminary but encouraging, pointing toward a future where ceramic casting can be made far more flexible and intelligent. We have shown a new way to bridge digital fabrication and traditional craft, and there is ample opportunity to refine and expand this approach. The hope is that this research serves as a stepping stone for further exploration into adaptive, human-assisted RF processes—not only for ceramics but for other crafting techniques that can benefit from the union of human intuition and robotic precision. The versatility and adaptability demonstrated here suggest a meaningful advancement in how we think about manufacturing customized objects in partnership with robots.

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