Robotic Sand Packing for Reusable Casting Formworks:

Integrating Vision-Based Toolpath Feedback for Geometric Accuracy

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Kinetic Sand presents promising potential as a reusable casting formwork material due to its cohesive and moldable properties. However, its semi-fluid behavior and tendency to deform under pressure make achieving high geometric accuracy a challenge. This paper introduces a vision-based 3D scanning and comparison methodology to evaluate and control the material behavior of Kinetic Sand during robotic packing. Building on previous research into robotic sand-packing grammars, the study analyzes the effects of various toolpath strategies and end-effector geometries to identify parameters that minimize material deviation. By integrating iterative feedback through digital scanning, the methodology enables the refinement of toolpaths and supports the production of complex cement panels with near-zero formwork waste. The result is a more controlled and repeatable process for fabricating accurate, seamless cast elements using emergent material behavior as a design driver.

Keywords: *Robotic Fabrication, Casting, Materially Informed Design, Reusable Formworks, Vision-Based 3D Scanning.*

INTRODUCTION

Sand has been effectively used as a reusable formwork material for centuries for casting metal parts (Meibodi et al., 2019; Khan et al., 2017; Ravi 2021), as well as for architectural components (Duyster 1959; Kovaleva et al. 2022: Çapunaman et al., 2023; Çapunaman et al., 2024; Naboni et al., 2022; Battaglia et al., 2018). This research takes advantage of the material capabilities and design possibilities of a particular variant of sand, *Kinetic Sand*, to develop a reusable methodology for casting cement panels. In the push for sustainable architectural solutions, the focus is often on material usage, or the characteristics of various performance elements within the built environment. This research instead focuses on the formwork as a significant contributor, both towards reducing the waste generated during the casting process, and to create unique design opportunities.

Limited use formworks are the current predominant choice for casting architectural concrete and cement forms. This research proposes an alternative reusable formwork methodology using a 6-axis robotic arm to pack *Kinetic Sand* and cast into the form created.

To understand the unique material behavior of *Kinetic Sand*, and to evaluate it in regard to certain robotic actions, a robotic fabrication grammar was developed (blinded). Previous studies using this grammar demonstrated the potential of Kinetic Sand for creating reusable formworks with emergent textures and patterns in cast concrete panels (blinded).

Building upon this foundation, the current paper focuses on analyzing and evaluating toolpath generation strategies in relation to geometric accuracy. By integrating a vision-based 3D scanning methodology, the research assesses *Kinetic Sand*'s performance as a formwork medium and identifies toolpath strategies that balance geometric fidelity with the expressive material behavior of *Kinetic Sand*. This enables the coexistence of accuracy and emergence within a single fabrication process. The paper presents a series of experiments in robotic sand packing, evaluated for geometric accuracy using vision-based 3D scanning. It culminates in a proof-of-concept prototype – four adjacent and geometrically continuous cement panels cast from separate instances of robotically packed *Kinetic Sand* formworks – demonstrating reusability and geometric fidelity of the proposed approach.

MATERIALS AND METHODS

The primary material used in this study is *Kinetic Sand*, a commercially available compound composed primarily of sand combined with a polymeric binder ("Kinetic Sand", 2025). *Kinetic Sand* exhibits distinctive mechanical behavior under varying stress conditions: under shear or minimal compression, its particles rearrange to adapt to complex toolpaths, where under high compression, it becomes highly moldable and retains its shape with minimal rebound. This dual response makes it particularly suitable for robotically packed formworks, where precise conformity and stable form are essential (Gago, 2022).

The robotic work cell developed for this research comprises an ABB 2400 industrial 6-axis robotic arm, a set of custom 3D-printed end-effectors, a work holder to contain the formwork material, *Kinetic Sand* as the formwork medium, and an aluminum insert for casting. To study the material's response to robotic interaction, three types of end-effectors were designed: spherical, cubic, and pyramidal. For further details on the development of the robotic work cell, the design of the end-effectors, and the fabrication parameters, the readers can refer to (blinded).

Robotic Fabrication Grammar

A robotic fabrication grammar was developed to formalize the robotic sand packing process and develop toolpaths for robotic fabrication (blinded). This formalization allows to explore the causal relationships between the fabrication parameters, toolpath strategies and *Kinetic Sand*'s emergent material behavior. The grammar is composed of four rule sets. Rule Set 1 generates the initial array of points. Rule Set 2 takes these points and converts them into selected toolpath targets. Rule Set 3 assigns a sequence in which each target is executed by the robot. Finally, Rule Set 4 assigns key toolpath parameters, including the end-effector tools to use, the depth at which the tool plunges, and rotational variations.

Vision-Based 3D Scanning and Analysis

To analyze the behavior of the *Kinetic Sand* in response to toolpaths and fabrication parameters, the digital *geometric estimates* (GE) of the *Kinetic Sand* formworks are generated and compared with the 3D reconstructions of the *material behavior* (MB) of the robotically packed *Kinetic Sand*, which are obtained through vision-based 3D Scanning.

To generate the GE of the sand, the geometry of the end-effectors are copied to each toolpath target with the appropriate orientation. Once the geometries are in place, they are subtracted ("Boolean Difference") from the rectangular prism abstraction of the initial flat-packed Kinetic Sand bed, naively assuming perfect compressibility.

The MB, on the other hand, was obtained using an Artec Eva Lite 3-D scanner, which is a handheld device with a working distance of 0.4 – 1 m within a 30 x 21° angular field of view ("Artec

Eva Lite", 2025). It is able to capture with a resolution of up to 0.5 mm, which was found to be sufficient in scanning the sand surfaces for the purposes of this research. The raw data output by the scanner was post-processed using Artec Studio 18 Professional ("Artec Studio", 2025). Any scan data apart from the surface of the sand and the top of the work holder, used to localize the scans relative to the GE, was cleaned before the analysis. A mesh was then exported from Artec Studio 18 Professional as an STL file.

Using the GE as a baseline, each vertex on the scanned MB mesh is measured to the closest point on the surface of the GE geometry. Each vertex is then assigned an RGB color value corresponding to its deviation: green indicates areas closest to the expected geometry, while red highlights regions with the greatest material deformation (Figure 1). These RGB values are used to generate a color-mapped rendering of the mesh, visually conveying the extent of deviation across the formwork surface.

The results reveal the effects of material spring-back, a key property of *Kinetic Sand* that contributes to emergent behaviors. Additionally, they highlight another significant factor influencing material emergence: *Kinetic Sand*'s inherent tendency to redistribute under applied pressure, which causes unforeseen material displacement during each execution, often leading to deviations from the GE.

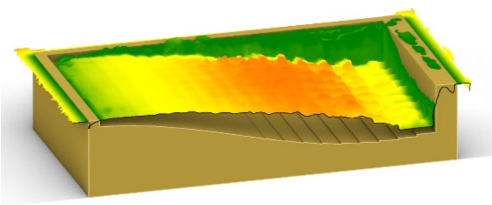

Figure 1
An overview of the digital comparison of the GE and MB.

A series of experiments were conducted to evaluate the geometric fidelity of various toolpath configurations developed using the robotic sand packing fabrication grammar. Although the digital comparison was not used to automatically adjust the tooling operations, it provided valuable feedback for the human operator to evaluate the effectiveness of each applied toolpath configuration. In this way, the scan data served as a supplementary assessment tool that guided manual refinements of the toolpath rules, establishing an iterative process for progressively enhancing fabrication accuracy.

EVALUATING TOOLPATH STRATEGIES FOR GEOMETRIC ACCURACY

To study the unique material behavior of *Kinetic Sand*, a series of experiments were conducted to determine the maximum achievable compression while maintaining a deviation of less than 5 mm from the intended geometry. To minimize the confounding effects of geometric complexity in assessing the results, a planar surface was packed at a given depth. In each of the first 3 experimental sets shown in Figures 2, 3, and 4, an identical toolpath was run three consecutive times.

In Figures 2, 3, 4, 5, and 8, the color assigned to the vertices is based on a scale of 0-45 mm, or in Figure 6 a scale of 0-70 mm. Each of these Figures, regardless of the varying plunge depths assigned to the toolpath, use a consistent scale to ensure the results are comparable during the experimentation.

In Figure 2, the target planar surface was positioned at 20 mm depth below the initial top boundary of the sand volume. In the first iteration (1), a scan and comparison were performed after a single toolpath execution. A second pass and scan were conducted in the next row (2), followed by a third pass (3). After the third consecutive execution, the *Kinetic Sand* was sufficiently compacted, showing minimal deviation from the GE. These results indicate that at a target depth of 20 mm, *Kinetic Sand* can be compressed to approximately 80% of its original volume while preserving geometric accuracy.

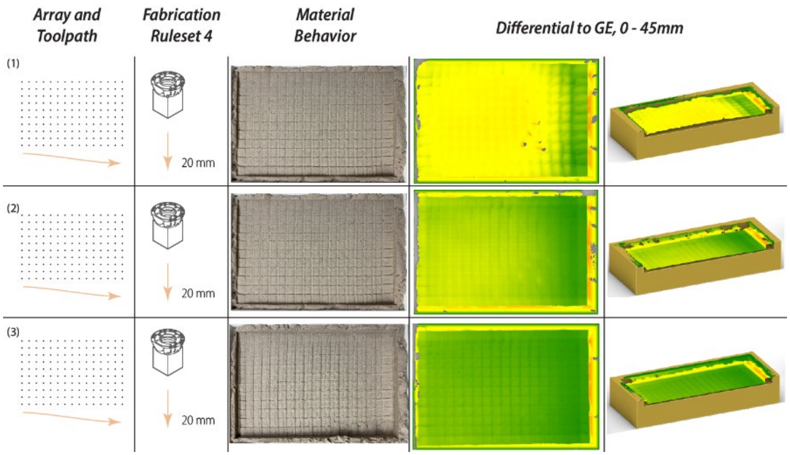

Figure 2
Flat surface packing experiments at 20 mm depth to determine the compressive limits of *Kinetic Sand* after the first (1), second (2) and third (3) run of the robotic packing tool path.

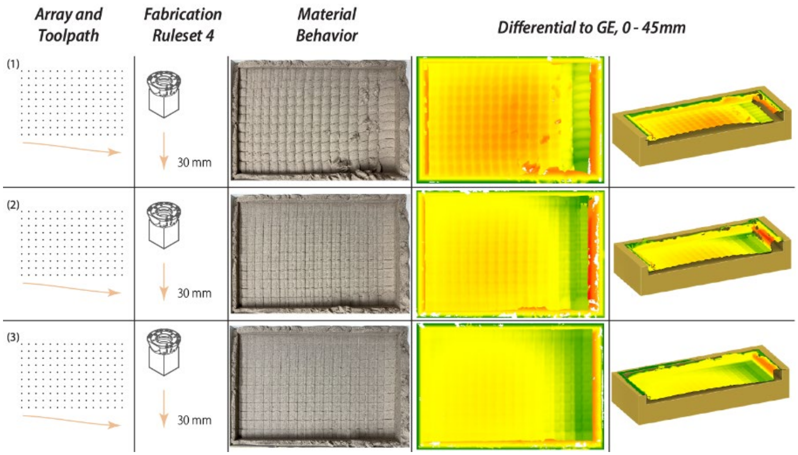

Figure 3
Flat surface packing experiments at 30 mm depth to determine the compressive limits of Kinetic Sand after the first (1), second (2) and third (3) run of the robotic packing tool path.

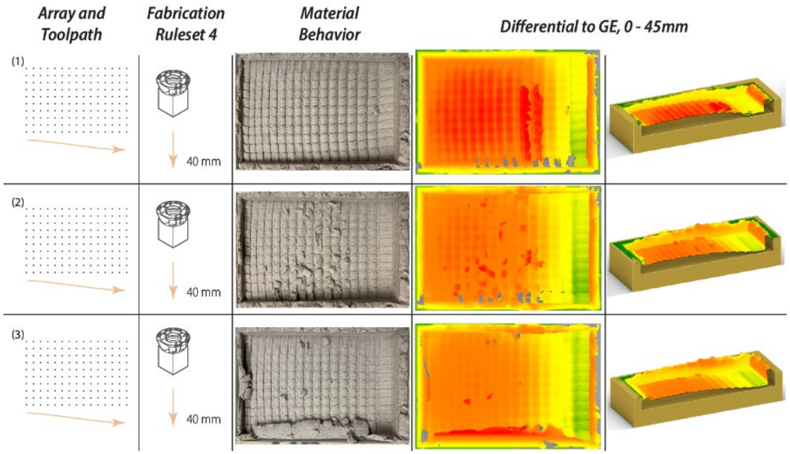

Figure 4
Flat surface packing experiments at 40 mm depth to determine the compressive limits of Kinetic Sand after the first (1), second (2) and third (3) run of the robotic packing tool path.

In the second experiment, the *Kinetic Sand* was packed to a depth of 30 mm below its initial surface (Figure 3). After three consecutive toolpath executions (3), the deviation from the GE was notably greater than in the previous experiment (Figure 2). This suggests that the effective packing limit of *Kinetic Sand* lies at approximately 80% of its original volume, as achieved in the 20 mm compression scenario.

Throughout this experiment, material deformation could be visually observed after each toolpath execution. In some instances, regions that had been previously compacted were gradually disturbed by subsequent packing operations due to the significant material displacement observed at this depth. These behaviors highlight the limitations of the material's compressibility and its tendency to result in unforeseen material displacement under excessive compaction.

When the *Kinetic Sand* is packed to a depth of 40 mm below the initial surface, the material fails to achieve the necessary level of compaction (Figure 4). The difference in measured material deviation between the second and third toolpath executions is minimal, indicating that by the third pass (3), the toolpath primarily causes redistribution of the material rather than further compaction. This suggests that the material has reached its absolute compression limit already, beyond which additional toolpath executions have little to no effect on improving geometric accuracy.

Another toolpath testing involved incrementally packing the *Kinetic Sand* in 10 mm layers, reaching a total depth of 40 mm (Figure 5), akin to stepdown approach typical in CNC toolpath planning. Surprisingly, the scan data revealed that the material deviation at each depth was comparable to the deviation observed when packing directly to that depth in a single operation. This outcome suggests that *Kinetic Sand* does not entirely compress when packed, but rather gets displaced to other areas of the work holder.

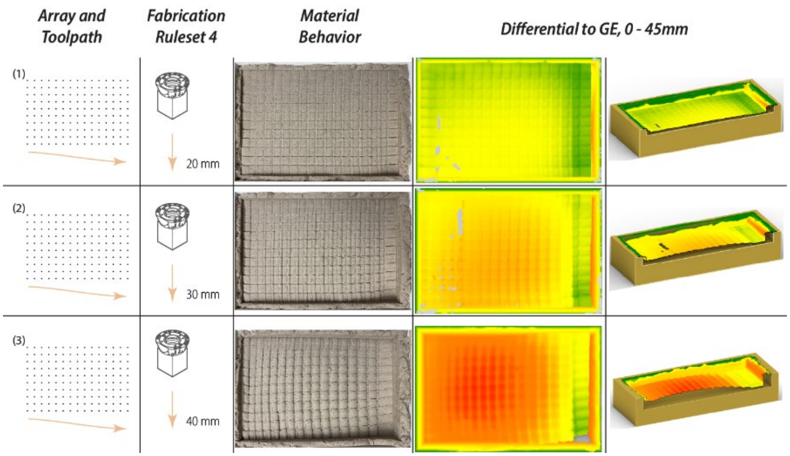

Figure 5
Flat surface packing experiments using incremental packing.

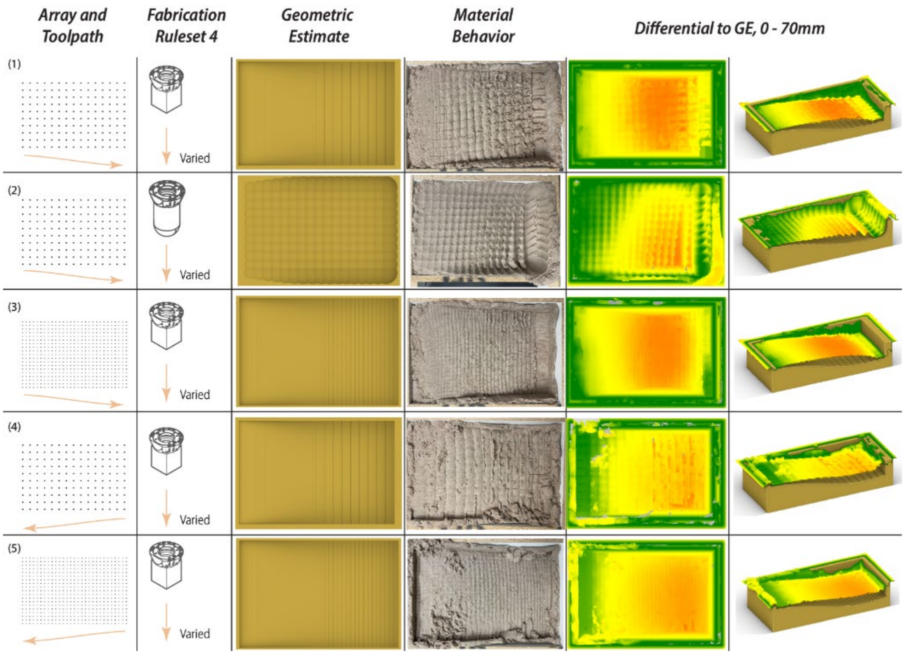

Figure 6
Experimenting with 5 different toolpath strategies to assess geometric accuracy of non-planar packing of *Kinetic Sand*.

Building on the earlier experiments, a series of toolpath generation strategies were tested on non-planar geometries to evaluate their impact on geometric accuracy (Figure 6). Variables included end-effector type, target array density, and the sequencing of target execution. The highest level of accuracy was observed in experiment (2) shown in Figure 6, which utilized a spherical end-effector instead of the cubic tool employed in other tests. Notably, some *Kinetic Sand* was observed spilling from the sides of the work holder during this trial, indicating lateral displacement as a material response. The most effective toolpath configuration identified through this set of experiments includes: using the spherical end-effector for all robot targets; prioritizing the deepest plunge points at the beginning of the toolpath and gradually reducing depth; and orienting each tool engagement perpendicular to the local surface of the non-planar geometry. Furthermore, consistent with earlier findings (Figures 2–5), executing the toolpath three consecutive times significantly improves compression and reduces material deformation.

PROOF-OF-CONCEPT CAST PANELS

To demonstrate the effectiveness of this methodology in producing geometrically accurate, complex panels, a set of four cement panels was cast (Figure 7). Each formwork was designed to approach the material's optimal compression threshold, approximately 80% of its original volume, as determined through earlier experiments. This threshold represents the maximum compression achievable before a noticeable decline in formwork accuracy, thereby maximizing the material performance without compromising geometric fidelity. Although this threshold was slightly exceeded in practice, scan data collected prior to casting confirmed that all formworks remained within the acceptable deviation range of 5 mm (Figure 8).

The resulting panels maintained sufficient geometric accuracy to form a continuous surface when assembled side by side. This proof-of-concept highlights the precision achievable through this approach, especially when toolpath rules are selected to minimize unintended material deformation.

Prior to casting, each panel was evaluated through digital comparison to ensure the corresponding formwork fell within the acceptable accuracy threshold (Figure 8). This step was critical in guaranteeing that the final panels would align seamlessly when assembled, as intended in the overall formwork design. The proof-of-concept panels were developed with progressively increasing geometric complexity. While all panels remained within the target tolerance range, slight material deviations began to emerge, most notably in the final formwork (4).

Assuming the material's compression characteristics remain consistent at larger scales, these findings suggest a relationship between the volume of *Kinetic Sand* available and the maximum achievable design complexity. As complexity increases, so too does the demand for volume and control to maintain geometric fidelity within acceptable limits.

DISCUSSIONS AND CONCLUSION

This paper presents a series of experiments in robotic sand packing and evaluated their geometric accuracy using vision-based 3D scanning. It also shows a proof-of-concept prototype made of four adjacent cement panels cast from robotically packed *Kinetic Sand* formworks.

Figure 7
Four adjacent proof-of-concept concrete panels cast using the robotically packed *Kinetic Sand* formworks.

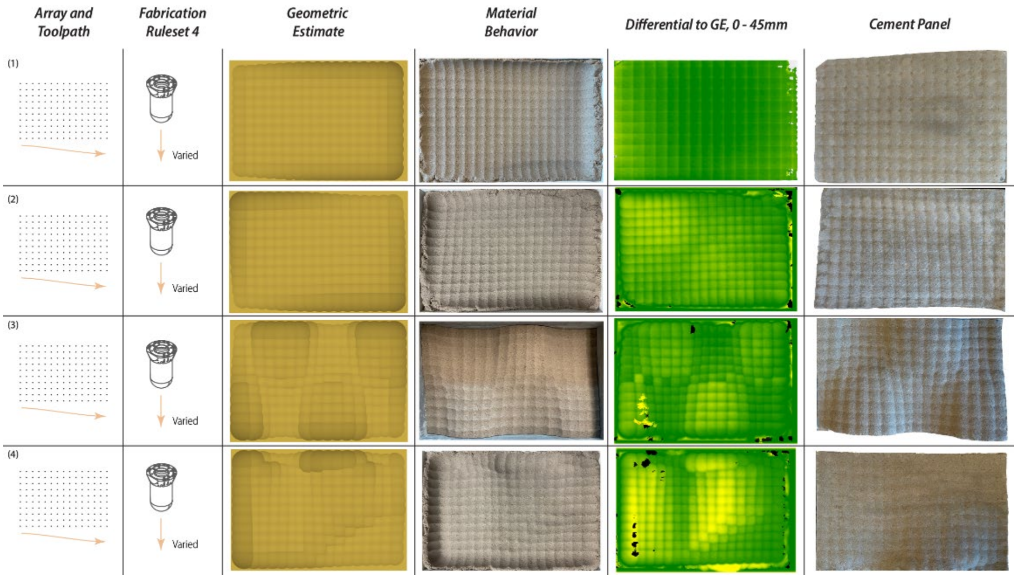

Figure 8
Cast panel formworks maximizing both available compression and accuracy.

The reusable formwork approach presented in this paper carries several geometric implications. The primary determinant of the final form of the cast panels within the work holder was the volume of *Kinetic Sand* available. With a larger volume of *Kinetic Sand*, further geometric complexity can be achieved while still maintaining a desired degree of accuracy. *Kinetic Sand* was found to behave in a semi-liquid fashion, which leads certain robotic packing actions to create specific emergent material behaviors that are retained during the casting process.

Unlike conventional sand formworks, which typically rely on a predefined positive to shape a negative mold, this methodology generates the negative form directly through the repeated packing of a small positive geometry using an end-effector. The toolpath and geometry of the end-effector define the patterns and textures inscribed into the *Kinetic Sand*, resulting in a formwork that is geometrically flexible, materially responsive, and texturally emergent.

In the development of the proof-of-concept panels, the toolpath design for the panels were iteratively refined until the desired level of geometric accuracy was achieved. After each formwork was robotically packed, its accuracy was assessed using vision-based 3D scanning. If the deviation exceeded acceptable tolerances, the toolpath was revised accordingly. The vision-based 3D scanning method used in this study offered a measurement precision of up to 0.5 mm, enabling detailed analysis of geometric deviations and providing effective feedback for refining toolpath generation strategies. Adjustments were made by modifying specific toolpath rules identified as influencing geometric accuracy. This iterative process, guided by vision-based scanning and geometric comparison, directly informed the design of the final proof-of-concept panels.

By applying the most effective toolpath strategies identified through experimental testing, and leveraging the highest accuracy attainable within the vision-based 3D scanning process, material deviation between the geometric estimate and actual material behavior was minimized to less than 5 mm. It is worth noting that the geometric comparisons performed in Rhino 8 involved manual alignment, which may have introduced minor inaccuracies and slightly affected the overall precision of the evaluation. Another limitation of this method is that the GE is constructed within the conditions of ideal material compressibility, and zero material displacement.

Despite its limitations, vision-based 3D scanning proved highly effective in refining the methodology for producing a seamless panelized surface. This feedback gives critical insight to capturing and understanding the material behavior of the *Kinetic Sand*. Once the behavior is understood constraints were developed to ensure the material deformation is within acceptable limits. The proof-of-concept panels presented in this paper successfully joined to form a continuous surface, which is resultant from the constraints applied to the toolpath generation.

This addition to the workflow enabled two key improvements: the identification of toolpath rules that yielded higher geometric accuracy, and the validation of formworks prior to casting. Together, these capabilities significantly enhanced the overall effectiveness of the methodology in producing geometrically coherent, seamlessly joinable cast panels.

Future Works

The vision-based 3D scanning undertaken in this paper could be further refined and expanded to allow for rapid, potentially real-time, feedback. Integrating such a feedback loop into the methodology would open further possibilities in using the *Kinetic Sand* material to its maximum potential. This could also allow the material to be held to a higher accuracy standard while achieving more geometrically complex formworks.

Further developing the generation of the GE by starting to incorporate material behavior would give more effective insights into the analysis of the formwork packing. Utilizing an Iterative Closest Point Algorithm (Zamani et al., 2023) as opposed to a simple subtractive process would help with understanding the material displacement.

In addition, if the vision-based 3D scanning were to be accomplished by the robotic arm, a more automated and hands-free system could be developed. This would allow for the responsiveness to material behaviors to not be over a long-term design process, but to be enabling the designer in real-time as the material behavior is occurring.

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