Digital Marble

Toward a Coherent Framework for Fabrication-Aware Design

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Abstract. *This research investigates the integration of manufacturing constraints into early-stage architectural design to bridge the disconnect between complex geometry and robotic subtractive fabrication. Focusing on marble façade systems, the study introduces a fabrication-aware framework within Grasshopper3D that embeds robotic kinematics, including toolpath continuity, depth modulation, and tool inclination, directly into the generative process. By shifting away from traditional linear CAD/CAM workflows, this approach reposition's machining parameters as primary drivers of formal expression rather than post-design technical constraints. The methodology was validated through the 6-axis robotic fabrication of two marble prototype series. Results indicate that encoding fabrication logic into parametric patterns significantly optimizes machining efficiency, reducing non-cutting motions while enhancing surface quality. Ultimately, this research proposes a design strategy where tool traces are utilized as a legitimate architectural language, aligning machine kinematics with material behavior to offer a precise and efficient paradigm for contemporary digital stereotomy.*
Keywords. *Parametric Design, Robotic Fabrication, Stone Machining, Toolpath Continuity, Fabrication-aware Design.*

INTRODUCTION

In contemporary architectural design, technological advancements have repeatedly reshaped the way buildings are conceived and constructed. The introduction of digital design tools has given architects the freedom to explore and control complex geometries through parametric and computational design environments. Yet this freedom also introduces new challenges such as the alignment between digital design and manufacturing processes. Production constraints, such as segmentation, material weight, dimensional limits, profile optimizations, tool accessibility, can substantially increase construction time and costs in direct proportion to geometric complexity. To address this, manufacturing criteria must be integrated into the earliest phases of design, ensuring that architectural forms are informed by fabrication constraints through a continuous data transfer that creates a seamless and reliable workflow. This research investigates how parametric design methodologies, specifically within the Grasshopper3D environment, can manage controlled variation and real-time feasibility evaluation for marble façade systems that are composed of multiple modular components. Marble is selected because of its architectural relevance and longtime cultural presence in Greece, but also because it is a heterogeneous and challenging material with regards to robotic fabrication. In traditional practice, these concerns are relegated to the final Computer-Aided Manufacturing (CAM) stage, often resulting in inefficient toolpaths characterized by excessive non-cutting motions and prolonged machining durations. The limitation of such workflows is both techincal and design-related. Geometry is often finalized without considering fabrication parameters, leaving tool depth and movement to be resolved later. This research proposes to connect design to construction by establishing a coherent, fabrication-aware framework that embeds robotic movement logic directly into the early-stage parametric design in Grasshopper3D. Adopting a research-by-design approach where formal exploration and production efficiency are optimized simultaneously, this unified workflow incorporates robotic movement constraints, such as toolpath continuity and depth modulation, directly into the generative design process to enable fabrication-aware formal explorations. Validated through the robotic production of two series of marble prototypes, the methodology demonstrates that depth-encoded patterns and continuous contouring significantly reduce machining time and pass counts, ultimately repositioning robotic capabilities as a core driver of the architectural creative process.

PRECEDENTS OF SUBTRACTIVE ROBOTIC FABRICATION

Traditional stone masonry, or stereotomy, has historically been a craft of complex geometric intersections. Natural stone remains a foundational material in architecture (Siegesmund and Snethlage, 2014), however its contemporary use is often limited by the high cost of manual labor and conventional CNC limitations. The shift toward "Digital Stereotomy" has been catalyzed by numerous researchers (Fallacara, 2009; Fallacara and Barberio, 2018; Ye, Gao and Xu, 2023) and studies that explored how variable volume carving and casting can reinterpret classical masonry through digital lenses (Clifford et al., 2014). However, these explorations often prioritize formal output over the kinetic efficiency of the machine itself and the understanding of how fabrication parameters can actively inform the design process. The evolution of digital fabrication has consistently sought to unify geometric intent with machine execution, a trajectory clearly defined by the development of parametric robot control and integrated CAD/CAM systems (Brell-Cokcan and Braumann, 2010; Braumann and Brell-Cokcan, 2011). These early breakthroughs in 7-axis flank milling established the potential for parametric design to directly dictate complex toolpaths (Brell-Cokcan et al., 2009), eventually leading to a philosophy of implementing manufacturing constraints as early design parameters, where toolpath logic is considered at both micro and macro scales (Brell-Cokcan and Braumann, 2014). In the context of stone and solid materials, this synergy is explored through the reinterpretation of historic craftsmanship, such as the Nabatean carving techniques (Busbait, Reinhardt and Globa, 2023, 2024) and the digitally-assisted restoration of heritage sites (Hayes, Fai and White, 2014). Recent frameworks have expanded these capabilities by applying robotic subtractive cutting to natural stone processing (Körükcü, 2023) and exploring the aesthetic value of craftsmanship in materials like terrazzo (Alencar, 2025). This shift toward Fabrication-Aware Design (FAD) moves manufacturing constraints from the end of the pipeline to the beginning of the creative process, as seen in wood plate milling (Schwinn, Krieg and Menges, 2013). However, a significant challenge remains in the optimization of robot movement and the minimization of time wasted during robotic repositioning. While several researchers have addressed robotic marble processing (Yin, Ji and Wang, 2021; Garcia Del Castillo Y Lopez, 2022; Fernando et al., 2024; Zhang et al., 2024), workflows often remain reliant on post-design path planning. The "Robotic Touch" (Gramazio, Kohler and Willmann, 2014) suggests that robotic motion should be a visible architectural expression that is legible in the final output, a strategy that is often echoed in robotic construction research, such as clay sculpting (Tan and Dritsas, 2016) and stone surface production (Steinhagen et al., 2016). As subtractive manufacturing becomes more sophisticated, the field is moving toward adaptive methods, including machine learning for anisotropic materials (Gottschild, Garivani and Nahmad-Vazquez, 2024) and adaptive training for real-time robotic response (Brugnaro and Hanna, 2017). Together, these contributions underscore a growing mandate to move beyond geometry toward a coherent framework where material constraints and machine kinetics are fundamentally embedded in the design process. This research aims to contribute to this discourse by presenting a coherent framework that links parametric design with robotic marble machining, optimizing geometry and robot motion in real-time, ensuring toolpath continuity, minimization of machining time, while driving the generation of designs that are compatible and efficient for the given tools and material.

METHODOLOGY

Geometric, sequential and material-driven

Within the framework of this research toolpaths transcend their traditional role as mere machining instructions, and define geometric trajectories, sequences of the robotic motion and conditions under with the tool engages with material. They determine not only where material is removed, but also how it is removed. Consequently, they influence how the robot moves, how long fabrication takes and how the material is affected during cutting. In subtractive processes of brittle materials, toolpaths directly impact the quality of the finished surfaces and stability of robotic motion. When toolpaths include discontinuities, frequent retractions and rapid movement, non-cutting time increases. In contrast, continuous toolpaths support smoother motion and more stable cutting conditions. Additionally, parameters such as depth of cut and overlap between passes heavily influence how material is removed and how surface quality is achieved. Therefore, toolpaths operate at the intersection of geometry, motion and material behavior. Within the context of this research, toolpaths are viewed as essential design elements rather than just post-processing processes (McGee, Feringa and Søndergaard, 2013). This approach allows for the exploration of parametric strategies in which geometry and robotic movement parameters are simultaneously designed in order to support efficient subtractive processes. The logic was implemented through an algorithmic workflow. Geometry was generated through curves, which guided both material simulation and toolpath creation with adjustable parameters such as depth, pass grouping, feed rate and orientation. As a result, changes in design simultaneously informed fabrication behavior (Figure 1).

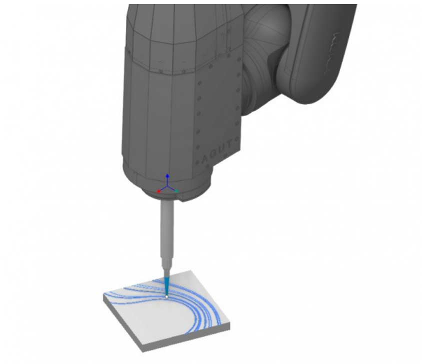


Figure 1
Simulation of the robotic toolpaths with conical tool

Patterns, depth modulation and toolpaths

Parametric patterning provides a framework through which geometric logic can be directly translated into toolpath behavior in robotic subtractive fabrication. Rather than serving purely

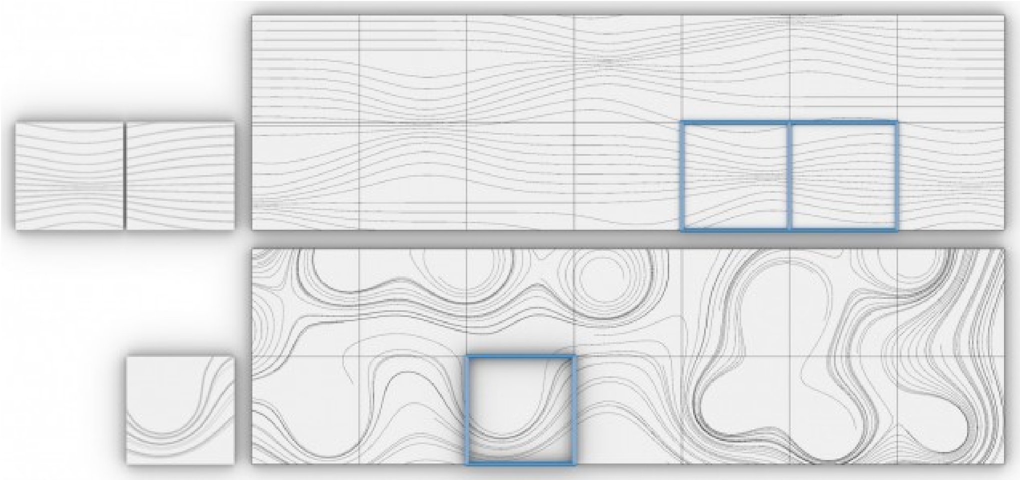
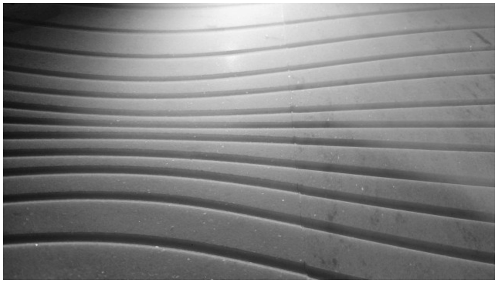


Figure 2
Algorithmically defined patterns of the first series of prototypes. Pattern A: Distorted Grid, Pattern B: Force Field

as surface ornamentation, patterns such as grids, tessellations and field-driven geometries can be considered as systems that organize directionality, continuity and variation in robotic motion. The generated patterns were non-standard linear systems through which algorithmic variation, toolpath continuity and fabrication constraints could be tested together. In subtractive fabrication, depth of cut is traditionally treated as fixed machining constraint, defined primarily by material properties, tool limitations and safety considerations. Within robotic subtractive processes, however, depth can be reconsidered as a design parameter that actively contributes to surface formation, material engagement and fabrication efficiency. Variable depth strategies allow material removal to be distributed unevenly across a surface, enabling differentiated carving with a reduced number of passes, instead of repetitive toolpaths with constant step-downs. This approach is relevant in robotic fabrication, where excessive pass counts increase machining time and introduce unnecessary motion. This way, depth variation becomes a mechanism for coordinating surface articulation, motion continuity and fabrication constraints, allowing differentiated carving to be achieved through fewer and more efficient toolpaths. The design and selection of the patterns was an important step for this research and needed to be aligned with the specific problem being addressed. Parametric patterns based on contour or rail-like curves are especially appropriate for this purpose because they are relatively easy to design and parametrically modify and are compatible with single-pass carving operations. These types of geometry align closely with subtractive carving logic. They can accommodate differentiated depth values and allow continuous tool movement along the carving paths. They also provide a testing ground for evaluating how design parameters affect fabrication time, surface quality and visual expression. After researching, assessing and experimenting with several algorithmic patterns, two families of prototypes where developed in order to test aspects of depth, precision, time, optimization of passes, tool types (conical, cylindrical), tool inclination and engagement strategies (tool movement tangents).

Figure 3
Two consecutive marble tiles of Pattern A placed together so that the seam is invisible



MARBLE PROTOTYPES

The robotically fabricated marble prototypes serve to evaluate the workflow as well as the end result. They are treated as iterative design studies that allow machining behavior, surface quality and pattern logic to be assessed together. The knowledge gained from each prototype, successful or not, is implemented in subsequent designs and pattern definitions, therefore increasing the complexity of patterns and fabrication strategy.

First series of prototypes: Validation and stabilization of machining strategy

The first series of prototypes was developed as an initial validation of the workflow and addressed patterns to be produced with a conical tool profile. The goal was to test the reliability and behavior of the toolpaths on stone and establish a stable cutting strategy before moving to more complex designs. The first pattern (Figure 2) comprises of a distorted grid created with Pinch n Spread component of Pufferfish plugin. Although the pattern itself is largely flat, the dynamic density of the curves created the visual impression of three-dimensional surface. A set of parameters controlled characteristics such as density, pinch location, falloff and number of curves. This pattern was selected because of its relative simplicity and continuous curves that made it an appropriate starting point for testing the workflow and producing physical samples. The strategy relied on single-pass movements with vertical lead in and out motions at reduced feed. Some of the initial test tiles were fractured along the edges of the stock, demonstrating the importance of entry and exit conditions for preventing chipping. To address this issue, the strategy was revised. The feed was reduced, the toolpath was extended and tangent lead in and lead out movements were added. The results of these decisions were the elimination of chipping, a more stable milling process and a significant improvement in the precision of geometry and surface quality. The sequence so far shows how fabrication feedback was transferred back into the toolpath definition, resulting in better surface quality. As seen in Figure 3 the seam between two tiles is almost invisible.

The second pattern (Figure 2) was generated

Figure 4
Robotic fabrication of a marble tile from Pattern B

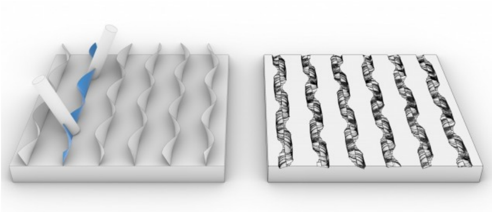


Figure 5
Pattern of parallel lines with sequential tool inclination to produce carvings of variable thickness and depth

Figure 6
Pattern of parallel circles with sequential tool inclination to produce carvings of variable thickness and depth

through force fields, producing a more turbulent and less uniform geometry. In this case, pattern density varied significantly and in some areas the curves overlapped. The depth of the curves was also adjusted parametrically and linked to the same field logic that informed their curvature. Compared to the first pattern, this design adds a higher layer of complexity since the stronger depth differences required a more sophisticated fabrication strategy. For the handling of deeper carving regions, the curves were grouped based on their local Z positions and a second or third passe was applied only on selected rail curves. With this approach, the cutting load was distributed more gradually across the carving process. The resulting prototypes (Figure 4) showed high surface quality in both shallow and deeper areas of the pattern and confirmed that depth-based grouping could support more demanding carving conditions, without adding significant cutting time, as the additional passes are generated parametrically only for the curves that need extra depth. While these two patterns served as a starting point to test the design-to-production workflow, the robot movements are comparable to 3-axis logic and therefore the constructed prototypes were relatively predictable. The most novel aspect here is the dynamic velocity of the tool and the grouping of the curves by depth to conduct multiple but limited passes on selected curves.

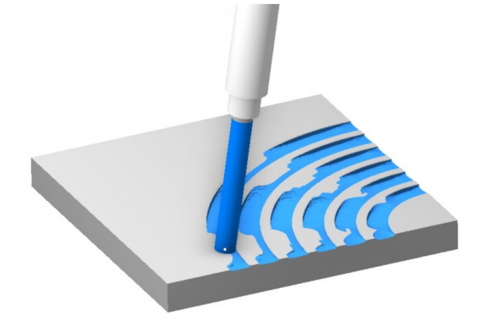


Figure 7
Simulation of the robotic milling of the circular pattern with variable tilted movements of the cylindrical tool

Second series of prototypes: Fabrication of inclination-based patterns

Based on the knowledge gained from the first prototype series, a second set of designs was developed to investigate a different group of fabrication-related parameters. The aim was to explore the kinematic possibilities of a 6-axis robot and to investigate how the variable tool inclinations could produce tool-related textures, variable carving widths and shadow effects on the stone surface. In contrast to the first pattern series, the results in this case were less predictable. There is an emergent behavior that occurs as a negotiation between tool geometry, movement, material, velocity and inclination. In this case, the final traces on the stone were not defined solely by the input geometry but also by the fabrication conditions themselves. For this series, a cylindrical tool of much larger diameter was selected. The resulting effect (Figure 5) was the creation of stripes with variable thickness and depth which generated interesting shadow effects when illuminated from specific angles. The first pattern in this group consisted of straight and parallel lines while the inclination of the tool varied dynamically within a parametrically defined range. By altering the inclination, the contact area

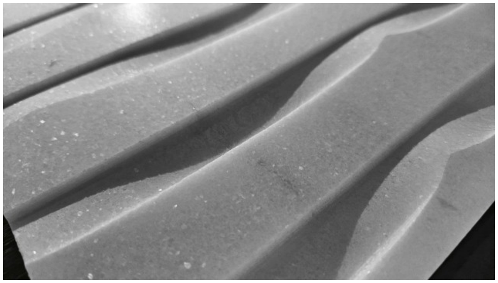


Figure 8
Detail of the marble tile prototype with parallel lines and sequential inclination of the milling tool

between tool and stone was adjusted and produced variable traces in a single continuous movement.

Using the same logic, another pattern was created based on a circular motif. This introduced another level of complexity, since the frequency of the tool titling is variable (Figures 6 & 7). Smaller circles produced higher tilt frequency than larger ones, allowing the relationship between curvature and tool inclination to be tested. Both patterns were designed as modular systems, displaying edge continuity, while the second pattern also allowed repeated arrangements that could form either circular or S-shaped compositions. Careful initial tool calibration at the beginning of the process together with the knowledge gained from the previous prototypes, all contributed to the reliability of the result. Therefore, this second series of prototypes acted as a validation of the inclination-based contouring and more directly exploited the additional axes of the robotic setup. Together with multi-pass strategy based on axis offsets, it produced high-quality results (Figure 8) and demonstrated how tool inclination could function as a parameter in the design of the carved surfaces, and increase the complexity of the end result without increasing machining time and cost.

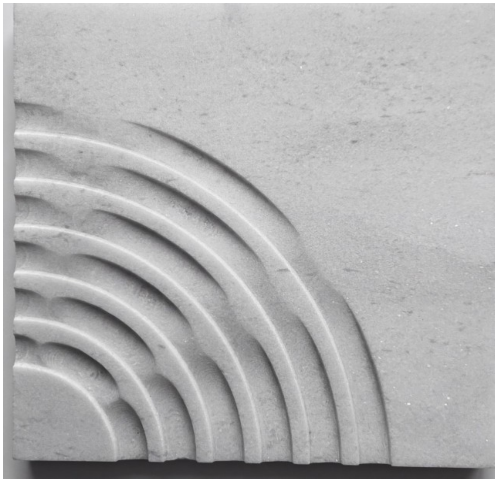


Figure 9
Robotically fabricated marble tile of the circular pattern

CONCLUSIONS

The Digital Marble framework presented in this research demonstrates that the integration of robotic constraints into early-stage parametric design is not merely a technical optimization, but a transformative generative strategy, through which geometry, tool movement and material behavior can be considered together. By internalizing toolpath logic, like continuity, depth modulation, and tool inclination, directly within the Grasshopper3D environment, this study successfully bridges the persistent gap between complex geometric intent and subtractive fabrication reality, exploiting the possibilities of a 6-axis robot. The aim was to achieve geometrically differentiated and fabrication-aware surface patterns without lengthy machining processes which usually comprise of the time-consuming stages of roughing, contouring, profiling. The goal of this research was to generate interesting results with primordially single-pass strategies, and minimize non-cutting robot movements. Embedding the fabrication logic in the design, the proposed framework is transitioning from a linear model of independent processes where design precedes fabrication, to a circular, fabrication-aware methodology ensuring that the kinetic capabilities of the 6-axis robot and the inherent material properties of marble are treated as primary drivers of the creative process rather than secondary technical hurdles.

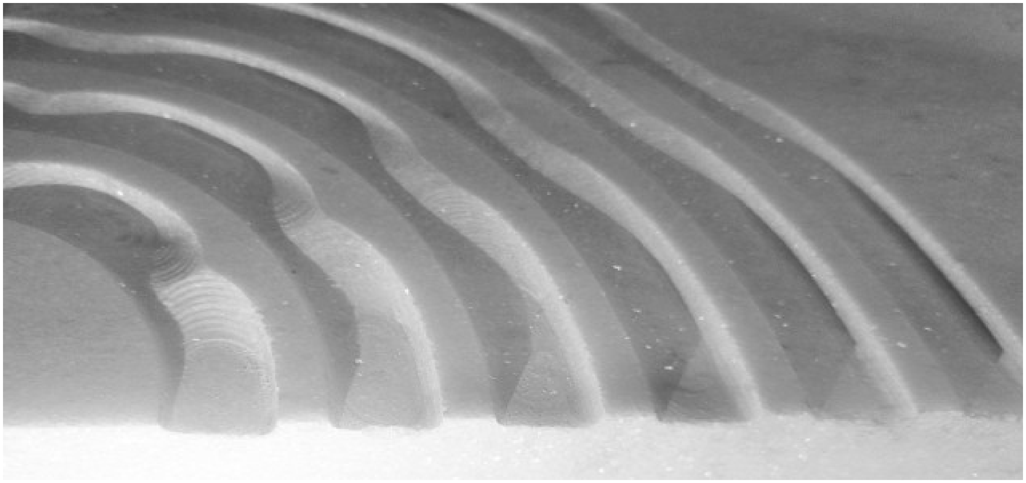


Figure 10
Detail of the robotically fabricated marble tile prototype with the circular pattern and sequential inclination of the milling tool. The traces of the tool are visible on the texturing of the surface.

The validation through two distinct prototype series confirms the efficacy of this integrated approach. The first series demonstrated that encoding depth and pass counts into design variables significantly reduces unnecessary non-cutting motions, while the implementation of tangent lead-in and lead-out strategies effectively mitigated the brittle behavior of marble, ensuring high-precision surface quality without edge-chipping. The second series pushed the framework even further, revealing that the dynamic tilting of large-diameter tools can produce emergent aesthetic effects, such as variable gradients of texture and shadow, that are fundamentally tied to the machine's motion profile (Figures 9 & 10). These results suggest a new digital vernacular where the "Robotic Touch" becomes an architectural expression in its own right, reclaiming the historical craft of stereotomy through contemporary robotic technologies.

However, challenges remain in scaling these geometries to non-planar or irregular stock volumes, where material heterogeneity may require more responsive workflows. Future research will explore the implementation of real-time adaptive feedback loops, utilizing sensors to adjust feed rates and tool inclinations dynamically in response to material density or tool wear. Furthermore, the expansion of this logic into more sophisticated subtractive processes could allow for a more nuanced application of the framework across various stone types and structural requirements. Ultimately, this research posits that the future of digital masonry lies in the seamless synthesis of geometry, motion, and material. By treating the toolpath as a fundamental design element, the architect can ensure that the precision of the industrial robot and the structural characteristics of natural stone remain inextricably linked, paving the way for a more coherent and efficient paradigm in fabrication-aware design.

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