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CONTEXTUALISING ACOUSTICS: Prototyping Conceptual Boundaries in Acoustic Design

Misri Patel[1], Dishant Patel[2]

[1]*School of Architecture, Georgia Institute of Technology, USA*
[2]*New Bedford Research and Robotics, Massachusetts, USA*

Abstract

Within architecture's inherently multisensory framework, contemporary acoustic design often remains secondary, addressed through applied absorptive treatments rather than embedded spatial strategies. Despite advances in computational tools, most built environments still rely on standardized reflective materials like concrete, glass, plywood, resulting in a limited, binary understanding of acoustic performance. This research challenges that paradigm by positioning acoustics as an integral design driver and exploring material behavior as a continuous spectrum rather than fixed categories.

The study investigates how emerging design and fabrication technologies can recalibrate architectural thinking, enabling acoustics to inform form, materiality, and spatial experience from the outset. It focuses on materially consistent yet geometrically varied surfaces, leveraging additive manufacturing to encode acoustic performance directly into form. Through controlled variation, a single base material is designed to exhibit a range of sonic behaviors, including reflection, diffusion, and absorption.

A catalogue of twenty-five prototypes was developed, from which four specimens of equal weight but distinct formal characteristics were selected for testing. Acoustic performance was evaluated using ASTM E1050-12 impedance tube measurements. Results demonstrate significant variation in absorption coefficients across the samples, confirming the presence of an embedded acoustic gradient. The findings situate these prototypes within an intermediate performance range, between highly reflective glass and absorptive fiberglass, an area that remains underexplored in architectural acoustics.

By integrating digital fabrication with acoustic performance, the research proposes a shift toward embedded, context specific sonic environments. It extends the provocations: How might designers and acousticians extend the acoustic continuum between material and materiality architecturally?

Keywords: *additive manufacturing, performance-based design, material, computation*

1. Introduction

While architecture is inherently defined by its pragmatic and spatial configurations, the discipline articulates a designer's perspective through a formal language that transcends the purely visual. Christopher Alexander (1979) posits that *"the life that happens in a building or a town is not merely anchored in the space but made up of the space itself,* framing architectural environments as active agents in the curation of human experience. Within this framework, acoustics emerge as a fundamental spatial component, generated through the intersection of direct sonic energy and the subsequent reflections of a site's material boundaries (Blesser and Salter, 2007).

In this framework, architectural acoustics, the study of sonic behavior within constructed environments draws upon legacies from antiquity, though its empirical rigor was formalized in the nineteenth century (Long, 2005). Following the seminal work of Wallace Clement Sabine, the field experienced a profound scientific and technological evolution. Concurrently, the nineteenth and twentieth centuries witnessed a tectonic shift in architectural praxis, moving from ornamental complexity toward a minimalist aesthetic. This transition was further catalyzed by industrial manufacturing, which favored the production of standardized, planar materials. The shift from hand-applied plaster to machine-fabricated gypsum board, for instance, yielded surfaces of extreme flatness,

Corresponding author: misri.3103@gmail.com.

effectively purging the subtle geometric irregularities once inherent in craftsmanship. While often visually negligible, such *nuanced surface variations* were instrumental in fostering the diffuse scattering of sound.

As the discipline prioritized the reduction of ornamentation and formal complexity, built environments became dominated by expansive, smooth surfaces that catalyzed specular reflections and extended reverberation periods. Remediation of these sonic repercussions necessitated the introduction of specialized absorptive materials. Consequently, acoustic performance was increasingly relegated to the application of secondary products, such as acoustic panels, rather than being conceptualized as an *inherent spatial or material property* of the architecture (Belanger, 2021).

Acoustic performance is determined not only by material composition but also by geometry and surface morphology. Materials such as glass illustrate this relationship: flat panes predominantly reflect sound, whereas fibrous glass provides effective absorption despite sharing the same chemical composition. This suggests that acoustic behavior exists along a geometric continuum rather than within fixed material categories (Belanger, 2021; Newell et al., 2022). Advances in computational design and digital fabrication have further enabled the exploration of such geometrically informed acoustic surfaces, creating new opportunities for performance-driven and interdisciplinary architectural design (Hensel and Menges, 2008).

Given the scale of these impacts, *Contextualizing Acoustics* explores several unresolved questions in this emerging field of performance-based design research, which is still in its early stages of development. By refining the relationship among the spatial conditions, material systems and advanced manufacturing processes, the research aims to expand the notion of the architectural design process and allied disciplines, enabling designers to craft spaces with more nuanced aural qualities. This research focuses on thermoplastic extrusion for the fabrication of multiscale prototypes. These prototypes show the potential of curating performance through material efficacy (Yang and Choi, 2015; Aghaei Meibodi et al. 2022). The methodology allows for evaluation through digital modeling and fabrication, combining effective performance criteria with material and shape considerations.

By integrating acoustic principles with emerging fabrication and evaluation methodologies, the research expands the potential for performance-driven material design. Rather than relying on alterations in material composition, it demonstrates that acoustic behavior can be strategically modulated through the geometric organization of a material system (Patel and Patel, 2026). The work reveals that variations in additive-manufacturing toolpaths, deposition densities, embedded air cavities, and surface textures can generate distinct acoustic responses—including reflection, diffusion, and absorption—within a single material framework. This approach provides architects with foundational knowledge for the iterative development of acoustically informed design strategies while also creating new opportunities to investigate the subjective, nuanced, and culturally diverse dimensions of auditory experience that remain underexplored in contemporary architectural practice.

2. Methodology

Conventional 3D printing workflows are predominantly driven by slicer software, which relies on digital models or their computational doppelgangers, to automatically generate extruder toolpaths and define material deposition (Figure 1). While this model-based approach has proven highly effective for rapid prototyping and geometric replication, it largely treats material as a passive medium whose primary role is to reproduce predefined form. By contrast, variable computational material deposition offers an opportunity to reconsider material not merely as a vehicle for geometry but as an active design parameter, opening alternative conceptions of material and materiality through the controlled manipulation of deposition behavior. To explore this potential, a custom computational workflow was developed to fabricate a series of 3D-printed samples with distinct material textures.

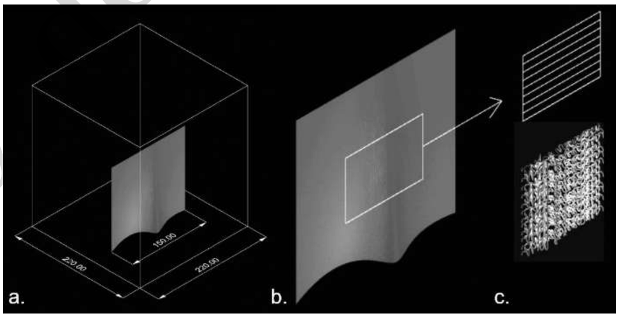

Figure 1. Axonometric view of a: desktop 3D printer, b: conventional layer-based slicing process and c: material extrusion.

Departing from conventional slicer-generated toolpaths, the proposed workflow employed a customized *Silkworm* script, a *Grasshopper* plug-in for *Rhino 8* to directly translate 3D point data into G-code for additive manufacturing. Rather than relying on automated slicing algorithms, the custom G-code explicitly controlled both printer motion and extrusion parameters, enabling precise manipulation of deposition patterns and material behavior (Figure 2). Fabrication was carried out using a Creality Ender 3 V3 SE desktop fused filament fabrication (FFF) printer with a constant bed temperature of 60°C and a nozzle temperature of 210°C throughout all experiments. Prior to printing, the filament was dried for four hours at 60°C using a VisMec Dryplus 50 dryer to minimize moisture absorption and ensure consistent print quality.

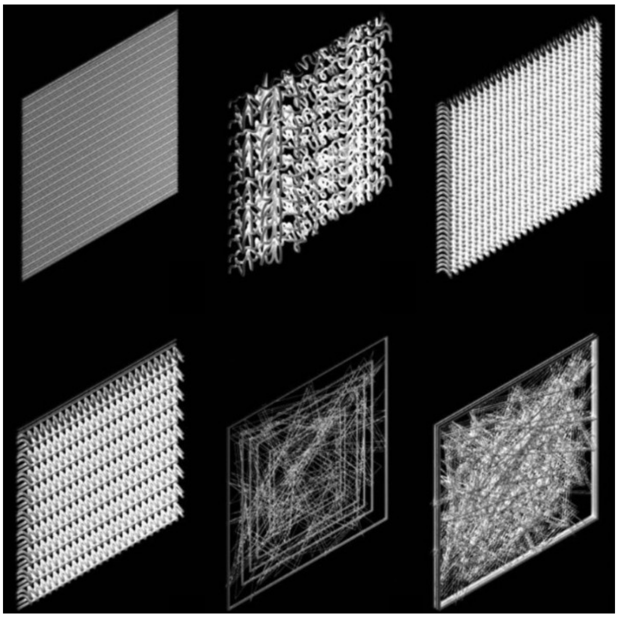

Figure 2. Simulation view of 3D-printed toolpath generating using custom computational workflow to achieve varied surface texture.

The following section presents the experimental methodology employed to design and fabricate twenty-five unique material specimens to investigate the relationship between digital design parameters, fabrication processes, and resulting material characteristics

2.1 Prototyping Material

A series of fabrication parameters including nozzle diameter, print speed, extrusion variables, and layer height were evaluated to achieve varying material textures (Figure 3).

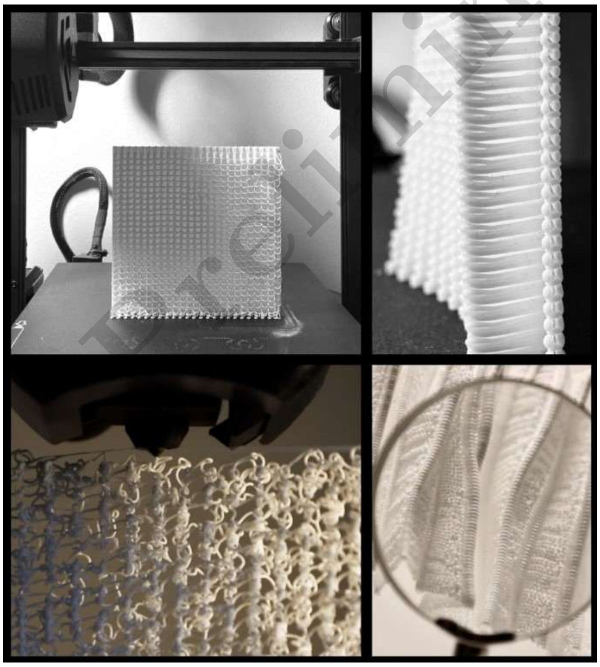

Figure 3. Preliminary 3D-printed prototypes showing variation in density and surface geometry.

All twenty-five specimens were fabricated using opaque polylactic acid (PLA) filament, a thermoplastic commonly employed in rapid prototyping applications. Figure 4 presents the designed prototypes, which encompass a broad range of surface areas and air-cavity configurations (Y-axis), and material densities (X-axis).

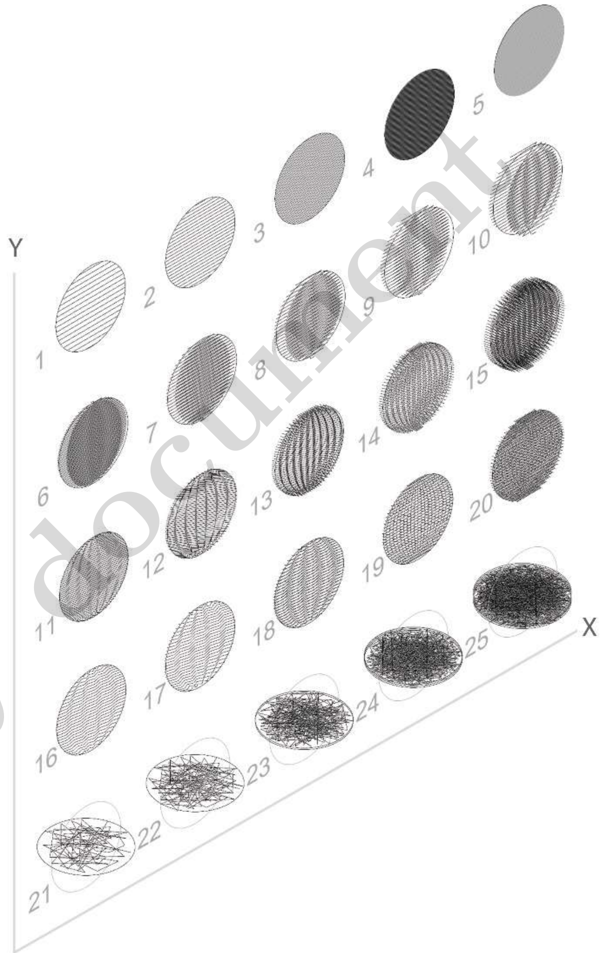

Figure 4. Designed prototypes capturing a spectrum of surface area, air cavity, and material density.

Samples 1–5 were fabricated using a 0.4 mm nozzle diameter and a uniform layer height of 0.4 mm. This deposition strategy produced fine, controlled material deposition with relatively smooth surface textures and high geometric precision. Samples 6–10 were fabricated using a 0.8 mm nozzle diameter and an increased layer height of 1.8 mm to investigate the influence of thicker material deposition on overall sample texture. This deposition strategy produced coarser surface textures with greater material accumulation and more pronounced layer definition. Samples 11–15 were fabricated using a 0.4 mm nozzle diameter and an increased print speed to promote filament stretching during deposition. This deposition strategy produced delicate fibrous textures composed of fine strands with increased surface porosity. Samples 16–20 were fabricated using a 0.6 mm nozzle diameter and an increased print speed to increase material throughput while maintaining filament stretching. This deposition strategy produced thicker fibrous textures with more pronounced strand formation and enhanced material connectivity. Samples 21–25 were fabricated using a 0.8 mm nozzle diameter and an increased print speed to maximize material flow and filament bridging. This deposition strategy produced voluminous textures with larger interconnected air cavities, yielding highly porous geometries that emphasized material accumulation and void formation rather than surface definition. The finalized fabrication parameters adopted for all specimens are summarized in Table 1.

Table 1. Fabrication settings of each prototype.

	Nozzle (mm)	Layer Height (mm)	Speed (mm/s)	Extrusion (%)
S1	0.4	0.4	150	80
S2	0.4	0.4	175	85
S3	0.4	0.4	200	90
S4	0.4	0.4	225	95
S5	0.4	0.4	250	100
S6	0.8	1.8	200	100
S7	0.8	1.8	200	105
S8	0.8	1.8	200	110
S9	0.8	1.8	200	1115
S10	0.8	1.8	200	100
S11	0.4	2.0	200	100
S12	0.4	2.0	225	100
S13	0.4	2.5	250	100
S14	0.4	2.5	275	100
S15	0.4	3.0	300	100
S16	0.6	2	150	110
S17	0.6	2	150	115
S18	0.6	2	150	120
S19	0.6	2	150	125
S20	0.6	2	150	130
S21	0.8	3	160	135
S22	0.8	3	170	135
S23	0.8	3	180	135
S24	0.8	3	190	135
S25	0.8	3	200	135

2.2 Curating Material

While the twenty-five prototypes demonstrate a broad range of material textures achievable through variable computational material deposition, they represent only a fraction of an effectively infinite design parameters. To enable a systematic evaluation of the relationship between fabrication parameters and material morphology, five samples exhibiting distinctly different geometric and textural characteristics were selected for further analysis. These samples were reformatted to facilitate an objective comparison of surface area and volumetric properties. Additionally, three samples with comparable weights were selected for subsequent acoustic laboratory testing to isolate the influence of material texture on acoustic performance. The material characteristics of the selected samples are highlighted in Figure 5 and Table 2.

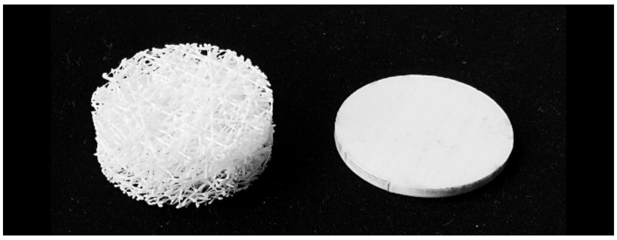

Figure 5. Distant view of selected samples A and B.

Table 2. Material characteristics of selected samples.

	Sample A (S25)	Sample B(S3)	Sample C (S13)
Weight (g)	18	18	18
Depth (mm)	10	2	15
Volume (m3)	6424.2	1284.8	3515.5
Density (kg/m3)	229	700	350

2.3 Measuring Material

Owing to the large specimen dimensions and substantial time and resource requirements associated with reverberation room testing for industry-standard metrics such as the Noise Reduction Coefficient (NRC), normal-incidence impedance tube measurements were adopted to enable rapid and repeatable evaluation of a large number of prototype materials. This approach is particularly well suited to the fabrication constraints of desktop additive manufacturing, allowing efficient characterization of numerous design iterations while requiring only small test specimens. The acoustic performance of the selected samples was evaluated using normal-incidence sound absorption in accordance with ASTM E1050-12, the standard test method for determining the acoustic impedance and absorption characteristics of materials using an impedance tube. A representative experimental setup is shown in Figure 6.

Figure 6. Selected samples A & B at Riverbank Testing Laboratories, Illinois.

Measurements were conducted over a frequency range of 80 Hz to 6.3 kHz, encompassing and extending beyond the standard architectural octave bands (125–5000 Hz). To achieve this frequency coverage, two impedance tubes were employed: a 100 mm diameter tube for low- to mid-frequency measurements (80 Hz–1.6 kHz) and a 29 mm diameter tube for mid- to high-frequency measurements (500 Hz–6.3 kHz). The overlapping measurement range ensured continuous and reliable characterization across the audible frequency spectrum. All samples were fabricated with an identical footprint and structural configuration to ensure consistent testing conditions.

3. Acoustic Test Results

The results of the standardized sound absorption measurements are presented in Figure 7, with the absorption coefficient plotted against the one-third-octave band center frequency. The red curve corresponds to Sample A (S25), representing a flat, densely deposited material, while the blue curve corresponds to Sample B (S3), representing a flat specimen with a fibrous deposition texture and Sample C (S13) represents a deeper thick dense texture.

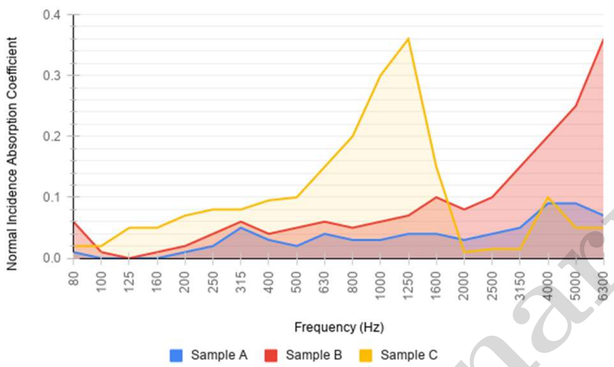

Figure 7. Comparative study of Sample A, B, and C highlighting their distinct absorptive characteristics.

Sample A exhibits consistently low sound absorption across the measured frequency range, with only a modest increase at higher frequencies above 3.15 kHz. The relatively flat response indicates limited interaction between the incident acoustic waves and the material morphology, resulting in minimal energy dissipation. Similar to highly reflective and ubiquitous plate-glass in contemporary architectural design, Sample A establishes a benchmark against which the influence of modified material deposition strategies can be evaluated. In contrast, Sample B demonstrates a pronounced increase in sound absorption across the majority of the measured frequency bands, reaching its highest performance at 6.3 kHz. This enhanced high-frequency response confirms the effectiveness of the modified deposition strategy in improving acoustic performance relative to the baseline design. Notably, this improvement was achieved without increasing the overall material volume, indicating that computationally controlled surface morphology alone can significantly influence acoustic absorption. Sample C exhibits a distinctly frequency-selective absorption response, characterized by a substantial peak between approximately 800 Hz and 1.25 kHz, where the normal-incidence absorption coefficient reaches approximately 0.35 before rapidly declining at higher frequencies. This localized enhancement suggests that the internal geometry and air-cavity configuration can be engineered to target specific frequency bands rather than maximizing broadband performance. Notably, this improvement was realized without increasing the overall material volume, indicating that computationally controlled surface texture alone can significantly influence acoustic absorption. Although the measured absorption coefficients are considerably lower than those of commercially available high-performance acoustic absorbers, which commonly exhibit normal-incidence absorption coefficients approaching 0.95–0.99 over their design frequency range, the present results demonstrate a promising proof of concept.

4. Conclusion and Future Work

The *Contextualising Acoustics* methodology demonstrates how computational control of material deposition transforms fabrication from a process of geometric reproduction into a means of orchestrating material performance. By spatially coordinating toolpaths, material behavior, and deposition patterns to incorporate controlled interstitial air cavities, the proposed workflow embeds acoustic efficacy directly within the material system rather than relying on material substitution.

The measured results show that acoustic performance can be significantly influenced through geometric and morphological manipulation alone. By varying deposition density, filament organization, and porosity while maintaining comparable material volumes, the prototypes exhibited a spectrum of acoustic responses, illustrating that fabrication parameters can become active design variables. Rather than producing discrete material categories, this approach enables the design of continuous acoustic gradients.

Beyond its acoustic implications, this research positions materiality as an emergent property of fabrication. The ability to intentionally modulate texture, porosity, and internal voids expands the expressive and performative potential of additive manufacturing, demonstrating that visual articulation and functional performance can be developed simultaneously rather than treated as separate design objectives. The integration of controlled air cavities further suggests opportunities for tuning acoustic absorption through localized geometric variation, providing a foundation for adaptive and context-specific material systems.

Collectively, these findings challenge conventional understandings of architectural materials as passive substrates with fixed properties. Instead, they suggest that materials such as 3D-printed concrete, ceramics, polymers, and glass can be reconceived as intrinsically acoustic systems whose performance emerges from the interplay of geometry, porosity, and computational fabrication. In this sense, acoustic behavior becomes not an applied characteristic, but a designed consequence of how material is orchestrated.

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