

From Error to Resolution: Gradient Printing through Extrusion Modulation

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Abstract. Extrusion-based 3D printing has become a central tool in architectural fabrication, yet it remains constrained by the assumption that irregularities such as under-extrusion, stringing, or banding are failures to be eliminated. This paper challenges that assumption by repositioning these deviations not as flaws but as manifestations of material-driven resolution, a second form of precision that extends beyond what hardware specifications alone prescribe. The research asks how extrusion "errors" can be instrumentalised as design parameters to generate controlled material gradients and new forms of expressivity on standard Fused Filament Fabrication (FFF) systems. Through systematic modulation of extrusion rate, print speed, and layer height, the study induces transitions in translucency, texture, and density across 1D, 2D, and 3D gradient prototypes. Results demonstrate that reproducible gradient effects can be achieved without specialized equipment, reframing fabrication error as a productive condition. By transforming inconsistency into a controllable design driver, the study contributes both a low-cost workflow and a theoretical model for resolution as a negotiation between computational control and material behaviour.

Keywords. Additive Manufacturing, Printing Error, Printing Resolution, Gradient Printing, Material Agency

1. Introduction

Additive manufacturing has gained considerable attention in architectural and design research, enabling new approaches to form, materiality, and fabrication (Kolarevic, 2004; Menges, 2012). Among various additive techniques, Fused Filament Fabrication (FFF) stands out for its accessibility and adaptability, allowing designers to experiment with material deposition using inexpensive, desktop-scale equipment. Yet despite this openness, FFF research and practice remain largely defined by a culture of precision and error elimination. Printing irregularities such as under-extrusion, over-extrusion, stringing, or banding are typically interpreted as failures, conditions to be corrected through calibration, manual troubleshooting, or algorithmic optimisation (Erokhin et al., 2023; Brion and Pattinson, 2022).

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Within the wider additive manufacturing literature, resolution has historically been treated as a function of slicing discretisation and layer thickness, with techniques such as adaptive slicing proposed to balance geometric accuracy, staircase effects, and build time (Dolenc and Mäkelä, 1994). While such treatments often approach variability as a deviation to be mitigated, architectural design practices have increasingly embraced variation, imperfection, and processual expression as creative tools (Picon, 2010; Hensel and Menges, 2006). This research builds on that sensibility, proposing that extrusion errors need not be treated as flaws but can serve as productive, repeatable design parameters.

Recent advances in gradient printing have achieved multifunctional structures through methods such as diameter-adjustable filaments (Qu et al., 2024) and synchronized multi-material deposition (Propst and Mueller, 2025). However, these approaches often depend on laboratory-grade or custom-built hardware. At the same time, research in computational fabrication has emphasized adaptive forms of making in which material behaviour and computational control continuously inform one another (Kannenbergh et al., 2024; Lu et al., 2025).

Within this broader context, error can be reinterpreted as a site of negotiation where material behaviour asserts itself against computational prescription. This view resonates with Schön's reflective practice (1983) and aligns with studies that reframe deformation and irregularity as sources of aesthetic or structural value (Kwon et al., 2025; Ahlquist and Menges, 2011). This paper extends those discussions into a more accessible domain by examining how the physical irregularities of single-material extrusion can act as embedded computation that encodes gradients of resolution. Specifically, It explores how low-cost FFF systems can generate material gradients through controlled parameter modulation, and how these gradients produce an alternate form of resolution defined not by hardware specification, but by material responsiveness. The study proposes that by recognizing and calibrating these conditions, designers can gain access to a new design vocabulary that values deviation as a source of resolution. The following sections review related work, introduce the experimental methods, and evaluate the potential of extrusion irregularities as design parameters.

2. Related Work

2.1. PRINTING DEFECTS AND ERROR CORRECTION IN FFF

Research on FFF has largely prioritized geometric accuracy and surface quality, focusing on identifying and correcting extrusion-related defects. Erokhin et al. (2023) catalogue issues such as layer gaps, stringing, and inconsistent deposition, proposing corrective strategies to enhance dimensional precision. Brion and Pattinson (2022) extend this effort using neural networks for real-time error detection and correction.

These approaches reflect a paradigm where deviation is synonymous with failure. At the process-planning level, the same orientation is visible in slicing strategies that regulate layer thickness to minimize staircase artefacts and meet geometric tolerances (Dolenc and Mäkelä, 1994). However, alternative studies have shown that such deviations can also serve creative or functional goals. Holzmond and Li (2017)

developed an in situ detection system for quality assurance, and Takahashi and Miyashita (2017) intentionally varied print height and extrusion rate to produce decorative patterns that emphasized process visibility. These studies suggest that what counts as error is context-dependent and can be repurposed for controlled variation.

2.2. GRADIENT PRINTING AND MULTIFUNCTIONAL MATERIAL SYSTEM

In parallel, research in gradient printing has explored how continuous modulation of material properties or deposition parameters can create multifunctional, spatially heterogeneous structures. Qu et al. (2024) used diameter-adjustable filaments to control filament width and produce mechanical and optical gradients. Propst and Mueller (2025) introduced a Time Code method to synchronize multi-channel material deposition, enabling spatial material blends. Moon et al. (2024) employed temperature modulation in wood-based filaments to generate tonal shading effects.

These studies showcase how dynamic control strategies can induce gradience across multiple scales; however, most existing approaches rely on complex, pressure-driven or multi-channel systems that require specialized hardware and limit both reproducibility and accessibility (Oxman, 2010). The reproducibility challenges are particularly acute when implementing these systems in standard laboratory or design studio settings, where equipment costs and technical expertise become significant barriers to adoption.

Table 1. Comparative overview of gradient-printing approaches

Approach	Printing System	Control Strategy	Material Focus	Key Contribution
Qu et al. (2024)	Pressure-driven (DIW)	Real-time filament diameter adjustment	Multi-material composites	High-fidelity control of gradient printing via hardware control
Propst & Mueller (2025)	Multi-channel extrusion (DIW/SLA)	Synchronized multi-input control	Functional composites	Introduces time-based modulation for multifunctional printing.
Moon et al. (2024)	Single-nozzle, Temperature-driven (FFF)	Dynamic nozzle temperature variation	Wood-based filament	Aesthetic gradients through thermal control
This research	Single-nozzle, Temperature-driven (FFF)	Parametric calibration of error-induced variation	Polylactic acid (PLA)	Gradient resolution through systematic extrusion modulation

2.3. MATERIAL AGENCY AND POSITIONING OF THIS RESEARCH

A growing body of computational design research has reinterpreted fabrication as an interactive relationship between human intention, material behaviour, and computational control. Oxman (2010) describes material intelligence as design knowledge emerging through negotiation between digital and physical systems, while

Ingold (2013) understands making as a conversation where responsiveness and adaptation are central to creative practice. Recent scholarship has explicitly reframed variability and error as productive phenomena (Kwon et al., 2025; Schön, 1983), suggesting that design intelligence can arise from the orchestration of imperfect conditions rather than their elimination.

Most gradient-printing research relies on specialized hardware or advanced infrastructure that limits accessibility. The present research contributes by demonstrating that similar material agency can be achieved through parametric calibration of extrusion variability on standard, commercially available FFF systems. By reframing error as a systematically controllable design parameter rather than a hardware failure, this work makes feedback-driven fabrication principles accessible to a broader design community, establishing that precision and sophistication in digital fabrication need not depend on equipment complexity.

3. Methodology

The experimental process follows a structured workflow that integrates gradient path generation, fabrication, and output evaluation (Figure 1). Initial paths are generated from either closed boundaries or open curves within a visual programming environment (Grasshopper; build 1.0.0008) running within a CAD 3D-modeling software (Rhinoceros 3D; version 8 SR22). These paths are then arrayed and segmented to form printing trajectories with gradual parameter shifts. Parameter values such as print speed, layer height, and extrusion rate are defined using parametric controls in the Rhinoceros Grasshopper, enabling continuous modulation along each print path.

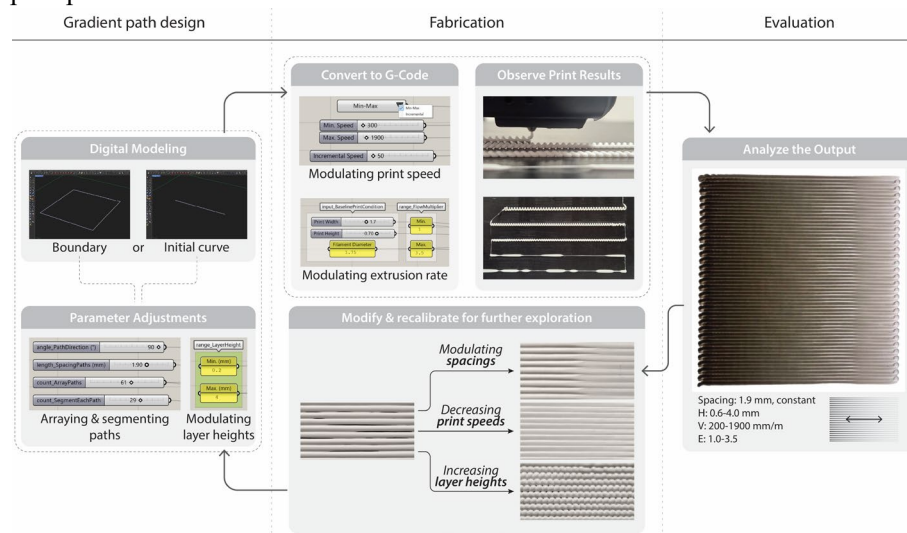


Figure 1. Workflow for gradient path design and fabrication, integrating feedback through parameter recalibration.

Once the path and parameter logic are established, they are converted into G-code. Custom scripts translate the parameter variations into incremental commands that modulate print speed or extrusion rate in real time. The generated G-code is tested using an off-the-shelf FFF printer (Creality Ender3 V3 SE equipped with a 1.0 mm nozzle to fabricate Polylactic Acid (PLA) (Polymaker PolyTerra, 1.75 mm diameter, Cotton White) samples. This printer was selected for its wide availability and open-source firmware that allows for direct manipulation of extrusion parameters. The large nozzle diameter (1.0 mm) enhances the visibility of extrusion effects for clearer observation, and it enables a wider range of layer height modulation while maintaining mechanical strength (Kuznetsov et al, 2019).

Printing was performed under stable laboratory conditions, and following printing settings were maintained across all tests to ensure consistent material flow as shown in Table 2. Each parameter combination was tested in triplicate ($n=3$) to verify reproducibility.

Table 2. Baseline printing parameters

Filament diameter (mm)	Nozzle diameter (mm)	Extrusion width (mm)	Nozzle temperature (°C)	Bed temperature (°C)	[†] Layer height (mm)	[†] Print speed (mm/min)	[†] Extrusion multiplier
1.75	1.0	0.4	210	60	0.7	1600	1

[†]Parameters that are subject to modulate at a time to generate gradient effects

Print results were observed and were documented through photographic analysis under consistent lighting to capture gradient transitions in translucency, surface roughness, and local density. Measurements of printed height (H_m), width (W), and surface texture were extracted from optical images using ImageJ software. Each printed sample was evaluated for its spatial consistency and the smoothness of transition across the print direction. Observation emphasized visual outcomes as indicators of process stability and material responsiveness. Variations in opacity, relief, and local elasticity were treated as evidence of the material's active contribution to texture generation, aligning with the study's focus on material agency and calibration rather than correction.

4. Results and Discussion

4.1. GRADIENT PATH DESIGN

Three primary parameters were explored: extrusion multiplier (E), print speed (V), and layer height (H). Initial tests varied one parameter at a time to establish isolated effects. Subsequent iterations combined all three variables to define broader print envelopes, allowing continuous gradient transitions across a single print.

Each parameter set was visualized and documented as plots illustrating the relationship between extrusion volume and different parameters as shown in Figure 2. This mapping informed the generation of GCode scripts capable of gradual modulation along the printing trajectory. After a series of parameter tests, gradient paths were

designed modulating different parameters within a single batch. The computational workflow supported incremental control along the print direction and facilitated feedback-driven iteration. This process informed the refinement of the G-code logic and the calibration of transition zones.

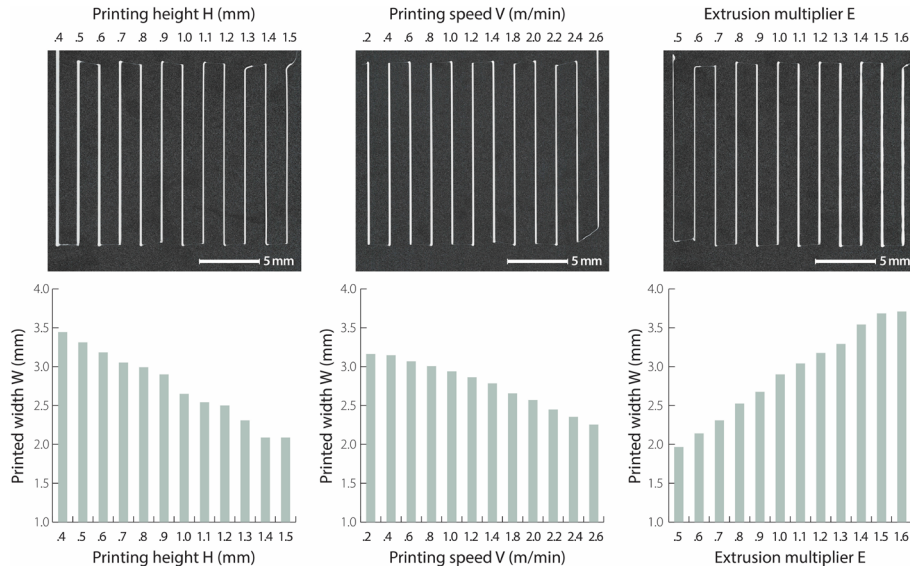


Figure 2. Extruded states (Top) and measured cross-sectional width W (Bottom) at different printing parameters. Quantitative W was obtained from top-view optical images using the software ImageJ.

Measured path widths and heights were recorded and plotted to verify the consistency and physical impact of parameter variation as shown in Figure 3. The upper path exhibits a consistent flat height yet the printed width tapers corresponding to the print speed decreases. In case of the lower path, the width is maintained due to the printing height modulation, while waviness emerges gradually as the material deposition increases due to lowering speed.

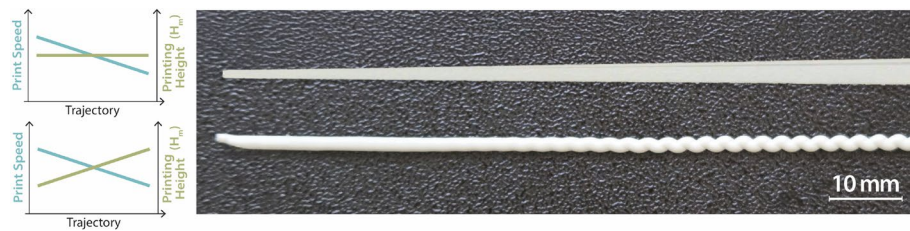


Figure 3. Comparison of the top view of printed results under coordinated variation of print speed and layer height. Left showing the relationship between print speed and printing height. Corresponding printed paths demonstrate the material's physical response (Right).

The experiments demonstrate that continuous modulation of extrusion parameters can produce controlled gradients in both visual and structural properties without hardware modification. The results confirm that extrusion irregularities, when calibrated rather than corrected, function as reproducible design parameters that expand the material resolution of FFF.

4.2. SURFACE GRADIENTS: TRANSLUCENCY AND PATTERNING

Surface-level gradients as shown in Figure 4 reveal how subtle changes in extrusion rate and print speed directly affect light transmission and surface density. Reduced extrusion flow (E multiplier: 0.5–0.8) generates fine gaps between filament paths, producing translucent, mesh-like surfaces. Optical analysis revealed light transmission rates ranging from 45–70% in under-extrusion zones, compared to 15–25% in fully deposited regions. In contrast, higher deposition volumes (E multiplier: 1.2–1.5) create denser regions that read as opaque fields. In contrast, higher deposition volumes create denser regions that read as opaque fields, offering spatial variation in visual depth. These outcomes demonstrate a controllable relationship between material thickness and optical performance, suggesting that translucency can be designed parametrically rather than treated as an incidental effect.

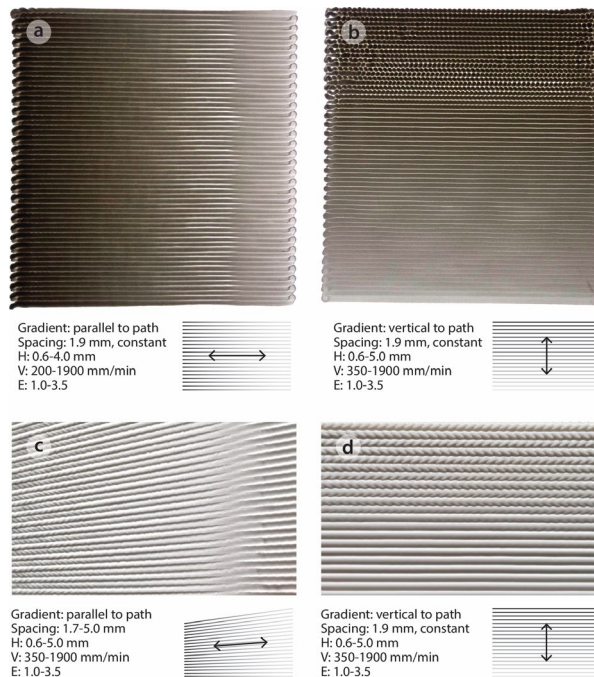


Figure 4. Gradient-printed specimens demonstrating variation in translucency and texture. The top row shows two samples backlit to reveal internal material density gradients oriented (a, c) parallel and (b, d) perpendicular to the toolpath. The bottom row presents close-up surface views of each condition. Parametric variations include print height (H), speed (V), and extrusion multiplier (E), revealing how directional modulation affects both visual and physical properties of the printed surfaces.

4.3. VOLUMETRIC GRADIENTS: DENSITY AND ELASTICITY

At the volumetric scale, controlled over-extrusion produced localized thickening that increased stiffness while maintaining smooth transitions across print layers as shown in Figure 5. These gradients exhibit a continuous range of mechanical behaviours that emerge from the modulation of extrusion rate and layer overlap. The observation that local elasticity can be tuned through parameter variation reinforces the notion that error is not merely deviation but a design resource capable of encoding structural information directly into the print process.

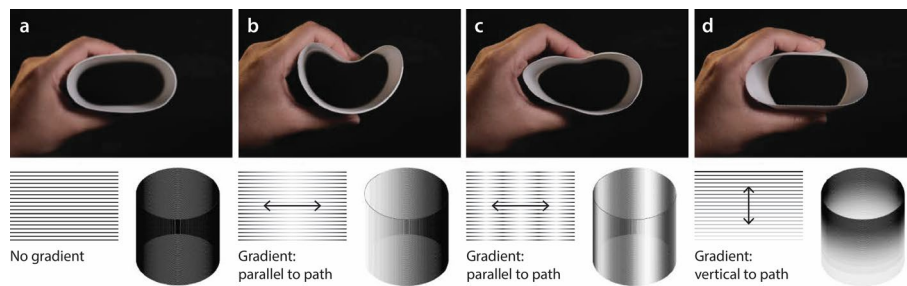


Figure 5. Gradient-printed cylindrical prototypes exhibiting diverse deformation behaviors under hand pressure. (a) A cylinder printed with consistent print settings displaying deformed evenly compared to (b, c, d) cylinders printed with gradient modulation. Gradients oriented (b, c) parallel, and (d) vertical to the paths.

4.4. DISCUSSION: FROM CALIBRATION TO RESOLUTION

Across all experiments, the outcomes indicate that gradient effects arise from cumulative, small-scale deviations rather than discrete procedural changes. This finding supports the study’s theoretical claim that resolution is not fixed by hardware limits but co-defined by material responsiveness and computational calibration. By intentionally working within the variability of extrusion, the designer operates in a reciprocal mode of control, responding to material feedback while directing its tendencies toward desired outcomes.

While the modulation strategy produces a wide range of effects, its controllability is bounded by physical limitations. Excessive under-extrusion can result in filament discontinuities or nozzle clogging, while over-extrusion may lead to pressure build-up and slippage between the filament and feeding gear (Ghorbani et al., 2022). These limits indicate that variation must be managed within the material and mechanical thresholds of the system. Within this framework, calibrating extrusion irregularities becomes a practical method for incorporating variability into digital fabrication. It enables designers to work responsively with material behavior, balancing precision with emergence across human, machine, and material interactions.

5. Conclusion

This research reframes extrusion “errors” in FFF not as flaws to be corrected, but as opportunities for calibration that expand the designer’s agency. By systematically

modulating extrusion rate, nozzle speed, and layer height, the study demonstrates how continuous parameter variation can produce reproducible gradients in translucency, porosity, and surface texture using conventional, low-cost hardware. These outcomes reveal a form of resolution that emerges through the interplay between computational control and material behaviour.

Rather than eliminating errors, this research redefines fabrication precision as a process of negotiation for programming managerial behaviour and form resolution. This perspective supports a humanistic mode of computation where design intelligence is shared among human, machine, and material. In addition to offering a replicable workflow for gradient printing, the study proposes a broader framework for understanding error as a generative condition. It positions imperfection as a catalyst for architectural expression and material innovation.

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