Spatial Additive Manufacturing

Functionally-graded periodic lattice internal structures

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Abstract. Spatial 3D printing is emerging as a transformative technology in architecture and construction due to its ability to reduce anisotropic weaknesses in traditional additive manufacturing processes. This study addresses the challenges of designing and fabricating functionally graded lattice structures through robotic spatial extrusion. Lattice structures, known for their superior strength-to-weight ratios, are ideal for applications requiring high-performance, lightweight structures. However, existing methods focus on uniform lattice or path-planning methods of smaller-scale, non-trivial spatial structures. This research proposes a computational framework for generating and fabricating varied-density lattice structures informed by finite element analysis (FEA). The framework includes translating stress data into voxelized geometries categorized by density of three-unit cell topologies, assigning toolpath priorities through weighted graph networks, and sequencing extrusion paths using geometric reasoning and depth-first search. This method ensures collision-free, efficient robotic planning. A case study involving a lightweight, varied-density spatial lattice demonstrated the approach's feasibility. While the framework significantly advanced spatial toolpath generation, limitations in extrusion speed remain.

Keywords. additive manufacturing, spatial 3d printing, lattice, cellular material, finite element analysis

1. Introduction

Spatial 3D printing is increasing in the architecture, engineering, and construction (AEC) industries. Recent research explores the integration of industrial robot arms with additive manufacturing technologies to enable multi-plane 3D printing, overcoming the limitations of conventional layer-by-layer methods. This approach combines fused deposition modeling techniques with 6-degree-of-freedom robot arms, allowing for extrusion in any direction (Ishak et al., 2016; Ishak &

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Larochelle, 2017). The multi-plane capability enables printing complex structures, such as overhangs, without support material and improves the production of lattice structures (Ishak et al., 2016; Ishak & Larochelle, 2017). Lattice structures are ordered cellular materials with internal geometries defined by their voids, and we classify them as either stochastic (foam-like) or ordered (such as honeycombs and lattices) (Tam et al., 2018). Unlike stochastic geometries, ordered lattice structures offer greater control over tailored mechanical properties, enabling precise customization to meet specific design and performance requirements (du Plessis et al., 2021). Lattice structures also outperform foams and honeycombs in strength and stiffness, making them ideal for compressive and shear strength (Pan et al., 2020). Our interests lie in the research domain of spatial 3D printing of varying lattice geometries that enable the optimization of properties like density and porosity for functional applications.

Additive manufacturing (AM), particularly fused deposition modeling (FDM), is widely used to create intricate geometries by extruding thermoplastic materials layer by layer. However, these traditional methods have limitations, especially when printing complex and anisotropic structures (Mueller et al., 2014). This process can result in anisotropic printed artifacts, where the strength can be significantly reduced across the printed layers compared to the strength within an individual layer (Tam et al., 2018). Spatial 3D printing involves depositing material freely in 3D space, allowing for directed extrusion and aligning filaments along force trajectories for more substantial continuity (Tam et al., 2018). It also provides an opportunity to investigate cellular materials and lattice structures, which have many benefits, such as a high strength-to-weight ratio (Gibson & Ashby, 1999). Focusing on spatial extrusion requires overcoming fundamental problems that limit the development of large-scale spatial structures. Key limitations include the accuracy of the spatial extrusion due to material deformation (Huang et al., 2018a; Huang et al., 2016), collisions between robotic movement and the previously printed structures (Tam et al., 2018), and extrusion sequencing (Garrett et al., 2020; Huang et al., 2016).

This paper introduces a method for generating lattice structures with varying densities, guided by finite element analysis (FEA) data, to create functionally graded designs with multi-node connections. Next, we organize and generate toolpaths using a weighted graph network, prioritizing critical edges during fabrication. Finally, we share the results of our approach, laying the groundwork for advancing the design and fabrication of functionally graded lattices with multi-node connections.

2. Background

2.1. 3D PRINTING STRATEGIES FOR SPATIAL EXTRUSION

Researchers generally divide strategies for spatial extrusion into two approaches which include ensuring the continuity of extrusion and prioritizing motion planning with discontinuous sequencing. The first approach emphasizes uniform lattice configurations, such as N-trusses (vertical-to-angled connections) or V-trusses (angled-to-angled connections). Examples include Branch C-Fab Technology for lightweight facade panels, Free-Oriented Additive Manufacturing for thermoplastic lattices, Mesh Mold for integrated structural formwork (Hack & Lauer, 2014), and robotic fabrication methods for lattice optimization (Tam et al., 2018). These methods improve speed and simplify toolpath planning, as demonstrated by Tam et al. (2020), who developed a topologically aware, layer-based sequencing strategy for continuous extrusion paths.

The second approach uses toolpath sequencing for more complex, discontinuous extrusion processes. Computational frameworks like Choreo automate sequence planning and robotic path generation for topology-optimized trusses (Huang et al., 2018a). Other studies, such as Scalable and Probabilistically Complete Planning for Robotic Spatial Extrusion (Garrett et al., 2018) and Automated Motion Planning for Robotic Assembly of Discrete Architectural Structures (Huang et al., 2018b), address structural and collision constraints in extrusion planning. These approaches highlight the potential for computational strategies to tackle the challenges of spatial extrusion in additive manufacturing. This second approach is best suited to fabricate highly connected lattices.

3. Methods

3.1. ROBOTIC 3D PRINTING SYSTEM ARCHITECTURE EXPERIMENT

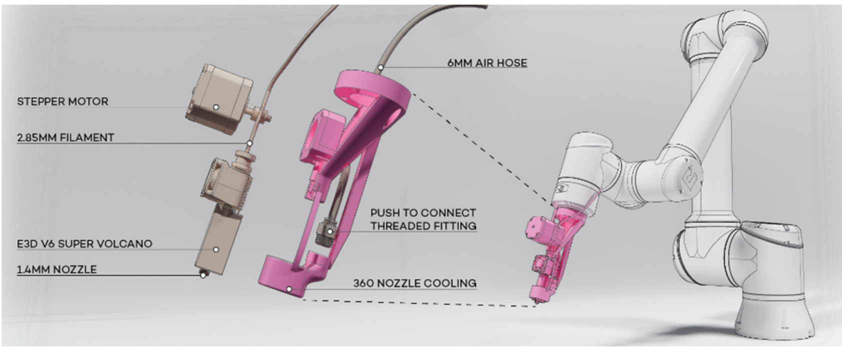

Figure 1. Spatial 3D printing End-Effector Design

This experiment involved a Universal Robot UR-10e, a 6-axis multipurpose industrial robotic arm equipped with a custom Fused Deposition Modeling (FDM) extruder. The material used for the extrusion was 2.85mm Polylactic Acid (PLA), a type of thermoplastic. An Arduino Uno was utilized to control the temperature of the extruder, the speed of the feed motor, and a solenoid valve to activate the cooling system.

We designed a customized end effector (Figure 1) compatible with the E3D 2.85mm 24V Super Volcano system. The integrated cooling system features a 360-degree wrapped design inspired by Patent 10,807,292 B2 (McGee et al., 2020). This design includes an exterior air channel encircling the main body of the heater block, directing airflow toward the heated plastic for precise and rapid cooling, as illustrated in Figure 1. This innovation allows for faster cooling of the thermoplastic, facilitating extrusion in any direction.

3.2. DESIGN STRATEGIES OF GENERATING PRINT PATHS FROM FEA LOAD DATA

The first step in creating a functionally graded lattice material framework is developing a performance-based cellular internal structure. Using Finite Element Analysis (FEA) to evaluate structural performance data informs the optimization of internal structural configurations for a wall (Figure 2).

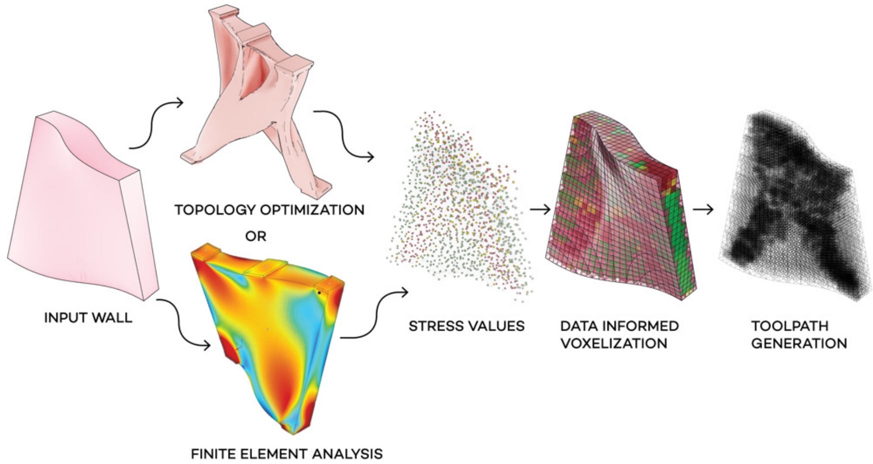

Figure 2. Computational workflow of generating functionally graded lattice

We can evaluate the wall's structural forces under a simple loading condition using two approaches: finite element analysis (FEA) based on specified support and load parameters or topology optimization, which reduces the structure by 50% while maintaining the same loading and support conditions.

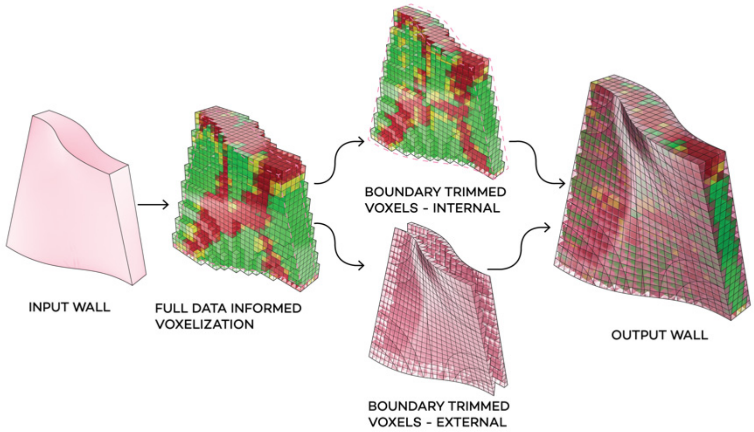

Figure 3. Voxel boundary rep sorting

The FEA geometry was generated using ANSYS Discovery 2024, applying a uniform load to the wall with two support constraints. The internal load data exported as a point cloud from ANSYS Workbench, containing X, Y, and Z coordinates and stress values, served as the basis for the cellular structure. This data was then imported into Rhino3D for voxelization (see Figure 3).

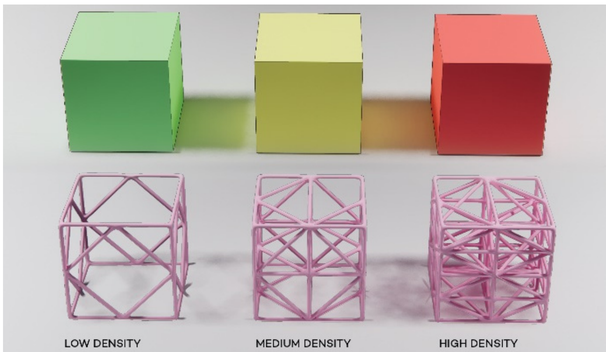

Figure 4. Voxel colour to toolpath density

The geometry is divided into a 3D Cartesian grid of voxels sorted by color according to load values: red for high-density unit cells, yellow for medium-density, and green for low-density (Figure 4). The method produced cuboidal cells and irregular polyhedral at the boundary (Figure 3).

Voxels are categorized into three spatial toolpath densities: low density with 58 lines, medium density with 101 lines, and high density with 153 lines (see Figure 4). These complex configurations complicate the development of collision-free extrusion sequences and robot motion planning (Huang et al., 2018). After generating the voxels, we link each to a corresponding stress value and toolpath density. The highest stress values align with the highest-density lattice units, and we divide the edges within the structure into segments at each intersecting member.

3.3. GRAPH-BASED OPTIMIZATION FOR TOOLPATH PLANNING IN ROBOTIC SPATIAL EXTRUSION

The process of extrusion planning for fabrication is highly complex, incorporating parameters related to robotic orientation and assembly sequences while ensuring that the robot has adequate space to perform its functions during each extrusion step (Huang, Carstensen, Mueller, 2018). Successful methodologies were developed to address multi-orientation extrusion planning (Huang, Garrett, Mueller, 2018; Huang et al., 2018c; Garrett et al., 2018). Given the non-standard topologies of spatial trusses, the researchers employed a geometric graph structure within their assembly planning framework, Choreo, to facilitate efficient motion planning while fully utilizing the industrial robots' axes of movement.

Likewise, this study adopts a computational approach to optimize toolpath generation for robotic additive manufacturing. The algorithm computes weights for each edge based on its geometry and interactions with adjacent elements by utilizing a graph-based representation of spatial structures. These weights inform the extrusion sequence, ensuring efficiency and structural integrity during fabrication. Depth-first search (DFS) traversal is employed to explore and visualize graph connectivity, minimizing redundant operations. Implemented within the Rhino/Grasshopper environment, this algorithm enables robust planning for collision-free robotic extrusion in spatial structures.

The core functionality of our method involves assigning weights to each edge based on the average Z-coordinate of its neighboring vertices and the orientation type (horizontal, vertical, or angled). This algorithm integrates graph theory with geometric reasoning to optimize the sequencing of robotic toolpaths for additive manufacturing. The key components of the algorithm are outlined below:

Graph Representation:

The input data is converted into a graph-based model where nodes represent spatial coordinates (Rhino.Geometry.Point3d), and edges represent connections between points as (Rhino.Geometry.Line) objects.

Weight Assignment:

The algorithm assigns weights to each edge based on three primary criteria:

Geometry**:** The average Z-height of both the start and end points of the edge, which captures vertical positioning within the 3D structure.

Connectivity**:** Intersections with other graph lines are categorized and processed as follows:

- Vertical-to-angled intersections
    - Weight added for the intersection at the start point (figure 5a)
    - Weight added for the intersection at the endpoint (figure 5b)

Special Cases: Unique cases, such as vertical lines with angled intersections at both the start and end of the edge (figure 5c).

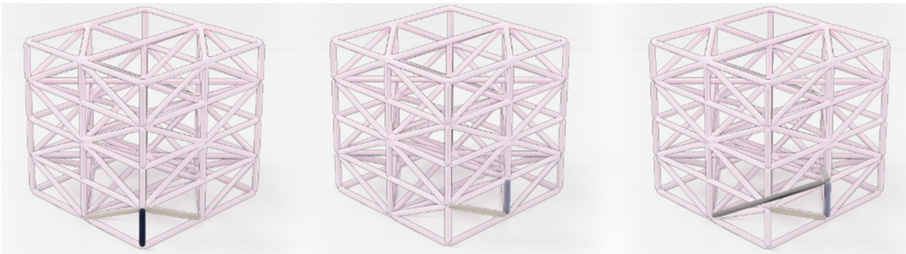

Figure 5. a) Left: vertical to the angled connection at the end; b) Middle: vertical to the angled connection at the start; c) Right: angled to the vertical connection at the start/end

Sorting and Traversal:
Edges are prioritized based on their calculated weights. Then, a depth-first search (DFS) traversal is employed to explore graph connectivity, ensuring efficient and non-redundant exploration of all graph edges.
Visualization:
Each line visited is color-coded and moved to a designated "visited" layer, facilitating debugging and visualization. The layer represents the traversal order within Rhino/Grasshopper's interface.

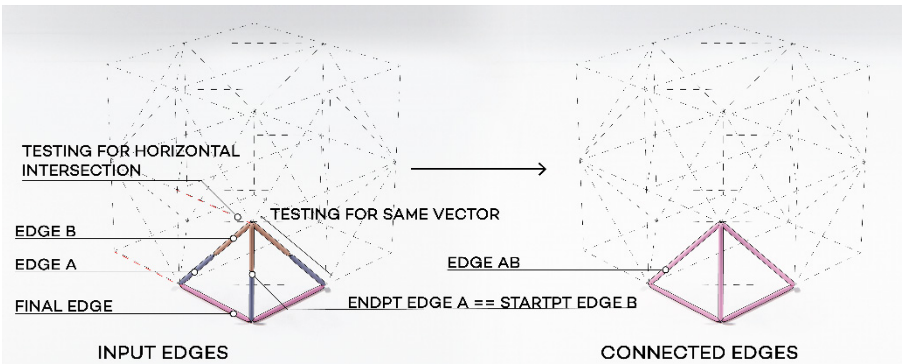

Figure 6. Linear connectivity based on geometric relationships for the creation of continuous paths

Integrating weight-based sorting, robust graph traversal, and customized geometric analysis enables effective planning and sequencing to create collision-free paths. The method automates the identification and merging of line segments based on their geometric relationships. The edges in the graph are tested for alignment in the same vector direction and then checked to determine whether the connecting point between edges is the same. Next, the edges are tested for intersections with a horizontal line, which indicates the endpoint of edge joining (figure 6). This step is crucial, especially when dealing with lower-density lattices, which are split at the same Z-height as the endpoint of the highest-density lattice (quadrant height), ensuring that initial sorting weights are accurately assigned. Once the weights are assigned, the linear connectivity function is applied.

4. Case Study/Results

The 3D printed functionally graded spatial geometry was produced using a system that successfully generated interconnected spatial tool paths that accommodate the ordering sequence to avoid collision with the existing printed material. As the object progressed in size, changes were made to how the lines were sequenced/ordered and the extrusion parameters for spatial elements. The cells are broken down into quadrant heights, which was crucial for sorting the edges in a sequence that did not produce collisions. Improvements to the toolpath generation included combining longer segments of the same vector and not intersecting them with another edge. This created a cleaner extrusion and decreased the print time by reducing the travel distance and the number of lead-ins and lead-outs.

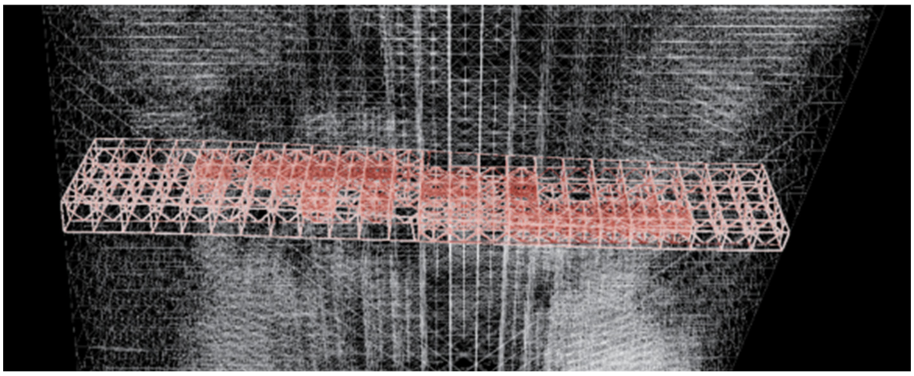

Figure 7. Functionally graded wall showcasing the spatial toolpaths and the cellular density

Limitations remain. The extrusion process for such a high-density structure proved time-consuming. There are 150 total extrusions in each cell, and the overall case study well exceeds 200,000 extrusions (Figure 7). The speed is limited by the cooling factor and the continuity of the toolpath, so each cell layer takes around 4-6 hours. However, there are opportunities to reduce the time by creating faster speeds for different aspects of the extrusion, including traversal and fine-tuning speeds for multiple extrusion orientations.

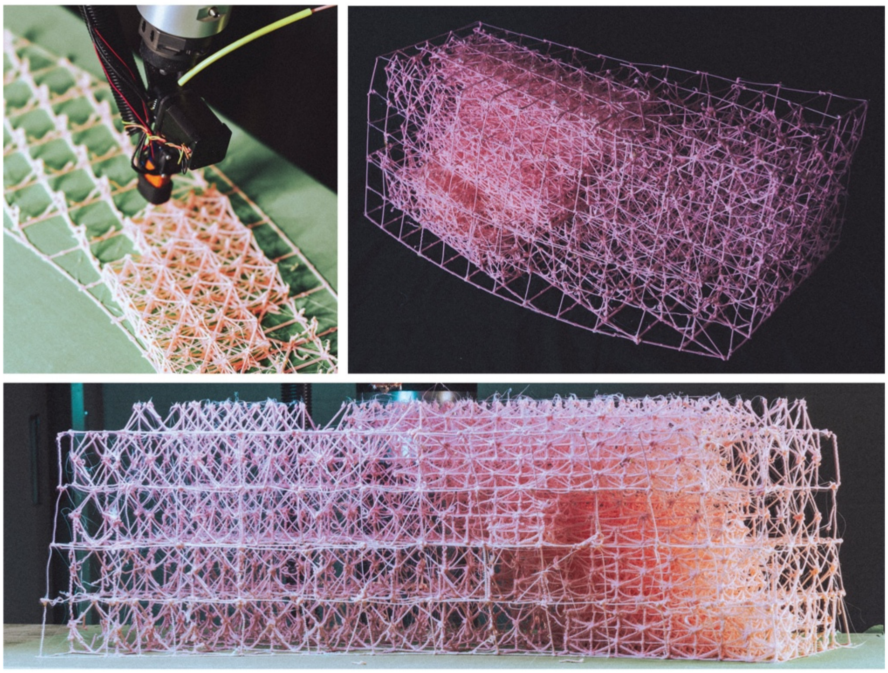

Figure 8. Spatial extrusion result

5. Conclusion

This paper introduces a computational framework for designing and fabricating functionally graded lattice structures (see Figure 8). By combining finite element analysis with graph-based optimization, we tackled challenges in extrusion planning, including tool-path sequencing and collision avoidance. Our case study illustrates the feasibility of producing high-density graded lattices with optimized tool paths, highlighting the potential to create intricate and structurally efficient geometries.

While speed and process efficiency improvements are still needed, spatial 3D printing presents significant advantages by optimizing the relationship between complete infill and spatial infill volume. Unlike full infill, which results in heavy prints and consumes excess materials, spatial infill allows for strategically placing material only where it is structurally necessary. This approach reduces weight and material usage without compromising performance.

This work lays the groundwork for future advancements in scalable, high-performance spatial additive manufacturing of functionally graded structures. This paper proposes a computational framework for designing and fabricating functionally graded lattice structures (Figure 8). By integrating finite element analysis and graph-based optimization, we addressed critical challenges in extrusion planning, such as tool-path sequencing and collision avoidance. Our case study demonstrates the feasibility of producing high-density graded lattices with optimized tool paths, showcasing the potential for achieving intricate and structurally efficient geometries.

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