

Robotic Concrete 3D Printing Continuous Toolpath Planning: From Single Curve to Voxel-Based Systems for Design-to-Production of Urban Furnitures

Sina Mostafavi¹[0000-0002-7558-7569], Edgar U. Motejano-Hernandez¹[0009-0004-9357-072X], Bahar Bagheri¹[0009-0005-4400-418X], Ali Etemadi²[ORCID], Cole Howell¹[0009-0009-4383-974X], Asma Mehan³[0000-0002-7381-6663]

¹Texas Tech University Huckabee College of Architecture, Hi-DARS lab, Lubbock, TX, United States

²Dessau Institute of Architecture HS Anhalt, Dessau, Germany

³Texas Tech University Huckabee College of Architecture, AHU lab, Lubbock, TX, United States

ABSTRACT: This paper discusses the development of integrated design-to-production frameworks for Robotic Concrete 3D Printing (RC3DP) of context-specific urban furniture projects. The study focuses on two main objectives: developing computational methods for continuous toolpath planning of bespoke components and examining integrated frameworks to make design-to-production systems more socio-environmentally inclusive and tailored to specific contexts. Following an introduction to outline the key challenges of continuous robotic concrete 3D printing, the paper is organized into two sets of case studies. The first set explores curved-based continuous 3D printing for surface-based design strategies, and the second set investigates voxel-based approaches for volumetric design 3D printing. Curve-based projects consisted of three case studies. The first case uses an AI-enabled generative system to translate a porous, cellular structure to a continuous toolpath with variable heights. The second case study is based on a workflow using a controlled reaction-diffusion algorithm as a generative strategy to create continuous infill for complex geometries. The third project focuses on growing larger than the size of the production setup by testing the assembly of multiple printed components, all produced with continuous toolpaths. The workflows and projects are developed as an integral part of a graduate-level digital design and fabrication course focusing on inclusive automation and robotic concrete 3D printing. Therefore, in addition to sharing the details of the developed computational design to production methodologies, the paper discusses the research findings from pedagogical lenses. Building on these cases, the investigation advances to the development of a generative system centered on voxels, employing a tetrahedron structure. This volumetric approach simultaneously produces external surface tectonics and internal infill through a seamless toolpath. The paper concludes by presenting sets of guidelines and future directions for both the introduced curve and voxel-based approaches in Robotic Concrete 3D printing, emphasizing the early integration of computational and fabrication intelligence into the design process.

KEYWORDS: Continuous toolpath planning, robotic concrete 3D printing, voxel based 3D printing, urban manufacturing, integrated design-to-production

INTRODUCTION AND BACKGROUND

Recent research in 3D concrete printing technology has shown significant potential to revolutionize the construction industry by enabling the fabrication of complex building and structural elements such as columns and bridges (Anton et al. 2021; Ahmed et al.). Several physical factors, such as fluidity, print speed, material aggregates, temperature, and admixture, all influence the printing quality (Lyu et al. 2021). Moreover, having a successful print heavily depends on toolpath planning since on-and-off printing with a liquid material like fluid concrete is nearly impractical with commonly available technologies. Therefore, it is crucial to develop customized workflows for toolpath planning during the initial design phase when printing non-standard and context-specific designs.

In the realm of digital prototyping for additive manufacturing, this paper presents recent advancements in toolpath-based design methodologies, particularly tailored for applications in Fused Deposition Modelling (FDM). FDM is characterized by the layer-by-layer linear deposition of molten material. The methodologies developed in this study harness advanced techniques, including topology optimization, principal stressed lines, and bio-inspired generative patterns, to inform toolpath design and planning (Bressegello and Naboni 2022; Mostafavi et al. 2015; Mehan and Mostafavi 2022). Moreover, these approaches align with contemporary principles outlined in earlier research efforts focusing on data-driven 3D printing strategies (Bao and Yan 2023; Bao et al. 2020, Lu et al. 2023). These studies delve into domains such as data-driven, performance-based generative design, digital fabrication, and bioinspired architectural design, considering environmental and structural criteria (Mehan and Mostafavi 2024a; Azulay et al. 2023; Feng 2022; Li et al. 2023). Expanding on recent advancements in evolutionary topology optimization of continuum structures, as explored (Mehan and Mostafavi 2024b; Huang and Xie 2010), these insights serve as a foundational basis for advancing toolpath-based design methodologies within the context of additive manufacturing and digital prototyping for creating architectural material systems (Bouaziz 2008)

This paper will present three urban furniture projects built on a one-to-one scale, each addressing specific challenges related to continuous toolpath planning. The first case uses an AI-enabled generative system to translate a porous cellular structure to a continuous toolpath with variable heights (Mostafavi et al. 2024). The second case study is based on a workflow using a controlled reaction-diffusion algorithm as a generative strategy to create continuous infill for complex geometries. The third project focuses on growing larger than the size of the production setup by testing the assembly of multiple printed components, all produced with continuous toolpaths. The workflows and projects are developed as an integral part of a digital design and fabrication graduate-level course focusing on inclusive automation and robotic concrete 3D printing. Therefore, in addition to sharing the details of the developed computational design to production methodologies, the paper discusses the research findings from pedagogical lenses (Mehan 2024; Mehan and Stuckemeyer 2023).

Expanding upon these three cases, the study progresses to the creation of a generative system based on voxels, utilizing a tetrahedron structure. This framework generates both the external surface tectonics and internal infill through a seamless toolpath. The purpose of this system is to overcome the challenges stemming from the lack of curvature in Concrete 3D Printing, thereby minimizing stress concentration on flat surfaces. To achieve this, the workflow incorporates a recursive subdivision technique in regions prone to tension accumulation, consequently reducing the risk of buckling during and after the printing procedure.

The resultant design materialization system is adaptable to various boundary representation forms as input. Through the voxelization algorithm, the input geometry is transformed into voxels, eliminating unnecessary inner fill while preserving essential voxel elements. Following this, two strategies for generating continuous toolpaths are formulated and assessed: the single-layer approach and the double-layer approach. Both strategies ensure the uninterrupted trajectory of the printing process.

1.0 CURVE BASED CONTINUOUS 3D PRINTING

The upcoming section introduces three continuous toolpath generation followed by case studies, each exploring the context and design objectives of forthcoming projects, the usage of generative AI, designer-based forms and computationally applied patterns into a pre-designed form. Employing Rhinoceros and Grasshopper 3D as CAD/CAM interfaces, the toolpath for concrete 3D printing utilizes the customized HAL robotics system for XtreeE's large-scale 3D printing extruder mounted on a KR210 KUKA robotic arm. The discussion further examines the approaches taken for continuous toolpath planning in each project to enable the application of required transformation of the initial concept design into design to production enabled workflow (Mehan et al., 2023). Each case description concludes by emphasizing key features and findings derived from the one-to-one prototyping and assembly phases of concrete components and structures.

1.1 AI-Generated printable porosity

The initial case employs Artificial Intelligence (AI)—to enable the generative system to transform a porous, cellular structure in the format of 2D images into a continuous 3D toolpath with variable heights. The design goal is to create a structure with openings that smoothly incorporate seating elements into the wall, each characterized by a distinct pattern and degrees of porosity. The goal is to enhance the overall quality of outdoor space by improving the entry of natural light and offering effective wind protection by creating seating areas with perforated walls between existing columns of the promenade. The design processes apply generative AI to produce a series of images with porous patterns, utilizing the Midjourney platform with targeted prompts such as "porosity," "canopy," "biomechanic," "bench," "wall," and "organic" as the foundation for subsequent stages.



Figure 1: AI-Generated Printable Porosity: Left - Macro-scale cellular structure generated with AI; Middle - Continuous printing at varied heights; Right - Simulation diagram of the print. Source: (First and second Authors, 2022. Design, methods, and research developed as part of ARCH 5354 at TTU, led by S. Mostafavi. Team: Abel Gonzalez, Edgar Montejano, Cristian Solis, Matthew Stevens, Benjamin Varner)

The next step in the process involves the images serving as input to a subsystem that applies a developed algorithm utilizing the Image Sampler. This algorithm translates the pixelated 2D result into a continuous 3D toolpath by reading the binary values of each voxel. Discretization techniques based on penalization algorithms, such as

Voronoi or hexagonal patterns, are then employed to create a cellular structure representing the generated porosity. A toolpath is generated, connecting the cellular structure in the subsequent phase. Following the generation of the continuous toolpath, the prototype undergoes concrete 3D printing, utilizing the defined toolpath for material deposition and materialization of the design (Figure 1).

By generatively creating sets of porous images and algorithmically translating the results into a printable continuous toolpath, the design-to-production system allows for iterative exploration of different structures with varying porosity levels. The density and quantity of polygons are transformed into an assembly of shapes arranged into a cohesive structure with varying depths, creating a gradient of solid and void areas. This form, applied to a walled screen with a bench, manifests inherent patterns in a structured manner, reflecting the algorithmically designed solar analysis and daylight gain. The shading wall serves as a criterion for choosing the desired porosity level, generated through AI and controlled with sets of parameters in the algorithm that translate the image to a robotic concrete 3D printing toolpath. Figure 2 illustrates the one-to-one prototype printed in three different heights in one continuous toolpath following the algorithmically generated curve.

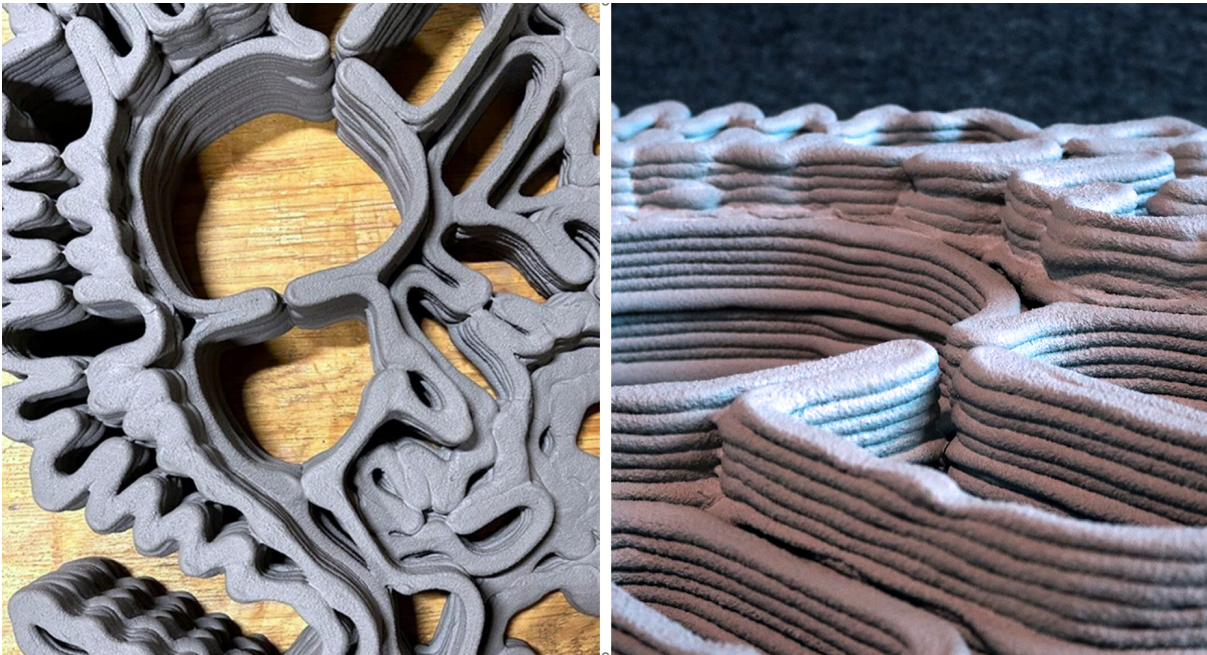


Figure 2: AI-Generated Printable Porosity: Left - Top view; Right - Side view with varied heights in three layers, produced with a continuous toolpath. Source: (First and second Authors, 2022. Design, methods, and research developed as part of ARCH 5354 at TTU, led by S. Mostafavi. Team: Abel Gonzalez, Edgar Montejano, Cristian Solis, Matthew Stevens, Benjamin Varner)

1.2. Concreted 3D printed stacked wall

The Concrete 3D Printed Stacked Wall project introduces a system where multiple components stack, creating a Tetris-like structure. This endeavor addresses challenges in 3D printing structures, particularly in assembly processes. The inherent challenge in 3D printing structures lies in assembly and producing components rather than continuous walls and shells. The initial concept involved the consideration of constructing a wooden shelter or causeway, drawing inspiration for the project from the specific urban context adjacent to an archaeological site. Additionally, the project explored integrating sets of niches—recesses with varying sizes and depths designed for displaying objects found in the archaeological site. The research aims to integrate the wooden shelter with traditional inset walls in adobe houses, examining ways to combine walls with shading. Within this context, the structure aims to create a wall using customized components, each featuring niches or cavities to showcase historical objects in the archaeological site. The wall consists of concrete-printed stacked components with a wooden shading structure above it.

The toolpath design strategy employed in this project centers on creating a continuous cavity within each component for concrete casting, followed by developing a continuous printing path for the outer boundary of the components connected to internal niches. Consequently, each stacked component comprises an extruded curve featuring internal niches with slightly tapered angles towards the front side of the wall. The outer surfaces are intentionally flat, contributing to a Tetris-like interlocking configuration for assembly. Despite the fragility of the straight, non-curvilinear outer boundaries, the internal cavities connected to the outer boundary significantly enhance the overall stiffness of each component. Figure 3 provides an overview of the design in a sectional model, illustrating the printing process of components with varying sizes and typologies.

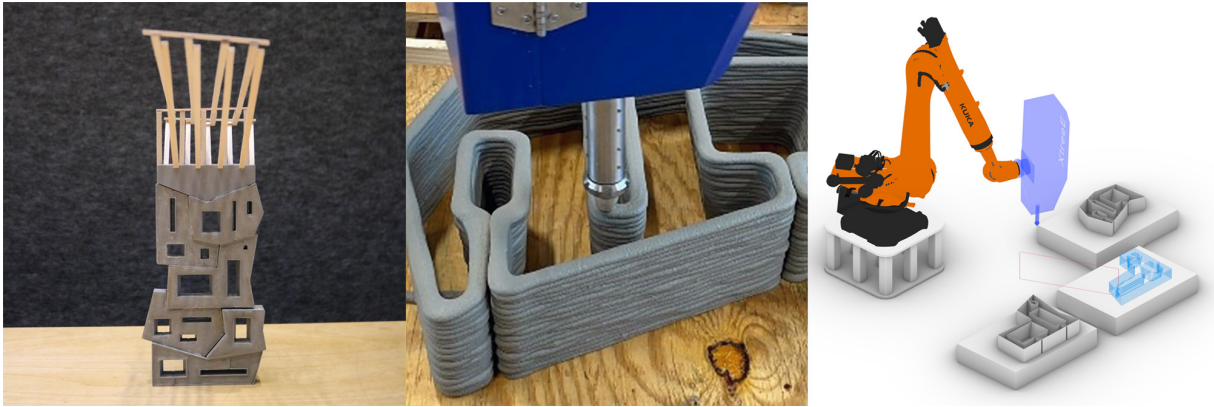


Figure 3: Concrete 3D Printed Stacked Wall: Left - Sectional model showcasing integrated niches and enclosed cases within the printed components; Middle - Continuous 3D printing process; Right - Simulation diagram of the print. Source: (First Author, 2022. Design, methods, and research developed as part of ARCH 5354 at TTU, led by S. Mostafavi. Team: Elias Hernandez, Alexis Hunsucker, Zahra Khodabakhsh, Maria Guadalupe Martinez, Derek Williams)

The one-to-one prototype of the stacked wall presented in this paper comprises three components with L and V typologies, systematically stacked on top of each other. Figure 4 represents the assembled wall within the internal cavities before the concrete casting process. A notable aspect of the developed material system involves integrating high-performance printable concrete materials with more readily available conventional concrete. The use of concrete glue acts as an adhesive to bind the elements together, and careful consideration is given to the weight distribution in each component and the positioning of the center of gravity post-assembly, addressing an essential criterion in the design development.



Figure 4: Left: A one-to-one prototype of the Concrete 3D-Printed Stacked Wall featuring three L- and V-shaped components; Right: a close-up view of the tapered niches. Source: (First Author, 2022. Design, methods, and research developed as part of ARCH 5354 at TTU, led by S. Mostafavi. Team: Elias Hernandez, Alexis Hunsucker, Zahra Khodabakhsh, Maria Guadalupe Martinez, Derek Williams)

1.3. RC3DP reaction-diffusion bench

The RC3DP Reaction-Diffusion Bench project focuses on integrating bio-inspired generative patterns into the continuous 3D printing process, aiming to enhance the stiffness and stability of printing surfaces during fabrication and post-production stages. In this case study, the reaction-diffusion model functions as a mathematical framework, elucidating the processes governing the interaction of materials or chemicals as they diffuse through a shared medium. This system's deliberate selection is driven by the intent to generate internal and external performative tectonics, reinforcing the structural robustness of the printed surface. Additionally, the internal porosity of the bench is designed to harmonize with nature, as the bench is tailored for site-specific community gardens. The porosity within the physical seating contributes to the overall aesthetics and fosters the growth of plants with healing properties, integrated into the built environment.

The developed toolpath planning system takes either single or double curvature surfaces as input, determining the depths of reaction-diffusion based on the reaction time. Increased reaction time results in greater penetration of the diffusion pattern into the internal area. Additionally, informed by previous cases, a preference for double curvature surfaces is observed over the single curvature starting extrusion. This preference leads to improved structural stability at both the micro and macro scales of the entire prototyped bench. The selection of surface geometry and its curvature represents progress in fortifying the structural rigidity of the bench, impacting both micro-surface scales and the overall macro-scale stability. Figure 5 depicts a series of iterations utilizing the generative system, along with printing and corresponding simulation diagrams, showcasing the production process of the prototyped bench.

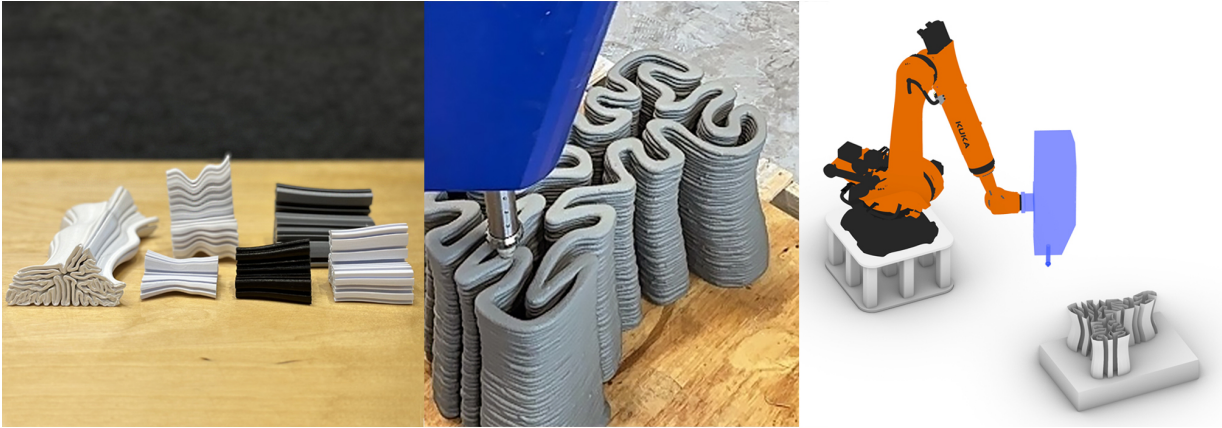


Figure 5: RC3DP Reaction-Diffusion Bench: Left, a sequence of design iterations displayed as scaled models; Middle, the 3D printing process; Right, a simulation diagram of the print. Source: (First Author, 2022. Design, methods, and research developed as part of ARCH 5354 at TTU, led by S. Mostafavi. Team: Luke Conrad, Saul Ortega, Judith Peralta Velazquez, Amanda Rich, Georgia Thomas)

The one-to-one prototype bench is contained within a 40x40x80 cm bounding box, incorporating both seating and leaning areas, printed in a single continuous course. The utilization of fractal tectonics and the double-curve surface properties of the bench minimizes material consumption in each layer. Consequently, the material flow has been optimized, enhancing efficiency in material utilization, and strengthening the overall structure of the bench.



Figure 6: Left: One-to-one prototype of RC3DP Reaction-Diffusion Bench, Close-up of the continuous printed pattern. Source: (First Author, 2022. Design, methods, and research developed as part of ARCH 5354 at TTU, led by S. Mostafavi. Team: Luke Conrad, Saul Ortega, Judith Peralta Velazquez, Amanda Rich, Georgia Thomas)

2.0 VOXEL BASED VOLUMETRIC CONCRETED 3D PRINTING

The paper's second set of case studies investigates a volumetric approach to toolpath planning involving the utilization of voxelization to translate voxelated geometries into a continuous toolpath. Subsequent sections will delve into the computational aspects, focusing on the voxelization process and the robotic production of tetrahedra-based pedestals. The study encompasses both single and double layers, aligning with voxel topologies.

2.1. Design computation: voxelization

The computational design system for voxel-based robotic toolpath planning is implemented as an integrated approach, accepting any closed Boundary Representation (B-Rep) volumes as input. The generative method employed in this system applies a voxelization routine, with a specific choice of using a Tetrahedral-Octahedral honeycomb space-filling tessellation. This selection is driven by the method's rectangular-based geometry in horizontal sections and triangular-based topologies in vertical sections. The chosen tessellation guarantees both printability and stability throughout the production process, as the angles consistently remain above 45 degrees during the print.

Figure 7 presents the developed generative system, incorporating recursive voxelization for added stability in critical areas prone to failure during and after the printing process. Recursive voxelization achieves this by subdividing each voxel into smaller units. Subsequently, the toolpath can either consist of a continuous single layer, delineating the volume's boundary, or a double-layer continuous toolpath that follows the internal surface of outer voxels, as depicted in the right portion of Figure 7. This approach reinforces specific regions that are subject to buckling, contributing to enhanced stability and structural integrity.

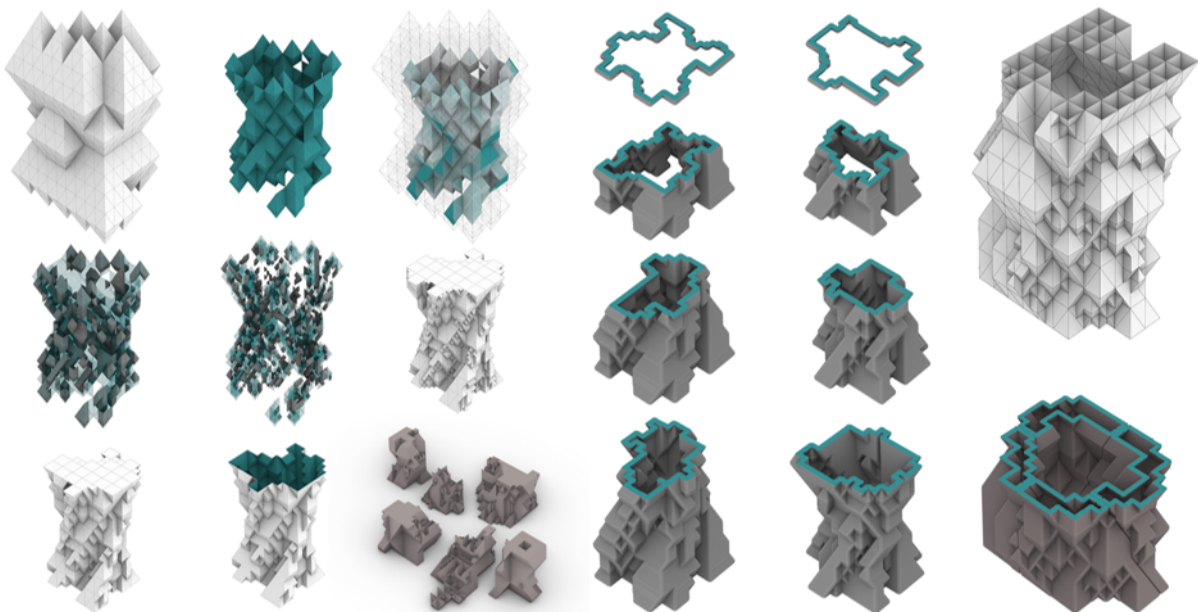


Figure 7: Overview of the computational design workflow translating voxels to surface and toolpath from a closed B-Rep volume. Columns one to three detail the step-by-step process, while columns four and five show the single-layer 3D printing strategy. The last column exemplifies the developed double-layer approach in voxel-based 3D printing. Source: (Authors, 2023. Design and research developed as part of the Design Computation (DCF) ARCH 5604 studio and Smart Materials ARCH 5303 course, led by S. Mostafavi, and the Urban Community Design (UCD) ARCH 5604 course, led by A. Mehan, at TTU in Spring 2023. Methods were further advanced and consolidated by author Ali Etamadi.)

2.1. Robotic production: single to double layer tetrahedral based pedestals

The one-to-one produced set of prototypes for the developed voxel-based toolpath planning, as presented in this paper, consists of four pedestals, each with distinct initial volumes serving as design inputs. The left portion of Figure 8 showcases the four robotically concrete 3D-printed prototypes, providing a visual scale comparison to human dimensions. On the right side of Figure 8, a finite element method analysis delineates areas prone to failure during the print. This analysis guides the application of an additional level of recursive voxelization to strengthen printability throughout the production process (Mostafavi and Mehan 2024). Alternatively, designers may opt for a double-layer voxel-based toolpath planning, as illustrated in Figure 7 and explained in the preceding section (Mehan and Mostafavi 2023). This strategic choice contributes to the overall stability and structural integrity of the printed prototypes.



Figure 8: Left: Prototypes showcasing the voxel-based continuous robotic concrete 3D printing approach; right Finite Element Method analysis of the surface, guiding recursive voxelization for additional reinforcement where needed. Source: (Left: Authors, 2023–24. Design and research developed as part of the Design Computation (DCF) ARCH 5604 studio and Smart Materials ARCH 5303 course, led by S. Mostafavi, and the Urban Community Design (UCD) ARCH 5604 course, led by A. Mehan, at TTU in Spring 2023, exhibited at the ECC Venice Architecture Biennale. Right: Photos taken and produced by XtreeE, an industry collaborator on the project)

CONCLUSION

This paper explores a series of case studies and pilot projects centred on continuous toolpath planning in the realm of Robotic Concrete 3D Printing (RC3DP). The transition from single-curve methodologies to voxel-based systems for designing and producing urban furniture is thoroughly investigated and elucidated. The inquiry initiated with an in-depth analysis and categorization of curved-based continuous 3D printing, showcasing case studies that leverage AI-driven generative systems, controlled reaction-diffusion algorithms, and innovative multi-component assembly strategies – all operating within the cohesive framework of continuous toolpaths. The exploration extends into voxel-based approaches, incorporating a tetrahedral structure to seamlessly integrate external surface tectonics and internal infill.

These projects exemplify the transformative impact of creative toolpath planning, demonstrating adaptability in design for specific contexts and functional requirements. Furthermore, they formulate strategies for implementing performance-driven tectonics that enhance structural stability throughout the printing process and beyond. As future directions for this research, a more comprehensive exploration and application of voxel-based toolpath planning is anticipated. The system holds the promise of delivering a high level of flexibility in design and ensuring structural integrity in the production of building elements and components.

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