INDIAN INSTITUTE OF TECHNOLOGY GUWAHATI
PhD-17 SHORT ABSTRACT OF THESIS

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Thesis Title: Computer-Aided Process Planning for Extrusion-Based Additive Manufacturing of Concrete

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Thesis Submitted to the Academic Division	:	Department of Mechanical Engineering
Date of completion of Thesis Viva-Voce Exam	:	21/01/2026
Key words for description of Thesis Work	:	Concrete 3D Printing, Digital Construction, Toolpath, Design for Additive Manufacturing, Computer-Aided Process Planning

SHORT ABSTRACT

Additive Manufacturing of Concrete (AMoC), also referred to as 3D concrete printing, is revolutionizing construction through layer-by-layer fabrication, enabling the creation of complex, customized geometries with reduced material use and construction time. Its advantages—geometric freedom, design flexibility, and tunable mechanical properties—have attracted attention across industries such as architecture, construction, and aerospace. AMoC employs gantry, robotic, and hybrid extrusion systems for large-scale construction, yet its widespread implementation remains limited by toolpath discontinuity, material rheology challenges, and lack of design standardization. Effective process planning—specifically toolpath generation—is essential to achieving high-quality printed concrete components. Toolpath design directly affects geometric accuracy, print continuity, and interlayer bonding, which influences the overall structural integrity and sustainability of printed parts. Unlike polymer or metal AM, there is a critical need for the development of Computer-Aided Process Planning (CAPP) systems specific to extrusion-based concrete printing. The main objective of this research is three-fold: (1) Development of systematic Design for Additive Manufacturing of Concrete (DfAMoC) framework—integrating design and manufacturing principles for contour-based toolpath generation, (2) Utilization of Travelling Salesman Problem (TSP) solver for generating continuous toolpath strategy to improve path continuity, isotropy, and printing efficiency in AMoC (3) Development of a growth curve-based printing path planning method that optimizes part strength, quality, scalability, computational efficiency, and further extending this approach to non-planar area filling addressing curved and complex geometries.

Firstly, DfAMoC framework is explored that integrates three design and two manufacturing principles: surface offsetting (half-bead width) to ensure dimensional accuracy, functional surface design defining overhang limits and print heights to prevent collapse, sharp junction elimination using a 2 mm fillet radius to minimize nozzle jerks and clogging, orientation and modularity to enhance scalability and continuity, and "As Continuous As Possible" (ACAP) toolpaths to reduce nozzle lifts and printing interruptions. Experiments on planar, non-planar, and embossed/debossed geometries demonstrated superior accuracy (±6 mm deviation) and improved interlayer bond strength (1.42–1.52 MPa). The DfAMoC workflow also surpassed commercial slicers (Cura, Simplify3D) in terms of surface finish, print continuity, and dimensional precision.

Secondly, a Traveling Salesman Problem (TSP)-based approach was implemented to generate optimized continuous toolpaths for solid area filling. The workflow involves contour offsetting, grid generation, and TSP optimization using the Lin–Kernighan–Helsgaun algorithm, followed by boundary trimming and smooth curve fitting. Experimental validation on geometries such as square, rhino, human face, chair, and bridge using a gantry-based printer with a 20 mm nozzle confirmed only one discontinuity per layer (compared to 20-118 in conventional paths), a reduction in printing time by up to 60%, underfilling reduced by 72–93%, improved isotropy by about 30–42%, and scalability up to 600% with maintained quality. The TSP-based method provided a robust, material-aware planning strategy suitable for large-scale, topology-optimized concrete structures.

To overcome the computational limitations of TSP, a growth curve-based continuous toolpath algorithm was developed. It iteratively grows a user-defined input curve inside a target area following a growth function, maintaining constant spacing and avoiding path crossings, producing a fully continuous Hamiltonian-like circuit. Parametric analyses revealed that a step-over of 20 mm reduced print time by 40–50% while maintaining less than 1.5% underfilling, scaling had minimal impact on quality, and a growth factor of 2 minimized computation time with excellent print quality. Analytical and experimental validation across numerous geometries demonstrates the method's scalability, robustness, and adaptability. The CAPP system achieves optimized toolpath by carefully adjusting important parameters, particularly step-over and growth factor, which reduces printing time, minimizes sharp turns, eliminates unnecessary interruptions, improves print quality (underfilling <0.015, overlapping <0.03), and computation efficiency.

The feasibility of non-planar fabrication using the growth curve toolpath was demonstrated using sand–sodium silicate support beds, shaped and cured with CO_2. Various surfaces (cylindrical concave, convex, and complex coral-like forms) were printed successfully. Dimensional analysis using laser scanning revealed mean deviations of –0.43 mm for the sand bed and +0.65 mm for printed parts, with overall deviations within ±6 mm—acceptable for AMoC applications, particularly for bio-inspired architectural structures. These results demonstrate the successful printing of functional curved structures using the proposed CAPP system along with recyclable, reusable materials.

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