Computational Fabrication with Multi-Axis 3D Printing

Principles and Hands-on Practice

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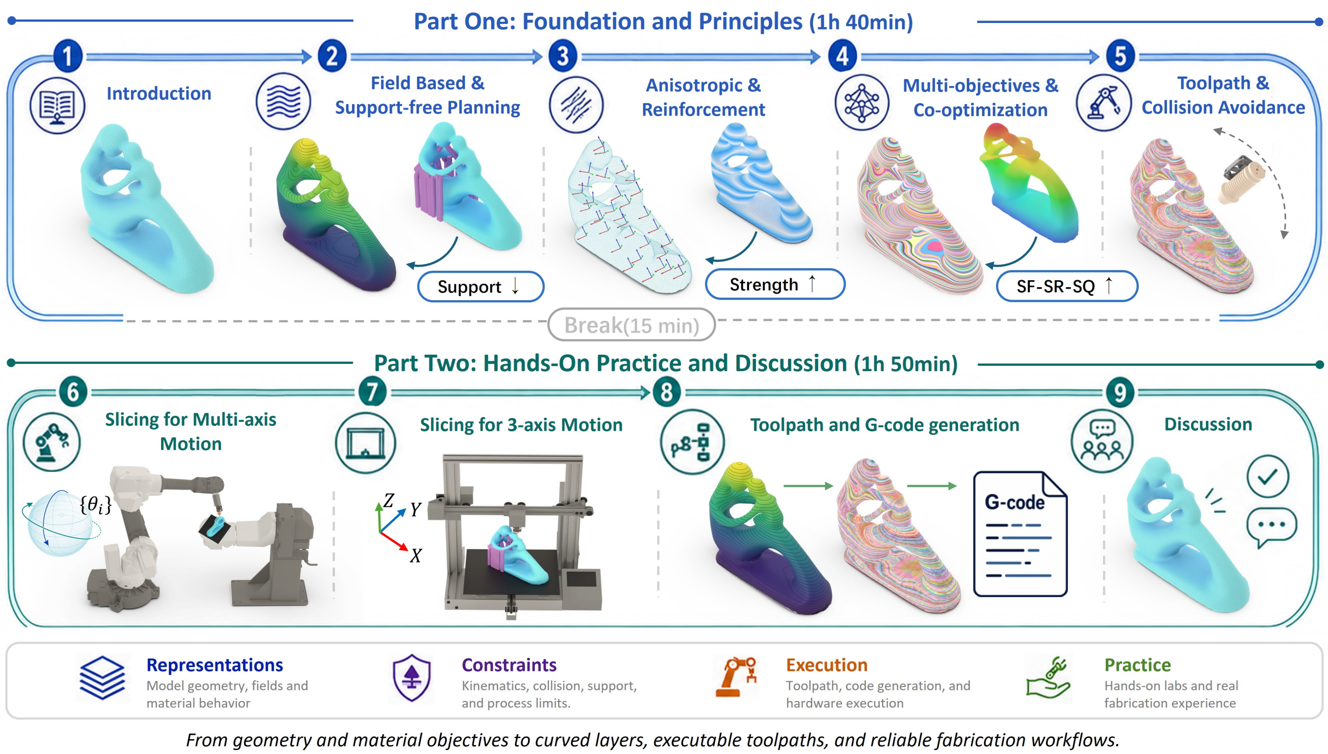

Figure 1: Concept of computation fabrication by multi-axis 3D printing and its essential components to be covered by this short-course.

1 Introduction and Motivation

Multi-axis 3D printing expands additive manufacturing from a layer-stacking process into a computational fabrication problem that jointly considers geometry, motion, materials, and machines. Instead of depositing only planar layers with a fixed nozzle direction, multi-axis and non-planar printing can use curved layers, varying tool orientations, and machine-aware toolpaths to improve manufacturability [Dai et al. 2018; Qu et al. 2025], surface quality [Etienne et al. 2019; Zhang et al. 2022], structural performance [Fang et al. 2020; Liu et al. 2024], and material placement [Liu et al. 2025]. This shift opens new opportunities in a wide range of downstream applications, including part repair, printed electronics, robotic construction, composite fabrication, high-performance optical components, and biomanufacturing.

At the same time, multi-axis 3D printing introduces significant computational challenges. A successful fabrication pipeline must coordinate curved-layer generation, tool orientation planning, support avoidance, collision checking, material anisotropy, surface quality, inverse kinematics, and machine-specific constraints. Recent research in computer graphics and computational fabrication, including work published at ACM SIGGRAPH and SIGGRAPH Asia, has made important progress on these problems. However, these advances remain difficult to compare, reproduce, and transfer into practical workflows, especially for researchers and practitioners who are new to the area.

This course presents multi-axis 3D printing as a coherent computational fabrication framework that connects algorithmic foundations with hands-on practice. The first part of the course surveys the state of the art in multi-axis printing algorithms and applications, focusing on how geometric representations, fabrication constraints, and design objectives are formulated, optimized, and verified. The second part provides hands-on experience with an open-source Python-based platform, Vector3DP, developed by the Digital Manufacturing Lab of The University of Manchester, enabling participants to explore curved-layer slicing, collision-aware planning, toolpath generation, G-code generation, and machine-related parameters through concrete 5-axis and 3-axis examples.

A central theme of the course is the relationship between frontier hardware and accessible fabrication platforms. Robotic and five-axis systems provide rich tool-pose freedom and enable advanced support-free, collision-free, and orientation-aware fabrication strategies. In contrast, ordinary desktop three-axis fused filament fabrication printers have fixed nozzle orientations, but can still benefit from non-planar surface-following toolpaths that improve surface quality, reduce stair-stepping, partially reduce support requirements, and provide limited path-driven control over material orientation. By comparing these settings, the course clarifies which multi-axis algorithms require advanced hardware and which can already be explored on widely available desktop machines.

Overall, the course aims to make recent advances in multi-axis and non-planar 3D printing more understandable, reproducible, and extensible. It will provide participants with both a conceptual map of the field and a practical starting point for applying and further developing computational tools for next-generation additive manufacturing.

2 Presenters

The course will be delivered by a team of five presenters. Short biographies of the presenters are provided below.

- **Tao Liu** is a Ph.D. student at The University of Manchester, who is a member of Digital Manufacturing Lab, working on neural-based design and manufacturing optimization. His research focuses on computational geometry, additive manufacturing, and robotics, with particular interests in multi-axis 3D printing, topology optimization, neural implicit representations for geometric modeling, surface reconstruction, fiber-reinforced composites, and material optimization.
- **Neelotpal Dutta** is a Postdoctoral Fellow in the Department of Mechanical and Aerospace Engineering and a member of the Digital Manufacturing Lab at The University of Manchester. His research interests include geometric computing, digital manufacturing, and computer-aided design and manufacturing, with a focus on toolpath generation and process planning for additive and subtractive manufacturing.
- **Guoxin Fang** is now an Assistant Professor in the Department of Mechanical and Automation Engineering at The Chinese University of Hong Kong. He leads the Computational Robotics and Manufacturing Lab and explores the intersection of computational science and engineering innovation through geometry computing, physical modeling, and artificial intelligence, developing technologies for robotics, advanced manufacturing, and smart systems. His research interests include robotic multi-axis spatial additive manufacturing, modeling and perception for soft robots, proprioception, and computational design and digital manufacturing for personalized multifunctional wearable devices.
- **Chengkai Dai** is a Postdoctoral Fellow in the Personalized Design and Fabrication Lab at the Centre for Perceptual and Interactive Intelligence, The Chinese University of Hong Kong, working with Professor Yeung Yam and previously supervised by Professor Charlie C.L. Wang. His research focuses on computational fabrication, additive manufacturing, and textile-based fabrication, developing computational and robotic methods that bridge digital design and physical fabrication. His work includes multi-axis slicing and robotic motion planning for freeform additive manufacturing, as well as knitting and weaving algorithms for functional-fiber sensing interfaces and robotic skins.
- **Charlie C.L. Wang** is currently Professor as Chair in Smart Manufacturing and Director of Digital Manufacturing Lab at The University of Manchester. His research spans geometric computing, computational design, additive manufacturing, robot-assisted fabrication, and digital manufacturing. His work has transformed the integration of design, analysis, and fabrication by establishing geometric computing and optimization as foundations for intelligent engineering across additive and hybrid manufacturing.

The hands-on practice session will be conducted by the five presenters, with additional support from **Yongxue Chen**, a Ph.D. student in robot-assisted manufacturing at the Digital Manufacturing Lab, The University of Manchester. His research interests include robotics and additive manufacturing.

3 Course Structure

The course is planned as two connected sessions. The first session will be tutorial-based, introducing the foundations of geometric optimization and numerical optimization, together with the working principles of multi-axis 3D printing. The second session will provide hands-on exercises using an open-source platform developed by the Digital Manufacturing Lab at the University of Manchester. The hands-on component will include two examples: one focused on five-axis 3D printing using high-end hardware and another on three-axis 3D printing that can be performed on most consumer-level fused filament fabrication 3D printers.

3.1 Schedule

The course will run for 3 hours and 45 minutes in total, including a 15-minute break. The tutorial session will last 1 hour and 40 minutes, and the hands-on practice session will take 1 hour and 50 minutes.

3.1.1 Part One: Foundation and Principles. Tutorial-style presentations will be given by five speakers in this session.

- **Introduction (10 minutes by Wang):** Importance and impact by multi-axis 3D printing and how it changes the design-to-fabrication workflow. Fundamental computational challenges for multi-axis 3D printing and their connections to robotic research topics such as motion planning and inverse kinematics.
- **Support-free planning (20 minutes by Dai):** Different decomposition strategies: region-based (multi-directional printing) vs. field-based (multi-axis printing) [Dai et al. 2018; Wu et al. 2020]. Scalar field-based algorithm for planning the sequences of curved layers, including iso-surfaces / iso-curves extraction for layers / toolpaths. Challenges in IK optimization [Chen et al. 2025b; Dai et al. 2020; Zhang et al. 2021].
- **Anisotropic mechanical property and reinforcement (20 minutes by Fang):** Challenges and opportunities caused by anisotropic mechanical property of fused filament fabrication. Vector-field based control of anisotropy, including filament alignment, material orientation and reinforcement goals [Fang et al. 2020]. Extension to fibre-reinforced thermoplastics [Fang et al. 2024; Zhang et al. 2025].
- **Multi-objectives and design-fabrication co-optimization (20 minutes by Liu):** Deformation-based planning for curved layer generation with multiple objectives [Zhang et al. 2022]. Benefit for neural-network (NN) based formulation [Liu et al. 2024]. End-to-end NN solution for integrated design-fabrication co-optimization and its application in fibre reinforced thermoplastics [Liu et al. 2025].
- **Direct control over collision avoidance and toolpath geometry (20 minutes by Dutta):** Accessibility, clearance, collision checking and their formulation in implicit signed-distance functions (SDFs) fields. Direct formulation of toolpaths and collision avoidance by neural implicit fields. Support and orientation aware optimization for layer / toolpath generation [Dutta et al. 2026].
- **Wrap-up (10 minutes by Wang):** Other recent development for multi-axis 3D printing, including reinforcement learning based path planning [Huang et al. 2024], in-situ control by force sensor [Huang et al. 2026], multi-axis DLP printing [Dai et al. 2025], and hybrid manufacturing [Chen et al. 2025a]. Briefing the arrangement for the hands-on practice session.

3.1.2 Break (15 minutes). During this break, attendees will start to download the Python-based open-source platform – Vector3DP developed by the Digital Manufacturing Lab.

3.1.3 Part Two: Hands-On Practice and Discussion. The detailed schedule of this hands-on practice session is planned as follows.

(1) **Environment setup (20 minutes, Liu and Dutta):** Attendees will download the Python code for the slicer and configure their runtime environment during the first part of the session. Presenters will assist attendees with this step. The basic modules will then be introduced, together with the main functions of the platform, including loading conditions, Finite Element Analysis (FEA), visualization, and result verification functions such as collision checking.

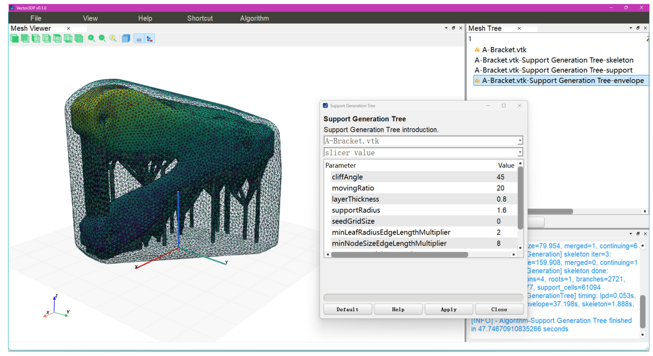

Figure 2: Screenshot of Vector3DP for its function of support generation.

(2) **Slicing for 5-axis motion (20 minutes, Fang and Dutta):** The first hands-on test will focus on generating curved layers for collision-free and support-free slicing of the Fertility model, as shown in Fig. 3(a), for 5-axis motion. Ablation tests will be conducted to demonstrate the effect of enabling or disabling collision-free optimization. The support-free constraints and printhead geometry will also be modified to further demonstrate the generality of the method.

(3) **Slicing for 3-axis motion (20 minutes, Liu and Dutta):** The second hands-on test will focus on generating curved layers for 3-axis 3D printing. This function will be tested on the A-bracket model shown in Fig. 3(b). The printhead geometry will again be modified so that attendees can observe its influence on collision-free layer generation. In this example, the objective of curved layer generation will be mechanical strength. FEA will be conducted to demonstrate the functionality of the generated curved layers in comparison with conventional planar layers.

(4) **Toolpath and G-code generation (20 minutes, Liu and Dutta):** Attendees will learn how to generate toolpaths on curved layers and how to produce G-code using inverse kinematics (IK). This part will cover both 5-axis and 3-axis cases, with the 5-axis example used to explain the importance of optimized IK solutions.

(5) **Machine-related parameters (15 minutes, Liu and Dutta):** Attendees will learn how to adjust the slicer parameters to reflect different machine configurations. The G-code generated from the previous steps, which will be provided offline before the course, will be printed in real time on hardware brought to the conference by the presenters.

(6) **Discussion and wrap-up (15 minutes, all presenters):** The session will conclude with a discussion of open problems in planning robustness, verification, material-aware slicing, machine constraints, and software accessibility. The presenters will also connect the lecture topics and hands-on examples to possible follow-up projects.

Multi-axis 3D printing hardware will be operated by the presenters during the hands-on session to demonstrate the functionality of the open-source platform on site.

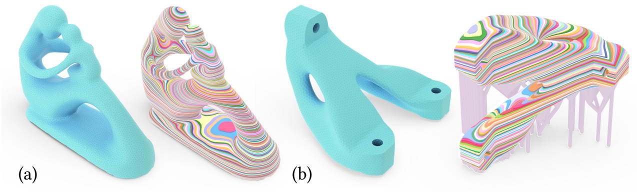

Figure 3: Models used in the hands-on session – (a) the Fertility model, demonstrating 5-axis support-free 3D printing, and (b) the A-bracket model, used for layer generation in 3-axis printing.

3.2 Audience and Prerequisites

The course is intended for students, researchers, and practitioners in computer graphics, computational fabrication, digital design, additive manufacturing, and robotics. Basic familiarity with geometric modeling, triangle meshes, surface normals, slicing, toolpaths, and material-extrusion 3D printing will be helpful. Prior experience with robot programming, inverse kinematics, finite-element simulation, or implicit neural representations may be beneficial but is not required.

The Python-based platform Vector3DP used in this course can be run on Windows, macOS, and Linux. Attendees should bring a laptop with a working internet connection; at least 16 GB of RAM is recommended for smoother performance. Before the hands-on session, attendees should install Git (https://git-scm.com/) and Conda (https://anaconda.org/). Detailed installation instructions will be provided.

4 Learning Objectives and Summary

This course is designed to help participants develop a coherent understanding of multi-axis and non-planar 3D printing as an emerging computational fabrication paradigm for modern design and manufacturing. It will introduce how the field has moved beyond conventional planar slicing and support generation toward curved-layer design, field-based slicing, collision-aware toolpath planning, and integrated design-fabrication optimization.

The course will guide participants through the complete computational pipeline, from geometric input and fabrication objectives to curved-layer generation, collision checking, toolpath planning, G-code generation, and machine-specific execution. Through the lecture session, attendees will learn the core principles behind geometric optimization, numerical optimization, support-free and collision-free slicing, FEA-based verification, inverse kinematics, and machine-aware planning. The course will also introduce representative computational pipelines used in this area, including scalar fields, deformation fields, neural fields, and self-learning-based optimization pipelines. These methods will be compared in terms of the design objectives they support, the constraints they can encode, and the verification steps required before physical fabrication.

The hands-on session will reinforce these concepts through practical exercises using a Python-based open-source platform developed by the Digital Manufacturing Lab of The University of Manchester. Participants will learn how to configure the software environment, load example models, generate curved layers for both 5-axis and 3-axis printing scenarios, evaluate support-free and collision-free constraints, modify printhead and machine parameters, and generate executable toolpaths and G-code. The 5-axis example will demonstrate the role of collision-aware optimization and inverse kinematics for richer machine motion, while the 3-axis example will show how non-planar slicing can be applied to more accessible material-extrusion printers for objectives such as anisotropic mechanical strength reinforcement.

By the end of the course, attendees should be able to:

- Explain the main motivations, opportunities, and challenges of multi-axis and non-planar 3D printing.
- Describe the computational pipeline from input geometry to curved layers, toolpaths, G-code, and machine execution.
- Compare different representations for curved-layer and field-based slicing, including scalar fields, deformation fields and neural fields.
- Understand how support-free requirements, collision avoidance, printhead geometry, machine constraints, and inverse kinematics affect fabrication planning.
- Use the provided open-source platform to run basic slicing, visualization, verification, toolpath generation, and G-code generation examples.
- Distinguish which multi-axis fabrication concepts can be transferred to consumer-level three-axis material-extrusion printers and which require rotary, five-axis, or robot-assisted hardware.
- Identify open research and development opportunities in planning robustness, verification, material-aware slicing, reinforcement-aware fabrication, and accessible software tools.

Overall, the course aims to equip attendees with both conceptual understanding and practical starting points for using, extending, and building upon recent research outcomes in computational multi-axis 3D printing.

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