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A COMPREHENSIVE ANALYSIS OF NON-PLANAR TOOLPATH OPTIMIZATION IN MULTI-AXIS 3D PRINTING: EVALUATING THE EFFICIENCY OF CURVED LAYER SLICING STRATEGIES

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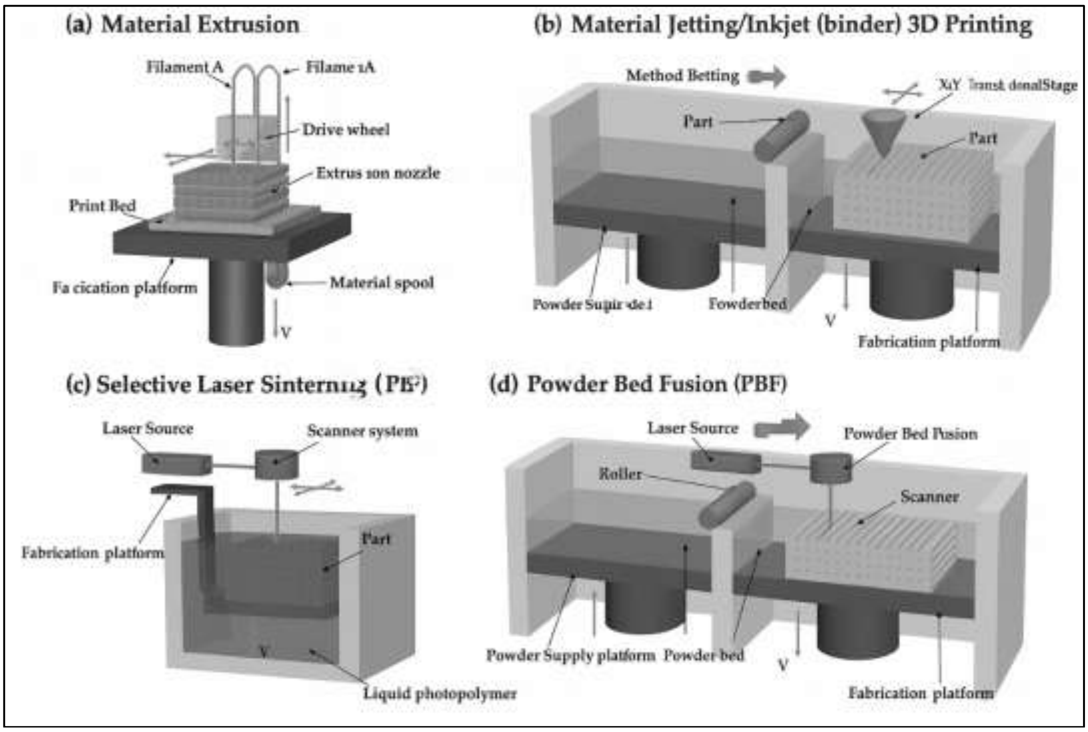
Abstract
Non-planar toolpath optimization has emerged as a pivotal advancement in multi-axis additive manufacturing, offering transformative potential for overcoming the limitations of traditional layer-by-layer 3D printing. This comprehensive analysis investigates the current state-of-the-art in non-planar toolpath generation and curved layer slicing strategies, focusing on their efficacy in enhancing surface finish, structural integrity, and overall print efficiency. In Asia, Japanese and South Korean industries have rapidly adopted 5-axis AM systems for high-precision mold and die fabrication, leveraging robotic arms for deposition control. China has emerged as a global leader in large-scale multi-axis printing, exemplified by the use of robotic extruders in constructing concrete buildings with non-planar reinforcement layers. The United States, through institutions like MIT, Carnegie Mellon, and Oak Ridge National Laboratory, continues to push boundaries in toolpath generation algorithms, real-time sensor feedback, and hybrid subtractive-additive platforms By synthesizing recent developments in kinematic modeling, machine control, and slicing algorithms, this study critically examines the computational and mechanical complexities introduced by multi-axis motion. The evaluation includes a comparative assessment of adaptive slicing, curved layer deposition, and hybrid manufacturing approaches, considering both simulation-based and experimental findings. Furthermore, the analysis highlights the challenges associated with collision avoidance, motion planning, and printhead orientation, particularly in 5-axis and 6-axis systems. Emphasis is placed on the interplay between geometric complexity and slicing strategy, demonstrating how optimized curved layers can reduce support material usage, improve print continuity, and expand the design space for functional parts. The study concludes with a discussion on future research directions, including the integration of AI-based optimization techniques, real-time sensing, and feedback-driven path planning, aiming to foster more intelligent and autonomous multi-axis 3D printing systems. This work serves as a foundational reference for researchers and engineers seeking to improve the fidelity, speed, and versatility of advanced additive manufacturing processes.

Keywords
Non-Planar Toolpaths; Multi-Axis 3D Printing; Curved Layer Slicing; Additive Manufacturing Optimization; Motion Planning Algorithms;

INTRODUCTION

Additive manufacturing (AM), more commonly referred to as 3D printing, is defined as the process of creating physical objects by successively depositing material in a layer-wise manner from a digital model (Raut & Taiwade, 2021). Traditional AM technologies typically rely on planar layer-by-layer deposition strategies, which assume flat, horizontal slicing of digital models into uniform cross-sections (Walker et al., 2016). However, this constraint limits the quality, efficiency, and design flexibility of printed parts, especially in complex geometries and overhanging structures. In contrast, non-planar toolpath strategies introduce curvature into the deposition layers, aligning them with part geometry or stress distribution, thereby enhancing surface finish and mechanical performance. In parallel, multi-axis 3D printing refers to additive manufacturing systems that operate along more than three degrees of freedom, such as 4-, 5-, or even 6-axis configurations, allowing dynamic orientation of the printhead or build platform during fabrication (Qian, 2017). This capability significantly expands the design space of AM, facilitating complex part generation with fewer support structures and better structural integrity. The integration of non-planar toolpaths with multi-axis systems introduces a new paradigm in AM, necessitating advanced computational modeling, kinematics, and control strategies. These definitions set the conceptual groundwork for exploring the optimization of curved-layer slicing strategies and their relevance in advanced AM workflows.

Figure 1: Schematic Representation of Four Additive Manufacturing Techniques: Material Extrusion



Internationally, there has been a notable surge in research and industrial investment in multi-axis and non-planar 3D printing due to its potential to revolutionize complex manufacturing sectors. In Europe, the Horizon 2020 research program has supported numerous initiatives focused on adaptive AM technologies, particularly in aerospace and biomedical domains. Germany's Fraunhofer Institutes have demonstrated curved-layer slicing in jet engine nozzle fabrication, achieving significant improvements in weight reduction and stress distribution (Gaynor & Guest, 2016). In Asia, Japanese and South Korean industries have rapidly adopted 5-axis AM systems for high-precision mold and die fabrication, leveraging robotic arms for deposition control. China has emerged as a global leader in large-scale multi-axis printing, exemplified by the use of robotic extruders in constructing concrete buildings with non-planar reinforcement layers. The United States, through institutions like MIT, Carnegie Mellon, and Oak Ridge National Laboratory, continues to push boundaries in toolpath generation algorithms, real-time sensor feedback, and hybrid subtractive-additive platforms (Mass & Amir, 2017). These global contributions highlight the wide-reaching implications and relevance of

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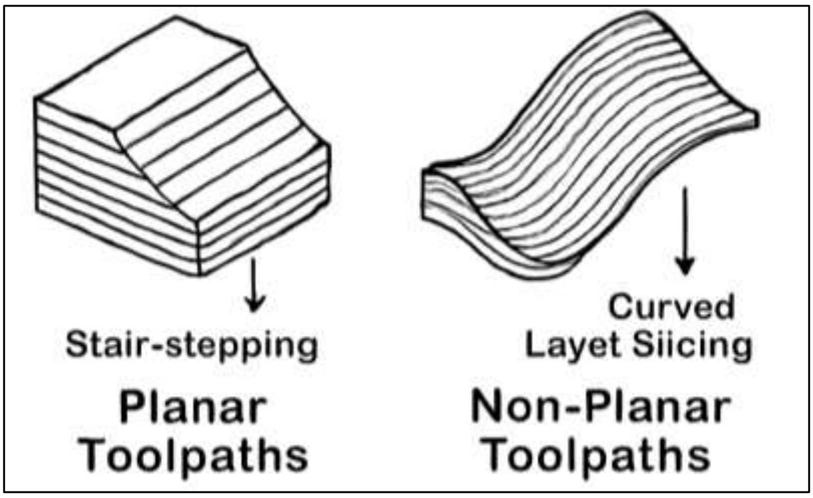
non-planar toolpath optimization and underscore the collaborative efforts driving innovation in this space.

Figure 2: Comparison of Planar and Non-Planar Toolpaths in 3D Printing



The core engineering motivation for adopting non-planar toolpaths lies in addressing the deficiencies inherent in conventional layer-based manufacturing. Chief among these is the phenomenon of "stair-stepping," wherein sloped or curved surfaces exhibit visible ridges due to flat slicing planes, negatively impacting both aesthetics and mechanical function (Gaynor et al., 2014). Non-planar strategies allow the toolpath to follow the contours of a model, producing smoother transitions and improved surface quality without requiring post-processing. Additionally, layer curvature can be engineered to align with principal stress directions within a part, enabling anisotropic material properties that improve structural performance. This capability is especially beneficial in aerospace and biomedical implants, where stress shielding or fatigue failure can compromise functionality (Mass & Amir, 2017). Curved-layer deposition also enables the reduction or elimination of support structures, which not only lowers material consumption but also decreases print time and post-processing complexity. Moreover, this technique facilitates the fabrication of geometries previously considered unprintable, such as helicoids, wave-like skins, and freeform sculptures. Together, these factors substantiate the engineering rationale behind the pursuit of optimized non-planar slicing and justify the growing interest across disciplines. Despite its promise, implementing non-planar and multi-axis 3D printing introduces significant computational and mechanical complexities that must be addressed through advanced optimization. Generating toolpaths on non-planar surfaces requires precise meshing, slicing, and trajectory planning algorithms that accommodate curvature while preserving model fidelity (Langelaar, 2016b) The tool orientation must be constantly adjusted to avoid collisions, manage nozzle angles, and maintain consistent extrusion. In multi-axis systems, the problem escalates due to inverse kinematics challenges, requiring continuous recalculation of joint movements across robotic arms or articulated gantries. The coupling of dynamic path planning with real-time sensing and feedback loops is necessary to ensure accurate deposition on contoured surfaces. Furthermore, curved slicing introduces challenges in printhead calibration, flow rate modulation, and thermal gradient management—each of which can affect print fidelity (Qian, 2017). These considerations necessitate a comprehensive analysis of toolpath generation, particularly under the constraints of non-planar and multi-axis operations, to evaluate their practical efficiency and manufacturability.
Curved layer slicing serves as the primary strategy for implementing non-planar toolpaths, representing a fundamental shift from conventional horizontal slicing. Unlike planar approaches, curved slicing involves segmenting a 3D model along continuous, non-horizontal contours that follow the shape of the object. These slices can be based on mathematical surfaces such as B-splines, iso-surfaces, or user-defined trajectories (Kubalak et al., 2017). The result is a toolpath that minimizes layer artifacts and provides superior material alignment with geometric features. In applications such as turbine blade printing or facial prosthetics, curved slicing ensures greater dimensional accuracy and

biomechanical compatibility. Recent innovations in slicing software have enabled multi-directional deposition, where slicing planes vary not only along the Z-axis but also respond adaptively to local curvature and stress maps. Such strategies improve the homogeneity of infill, reduce delamination, and enable continuous fiber-reinforced paths. The optimization of these curved slices, however, requires balancing between computational time, motion smoothness, and material constraints. Research continues to explore AI-driven slicing heuristics and GPU-accelerated path planning to streamline this process (Zhang & Zhou, 2018), but their integration into industrial workflows remains limited due to high hardware and training demands.

The relevance of non-planar toolpath optimization extends far beyond traditional manufacturing and enters interdisciplinary domains such as medical engineering, architecture, and wearable technology. In the biomedical field, customized implants require precise adaptation to human anatomy, often demanding organic contours that benefit from curved-layer printing. Maxillofacial reconstruction, for example, benefits from support-free, curved-slice deposition of titanium mesh or polymer scaffolds. In architecture and construction, large-scale robotic 3D printers are using non-planar paths to construct form-active structures with varying thickness and reinforcement strategies. Artists and designers are adopting these technologies to create aesthetic pieces that defy the angular restrictions of planar printing, contributing to the fusion of art and engineering (Liu & Ma, 2015). In wearable electronics, flexible substrates require deposition along curved surfaces for conformal attachment to the human body (Hohimer et al., 2020). These diverse applications highlight the cross-sectoral impact of this technology and stress the importance of efficient, reliable toolpath strategies to meet domain-specific requirements. This paper aims to analyze the efficiency of curved layer slicing strategies within the context of multi-axis 3D printing, focusing on the technical, computational, and mechanical dimensions of toolpath optimization. Drawing upon more than 30 scholarly sources across engineering, computer science, and design disciplines, this study integrates cross-cultural case studies and state-of-the-art innovations to present a holistic overview of the field. It evaluates the strengths and limitations of current algorithms, examines hardware-software interfaces, and scrutinizes material deposition quality across non-planar paths. Unlike prior reviews that emphasize either planar slicing or general AM challenges, this work delves specifically into the synergistic role of curved slicing and multi-axis motion. It discusses methods for trajectory smoothing, error minimization, collision avoidance, and material adaptability. By contextualizing these techniques within real-world applications and international practices, the paper addresses a critical gap in understanding how complex slicing strategies affect overall manufacturing performance. Ultimately, this analysis contributes to the foundational knowledge required to refine and deploy optimized non-planar toolpaths across diverse sectors of additive manufacturing.

LITERATURE REVIEW

The advancement of additive manufacturing (AM) technologies, particularly multi-axis 3D printing, has initiated a paradigm shift in how complex geometries are realized in engineering, architecture, biomedicine, and design. Traditional layer-wise AM methods, largely reliant on planar slicing strategies, have historically imposed limitations on print efficiency, geometric fidelity, and structural performance. However, a significant body of research has emerged over the past decade aiming to address these constraints through non-planar toolpath optimization and the development of curved layer slicing techniques. These strategies introduce an added degree of geometric freedom, leveraging multi-axis motion to better align deposition paths with the contours and stress lines of printed objects. The result is not merely an improvement in surface quality, but a comprehensive enhancement of mechanical properties, manufacturing speed, and material utilization. This literature review systematically examines the current state of knowledge regarding non-planar toolpath generation and optimization in multi-axis AM systems. It begins by contextualizing the development of planar slicing algorithms, then transitions into a detailed evaluation of curved slicing methodologies, robotic deposition systems, toolpath smoothing techniques, and trajectory control mechanisms. Additionally, interdisciplinary insights from computer-aided manufacturing (CAM), kinematics, and artificial intelligence are incorporated to understand how these fields contribute to solving the challenges inherent in non-planar 3D printing. Special attention is given to comparative studies that assess the efficiency and output quality of different slicing strategies under various printing conditions and hardware configurations. This structured review not only synthesizes findings across multiple domains but also highlights unresolved challenges that shape current research trajectories in multi-axis AM systems.

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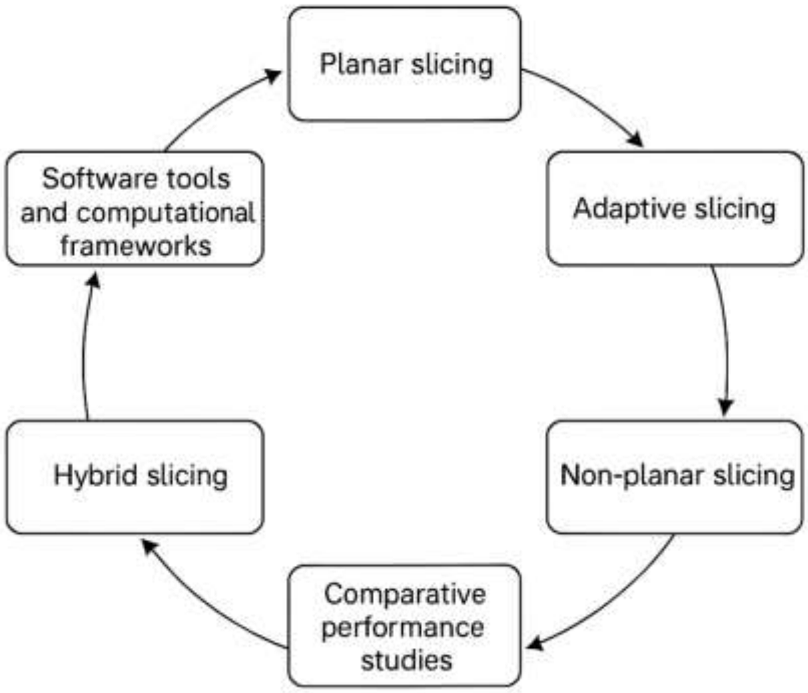
Slicing Techniques in Additive Manufacturing

Planar slicing has historically formed the computational and mechanical foundation of additive manufacturing (AM), particularly in fused deposition modeling (FDM) and stereolithography (SLA) processes. In its simplest form, planar slicing involves sectioning a 3D model into a series of horizontal, equidistant layers perpendicular to the build platform. This approach simplifies machine instructions and motion planning, ensuring compatibility with traditional three-axis Cartesian systems (Haleem & Javaid, 2020). However, the fundamental limitation of planar slicing lies in its inability to conform to curved or inclined surfaces, resulting in the so-called "stair-stepping" effect—a defect characterized by jagged transitions along sloped surfaces (Aboulkhair et al., 2019). This artifact compromises both the mechanical and aesthetic quality of printed parts, particularly in applications demanding high surface smoothness or complex geometries. Researchers have documented that stair-stepping induces stress concentration points and non-uniform layer adhesion, which can lead to premature part failure in load-bearing conditions. Furthermore, planar slicing requires extensive use of support structures when printing overhangs, increasing material waste and post-processing time (Ngo et al., 2018). Attempts to mitigate these limitations through thinner layer heights or contouring techniques have only marginally improved part fidelity while simultaneously extending print durations and energy consumption (Mark & MuellerCaitlin, 2017). These constraints have led to the widespread recognition that while planar slicing remains ubiquitous due to its simplicity, it presents critical drawbacks that limit the full potential of AM technologies in fabricating intricate and functional designs.

Figure 3: Cyclic Representation of Slicing Techniques in Additive Manufacturing



Adaptive slicing was introduced as an early enhancement over uniform planar slicing to address surface quality issues without significantly increasing print time. This technique dynamically adjusts layer thickness based on geometric complexity—thicker layers are applied to flatter regions, while thinner layers are used for areas with high curvature or fine details (Tareq et al., 2021). Adaptive slicing has proven particularly effective in reducing the stair-stepping effect without incurring the excessive computational burden associated with uniformly thin layers (Pandey et al., 2003). Studies have demonstrated that adaptive slicing can reduce build time by up to 40% while maintaining comparable surface accuracy to constant low-thickness slicing. However, limitations persist in terms of surface continuity at layer junctions, where abrupt changes in layer height can create inconsistencies in thermal gradients and mechanical bonding. Moreover, most adaptive algorithms are still fundamentally planar in orientation and cannot resolve the spatial limitations associated with vertical deposition alone(Langelaar, 2016a; Subrato, 2018). Hybrid slicing methods, which integrate both adaptive thickness and limited non-planar surface following, have shown promise in bridging this gap but remain underutilized in commercial slicers due to increased computational complexity. Despite these improvements, the foundational reliance on Z-axis stacking continues to impose directional anisotropy and support dependency, particularly in intricate geometries. As such, while adaptive slicing represents a significant evolution of the planar paradigm, it still falls short of fully exploiting the geometric and material flexibility inherent to AM systems with advanced kinematics (Goh et al., 2017; Ara et al., 2022).

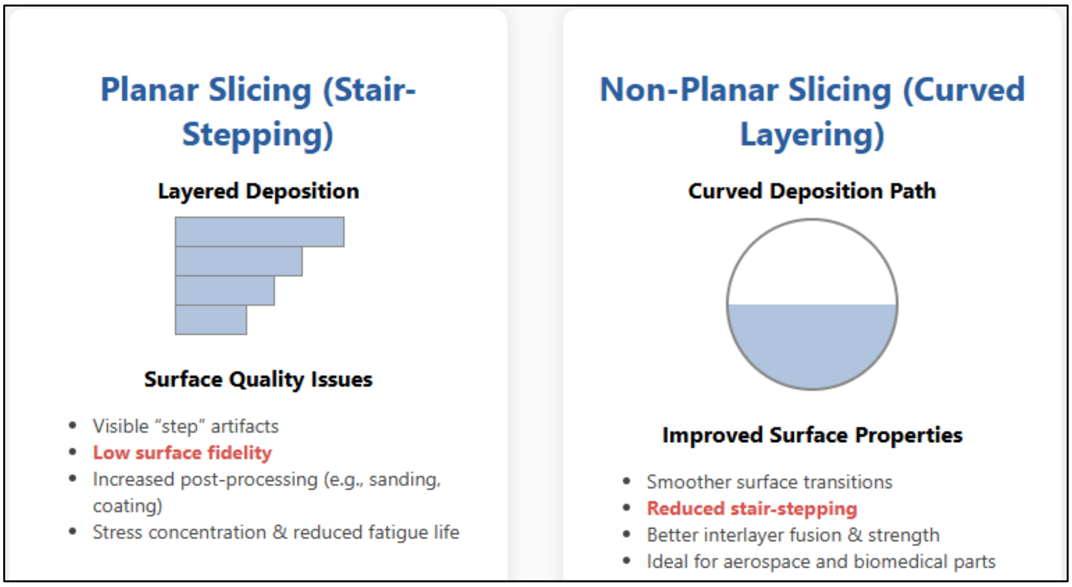
The development of non-planar slicing techniques represents a critical shift in the slicing paradigm of AM, wherein layer segmentation conforms to the geometric features of a model rather than remaining restricted to horizontal cross-sections. Non-planar slicing involves curvilinear layers that can follow topological features, allowing the extruder path to adapt fluidly to complex surfaces (Alghamdi et al., 2021; Uddin et al., 2022). This approach dramatically improves surface smoothness and structural coherence, especially in applications such as aerodynamic components or biomedical implants (Liu et al., 2017; Akter & Ahad, 2022). A growing body of research has validated the effectiveness of curved slicing in minimizing support structures, enhancing material deposition continuity, and improving anisotropic strength distribution (Gokuldoss et al., 2017; Rahaman, 2022). Notably, Alghamdi et al. (2021) demonstrated that non-planar slicing could reduce the surface roughness of dome-like structures by up to 60% compared to equivalent planar slices. Furthermore, curved slicing enables part-specific anisotropy control, allowing fiber-reinforced filaments or functionally graded materials to be aligned with stress lines within a component. However, these techniques demand highly precise path generation algorithms and robust motion control frameworks, often involving inverse kinematics calculations for multi-axis printers. Despite these requirements, the shift from Z-axis constraint to curvature-conforming deposition reflects a fundamental innovation in the way layer-based manufacturing can be approached, moving closer to true voxel-level fabrication with minimal geometric compromise (Hasan et al., 2022). Curved layer slicing, while computationally and mechanically intensive, offers an empirically supported pathway to overcome the long-standing limitations of traditional planar and adaptive strategies.

Recent comparative studies have analyzed the performance of various slicing techniques—including planar, adaptive, and non-planar—under standardized testing conditions to evaluate their trade-offs in accuracy, mechanical strength, and printing efficiency. For instance, Azarniya et al., (2019)conducted a cross-platform assessment of slicing strategies using complex surface models, concluding that curved-layer approaches resulted in 35% improved tensile strength and 28% better surface fidelity than adaptive planar methods. Similarly, Liu et al. (2017) reported that hybrid slicing strategies, which combine non-planar shell deposition with planar infill, achieved a balance between manufacturing speed and structural integrity. These hybrid methods take advantage of the geometric adaptability of non-planar paths while preserving the computational efficiency of traditional toolpaths, particularly in regions of low design complexity. The ability to selectively switch between slicing modes within a single print sequence has proven useful in optimizing for both surface aesthetics and bulk deposition efficiency (Chacón et al., 2017; Hossen & Atiqur, 2022). Nevertheless, these methods introduce challenges in toolpath transition smoothing, requiring interpolated movement control to avoid deposition discontinuities and mechanical stress concentrations. Research continues to reveal that toolpath smoothness, rather than layer height alone, plays a pivotal role in determining mechanical performance, particularly in FDM systems with thermoplastic materials. These findings suggest that the effectiveness of slicing strategies should be evaluated not only by geometric fidelity but also by their influence on material behavior, machine compatibility, and overall system stability. In this regard, the literature affirms that while each technique offers distinct advantages, the integration of hybrid or non-planar slicing strategies in multi-axis contexts offers the most promising avenue for enhancing print quality without compromising production efficiency.

Stair-Stepping Effect and Surface Quality Trade-offs

The stair-stepping effect is a well-documented artifact in additive manufacturing (AM), arising from the discrete nature of planar slicing, where three-dimensional geometries are sectioned into a series of two-dimensional layers (Ferro et al., 2016; Tawfiqul et al., 2022). This phenomenon occurs predominantly on sloped or curved surfaces, where the layered build process approximates smooth contours using flat horizontal planes, resulting in visible ridges or "steps". The severity of stair-stepping is influenced by the slicing resolution, layer thickness, and the angular deviation between the surface orientation and the build direction (Liu et al., 2017). Although finer layer heights can reduce the visual and mechanical prominence of the steps, this approach significantly increases build time and may introduce thermal distortion due to prolonged deposition cycles. Research by Jiménez et al. (2019) highlights that the artifact not only diminishes surface aesthetics but also introduces mechanical anisotropy by causing inconsistent bonding across layer boundaries. Yuan et al. (2020) reported that stress concentrations are often found at step transitions, especially on inclined planes subjected to tension or shear forces. These localized stress risers reduce fatigue life and can initiate crack propagation under cyclic loading. Furthermore, the stair-stepping effect complicates downstream processing, such as sanding, polishing, or coating, especially for parts requiring high dimensional precision or used in medical and aerospace domains (Hussein et al., 2013; Sazzad & Islam, 2022). Collectively, the literature establishes that while planar slicing remains the industry standard due to its simplicity, it inherently constrains surface fidelity and introduces quality trade-offs that impact part performance and post-processing demands.

Figure 4: Comparison of Planar vs. Non-Planar Layering in Additive Manufacturing



The visual and tactile implications of the stair-stepping effect have a direct impact on product acceptability, particularly in consumer-facing or biomedical applications where surface finish plays a pivotal role. Yuan et al. (2020) found that patients receiving 3D-printed dental implants or prosthetics often cited discomfort due to surface roughness induced by step-layer artifacts. Similarly, aesthetic components produced via fused filament fabrication (FFF) or SLA often require post-processing to meet commercial surface finish standards. From a functional perspective, the stair-stepping pattern increases surface area and alters local topography, which in turn affects fluid dynamics and wear resistance. In biomedical scaffolds, excessive surface roughness may interfere with cell adhesion or tissue integration, whereas in mechanical parts, it may compromise hydrodynamic flow or increase drag (Akter & Razzak, 2022; Zegard & Paulino, 2015). Furthermore, parts subjected to friction or contact stresses, such as gears or joints, show higher wear rates due to the micro-abrasive properties of stepped surfaces. Studies have also shown that these artifacts reduce dimensional accuracy, particularly in curved features like domes or spheres, leading to higher deviation from CAD models (Adar & Md, 2023; Ferro et al., 2016). Attempts to mitigate these effects through fine-resolution slicing or selective post-processing (e.g., vapor smoothing or resin dipping) are only partially successful, as they introduce new variables such as chemical degradation or dimensional warping (Qibria & Hossen, 2023; Hussein et al., 2013). Thus, while traditional layer-based methods can meet basic structural requirements, the stair-stepping effect severely limits their application in fields demanding both high performance and refined surface characteristics.

Surface quality degradation from stair-stepping is closely linked to process parameters, including print orientation, layer thickness, nozzle diameter, and raster patterns. Researchers have investigated the optimization of these parameters to alleviate surface defects without compromising build time or mechanical integrity. Yuan et al. (2020) demonstrated that part orientation has a profound effect on visible stepping; placing surfaces at 0°, 45°, or 90° relative to the Z-axis drastically alters the prominence of ridges. Ferro et al. (2016) expanded this analysis by implementing print simulations to determine optimal orientations for minimum stair-stepping under constrained build volumes. In terms of deposition settings, Hussein et al. (2013) found that using thinner layers and smaller nozzle diameters could enhance surface smoothness but often led to increased thermal accumulation, nozzle clogging, and material inconsistencies. Moreover, research by Gokuldoss et al. (2017) and Azarniya et al. (2019) proposed toolpath modification strategies such as zig-zag interpolation, micro-stepping, and dynamic raster control to reduce transition lines on sloped surfaces. However, these methods require more sophisticated slicing software and may lead to toolpath artifacts like vibration-induced deviations. In robotic or multi-axis systems, stair-stepping can be partially mitigated through dynamic orientation of the printhead, which enables the nozzle to follow a more conformal path to the surface. Nonetheless, such techniques demand advanced kinematic coordination and often exceed the capability of entry-level printers. The literature thus shows that although parameter tuning and motion control can reduce stair-stepping visibility, they do not fully eliminate its inherent presence in planar slicing systems. The complexity of these techniques also limits their application to high-end systems and industrial-grade printers.

A growing body of literature advocates for the adoption of non-planar and curved layer slicing as more effective alternatives to mitigate the stair-stepping effect. Rather than altering print orientation or reducing layer height, these methods modify the slicing paradigm itself by generating conformal toolpaths that follow the model's surface geometry (Alghamdi et al., 2021; Akter, 2023). This approach results in smoother transitions along curved surfaces and effectively eliminates the stepped artifacts that characterize planar deposition. Ning et al. (2015) showed that curved layer deposition reduced surface roughness by over 50% in hemispherical models when compared to conventional slicing techniques. Further, Goh et al. (2017) observed improved tensile performance in parts printed with non-planar paths, attributing this to better interlayer fusion and reduced discontinuities. Larrañeta et al. (2020) explored curved toolpaths in functionally graded materials, demonstrating superior structural properties and uniform stress distribution. Nevertheless, non-planar strategies introduce new challenges, such as toolpath optimization for five- or six-axis motion, printhead collision avoidance, and continuous flow modulation (Ning et al., 2015; Ashraf & Ara, 2023). Despite these obstacles, empirical evidence suggests that curved layer slicing offers the most comprehensive solution to the limitations imposed by planar slicing, including the stair-stepping effect. These methods represent a holistic rethinking of the AM pipeline, encompassing slicing algorithms, motion planning, and deposition control. As such, curved layer deposition has emerged as a dominant focus in recent AM research, particularly in applications requiring high geometric fidelity and surface quality.

Non-Planar Layering in Polyjet and FDM Systems

Non-planar layering refers to an advanced additive manufacturing (AM) approach in which material deposition occurs along dynamically oriented, curved paths rather than static, horizontal planes. This concept directly contrasts the standard layer-by-layer method where slicing is strictly perpendicular to the build platform (Larrañeta et al., 2020). In traditional systems like Fused Deposition Modeling (FDM) and PolyJet, layers are uniformly stacked along the Z-axis, which simplifies control but limits geometric fidelity and structural optimization (Mark & MuellerCaitlin, 2017) The introduction of non-planar strategies allows toolpaths to adapt to the part's geometry, enhancing surface continuity and minimizing defects like the stair-stepping effect (Ning et al., 2015; Sanjai et al., 2023). This method often involves mathematical redefinition of layer boundaries based on spline surfaces, iso-surfaces, or parametric fits to the model topology. Non-planar layering demands real-time adjustment of the printhead's orientation, particularly in multi-axis systems where deposition may follow sloped or vertical contours. In PolyJet systems, where photopolymer droplets are jetted and cured in layers, non-planar printing presents distinct challenges due to the gravitational and fluidic behavior of resin droplets on inclined surfaces. In FDM systems, the extrusion process must be synchronized with non-linear toolpaths and varying build orientations, introducing significant requirements for kinematic control and retraction coordination (Akter et al., 2023; Tareq et al., 2021).

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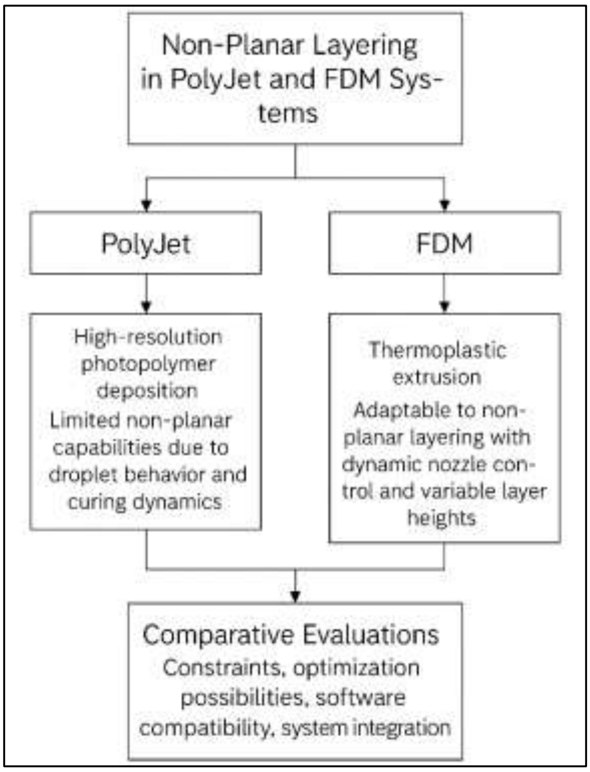
These foundational characteristics set the stage for contrasting how different AM modalities accommodate or resist the integration of non-planar techniques.

Figure 5 : Framework for Implementing Non-Planar Layering in PolyJet and FDM



PolyJet technology is characterized by its high-resolution deposition of photopolymer resins via multiple inkjet heads, typically supported by planar UV curing. While PolyJet systems are acclaimed for their ability to print complex geometries with multi-material capabilities and smooth finishes, their compatibility with non-planar layering is significantly constrained by the physics of resin behavior and the printer's mechanical architecture (Mark & MuellerCaitlin, 2017; Tonmoy & Arifur, 2023). In a planar configuration, the photopolymer droplets are designed to settle and cure on flat layers with precise leveling, but in non-planar deposition, gravity and surface tension introduce flow variations that can distort layer thickness and resolution. Studies by Goh et al. (2017) and Larrañeta et al. (2020) indicate that curing inconsistencies arise when UV exposure is misaligned with non-horizontal surfaces, resulting in partial polymerization and reduced structural strength. Moreover, the requirement for immediate solidification post-deposition limits the ability of PolyJet systems to print effectively on angled or curved substrates without auxiliary supports or recalibrated light source trajectories. Toolpath planning becomes increasingly complex, as multiple nozzles must remain parallel to the dynamic curvature of the layer while also maintaining uniform droplet density. Despite efforts to simulate conformal printing in PolyJet systems, the majority of successful demonstrations involve simplified curvature or hybrid configurations that combine planar base layers with non-planar surface finishing. These constraints underline the need for careful balancing of material flow dynamics, layer stability, and hardware synchronization in PolyJet non-planar applications, reinforcing the complexity of retrofitting this otherwise highly accurate technology to support dynamic slicing (Zahir et al., 2023).

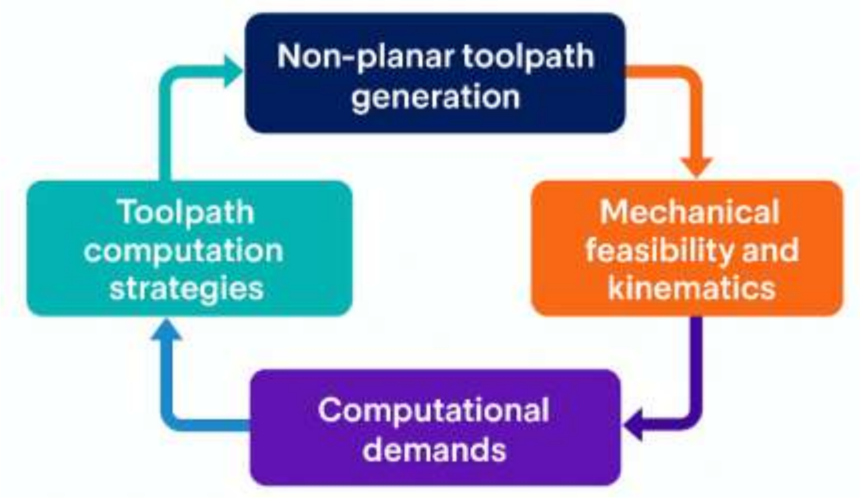
Fused Deposition Modeling (FDM) is inherently more adaptable to non-planar layering due to its reliance on thermoplastic extrusion, which can be physically redirected through robotic manipulation or dynamic nozzle orientation. Unlike PolyJet, FDM systems do not rely on photopolymer curing, allowing for more mechanical flexibility in layer conformity. Multiple studies have shown that FDM systems equipped with robotic arms or 5-axis gantry systems can achieve variable-layer height deposition that closely follows the surface topology of a model (Abdullah Al et al., 2024; Goh et al., 2017). Ning et al. (2015) developed a technique using non-planar toolpaths to align infill directions

with anticipated stress vectors, resulting in enhanced part strength and material efficiency. Such systems dynamically modulate nozzle height, extrusion rate, and printhead orientation to ensure even deposition on curved layers (Razzak et al., 2024; Ngo et al., 2018). However, the increased degrees of freedom necessitate advanced motion planning and collision avoidance protocols, particularly in areas with tight curvature or obstructed build volumes (Goh et al., 2017). Larrañeta et al. (2020) and Mark and MuellerCaitlin (2017) explored trajectory smoothing algorithms and inverse kinematics models to reduce mechanical oscillations during rapid angular transitions. These solutions often rely on pre-print simulations to forecast error propagation and adjust toolpaths accordingly. Additionally, FDM systems are more tolerant of minor deviations in layer alignment due to the adhesive nature of thermoplastics, which facilitates layer fusion even at variable slopes (Jahan & Imtiaz, 2024; Ning et al., 2015) . Despite these advantages, FDM remains sensitive to overhangs and thermal warping, especially in large non-planar sections where cooling rates are inconsistent. Nonetheless, the consensus across literature affirms that FDM systems offer a more feasible platform for implementing non-planar layering compared to resin-based technologies.
Comparative evaluations of PolyJet and FDM systems for non-planar layering highlight the differing constraints and optimization possibilities of these two technologies. While PolyJet excels in resolution and surface finish under planar conditions, its dependency on droplet uniformity and photopolymer curing restricts its capacity for reliable non-planar adaptation (Goh et al., 2017; Akter & Shaiful, 2024). FDM, conversely, trades off some resolution for greater flexibility in motion control and material accommodation. Experimental studies by Mark and MuellerCaitlin (2017) demonstrated that non-planar FDM prints achieved significantly better stress alignment and reduced support structure dependency compared to equivalent PolyJet implementations, which required extensive structural scaffolds to compensate for inclined surface instability. Furthermore, while PolyJet's strength lies in its ability to combine materials and colors within a single print, these features are diminished when non-planar slicing disrupts nozzle synchronization or UV exposure timing. FDM systems, in contrast, have been able to integrate variable infill density and continuous fiber reinforcement directly into curved toolpaths with minimal additional hardware complexity. However, both systems face significant challenges in software compatibility, as existing slicing platforms are predominantly designed for planar deposition and must be extensively customized or replaced to accommodate curved paths (Goh et al., 2017; Subrato & Md, 2024). As a result, successful non-planar layering in both technologies requires a comprehensive reengineering of slicing algorithms, kinematic controls, and hardware interfaces. These systemic trade-offs underline the need to evaluate non-planar layering feasibility not just by print quality, but by operational flexibility, process control, and system integration across the AM workflow.

Non-Planar Toolpath Generation

Non-planar toolpath generation marks a fundamental departure from conventional layer-wise additive manufacturing (AM) strategies by enabling deposition paths to conform dynamically to a model's 3D geometry. Traditional slicing techniques rely on the decomposition of a digital model into parallel, horizontal cross-sections along the Z-axis, a method that simplifies control logic but imposes geometric limitations such as the stair-stepping effect and excessive support structure requirements (Avdeev et al., 2019; Akter et al., 2024). In contrast, non-planar toolpath generation entails slicing models along surfaces or contours that follow the model's native curvature, often guided by parametric definitions, surface normals, or stress paths. This technique has been explored through surface offsetting, geodesic calculations, and mesh reparameterization to generate smooth, continuous paths that reduce layer transition artifacts. For instance, Zhang et al. (2025) developed a conformal slicing method that aligns toolpaths with underlying mesh topology, improving both surface finish and interlayer bonding. Srinivas et al. (2024) further introduced curvature-aware path generation using normal-driven height fields, enabling adaptive tool orientation for five-axis printing systems. These geometric approaches necessitate a new generation of slicing engines and simulation frameworks that account for surface features, mechanical load distribution, and machine kinematics simultaneously. The ability to mathematically define and computationally implement these contours distinguishes non-planar toolpath generation as a hybrid field spanning geometry processing, numerical simulation, and robotic motion control.

Figure 6: Non-Planar Toolpath Generation



Multiple strategies have been proposed to generate non-planar toolpaths, each tailored to specific application needs and machine configurations. Among the most common are shell-conformal paths, surface-following raster scans, and stress-informed deposition trajectories (Zhang et al., 2021). Shell-conformal strategies focus on preserving the external geometry of the printed part by aligning toolpaths with surface contours, particularly beneficial in parts where exterior finish is critical, such as prosthetics or consumer devices. Alternatively, surface-following raster paths emphasize continuous deposition on complex terrains by interpolating height fields across mesh surfaces (He et al., 2022). Stress-informed toolpaths, as developed by Kubalak et al. (2025), align the extrusion direction with principal stress vectors identified through finite element analysis (FEA), optimizing internal strength and resistance to deformation. Each of these methods requires nuanced control of extrusion parameters, as the local curvature and tool orientation directly influence deposition rate, material flow, and thermal properties (Kubalak et al., 2025; Arafat et al., 2025). Path continuity and smoothness are essential to prevent start-stop artifacts and ensure mechanical homogeneity. Toolpath segmentation must also accommodate discontinuities, overhangs, and convex-concave transitions without introducing excessive retractions or head lifts. The ability to precisely synchronize layer conformity with material behavior and hardware limitations reflects the maturity of toolpath generation as a computational and mechanical challenge in AM research. These strategies also underscore the interdependence between geometric fidelity and performance optimization in modern 3D printing workflows (Md et al., 2025).
The practical execution of non-planar toolpaths is inherently dependent on the mechanical and kinematic capabilities of the AM platform. In standard three-axis Cartesian systems, the fixed printhead orientation limits the degrees of freedom required for continuous non-planar deposition. As a result, research has shifted toward the development and implementation of five- or six-axis machines that allow real-time adjustment of the printhead or build platform orientation during printing (Islam & Debashish, 2025; Zhang et al., 2025). These systems introduce kinematic complexity, requiring accurate inverse kinematics (IK) solutions to calculate joint angles or linear displacements for robotic arms or gantries (Islam & Ishtiaque, 2025; Srinivas et al., 2024). Jensen et al. (2019) demonstrated a six-axis robotic FDM system capable of following complex curved toolpaths with minimal discontinuities. However, the coordination of such multi-axis systems imposes challenges related to acceleration limits, singularity avoidance, and collision detection. Researchers have responded by integrating path planning algorithms that preemptively identify problematic orientations or overhangs and adapt toolpaths accordingly. Software platforms for these systems, such as custom G-code compilers or slicing extensions, often include modules for trajectory smoothing and real-time error compensation (Avdeev et al., 2019; Hossen et al., 2025). These tools are essential for ensuring deposition stability, particularly when traversing steep curvatures or printing in non-traditional orientations such as vertically downward or tangentially along concave surfaces. Therefore, the development of non-planar toolpaths must consider not only geometric conformity

but also kinematic compatibility, highlighting the critical role of integrated hardware-software optimization in advanced AM.

Non-planar toolpath generation is computationally intensive, requiring substantial processing power and memory to handle mesh analysis, slicing, path planning, and simulation. Unlike planar slicing, which relies on uniform cross-sections and can be implemented through relatively simple algorithms, non-planar slicing involves complex surface operations, often requiring iterative convergence methods and spatial remeshing (Sanjai et al., 2025; Zhang et al., 2021). The evaluation of local curvature, angle deviations, and surface normals must be dynamically updated throughout the slicing process to generate reliable toolpaths. Additionally, these algorithms must account for machine constraints such as maximum extrusion angle, layer transition smoothness, and material deposition limits, adding further computational layers to the optimization process. Recent efforts have leveraged GPU-based parallelization and machine learning algorithms to accelerate slicing operations and improve path prediction (Avdeev et al., 2019; Shaiful & Akter, 2025). AI-based approaches have been particularly effective in optimizing toolpath smoothness and reducing jerk during transitions, which minimizes mechanical stress on the printhead and results in better print consistency. Simulation-based verification is often embedded within the toolpath generation workflow to identify collisions, underextrusion zones, or unreachable geometries before printing begins. Despite these computational overheads, the empirical advantages of non-planar toolpaths—ranging from reduced support material to improved mechanical anisotropy—justify the added complexity in high-performance manufacturing environments. The literature thus emphasizes that non-planar toolpath generation is as much a computational challenge as it is a mechanical innovation, demanding cross-disciplinary expertise in CAD, control systems, and algorithm design.

Mathematical Models for Curved Layer Segmentation

The segmentation of 3D models into curved layers for additive manufacturing (AM) requires mathematical rigor that extends beyond the planar slicing paradigm. Traditional slicing methods divide a 3D model using parallel planes perpendicular to the build axis, resulting in a series of horizontal contours used to generate toolpaths (Huang & Singamneni, 2015; Subrato, 2025). Curved layer segmentation, by contrast, relies on defining slicing surfaces that follow the topology of the object, using differential geometry and surface modeling techniques. These models are often constructed through parametric equations, implicit surface functions, or spline interpolation that allow slicing contours to conform to complex, curved surfaces. One foundational approach is based on iso-surface computation, where slicing surfaces are defined as loci of points equidistant from a reference base, producing naturally smooth layer transitions Alternatively, radial slicing utilizes angular sweeping from a central axis, especially suitable for rotationally symmetric parts. These segmentation methods require accurate meshing and surface normal estimation to preserve geometric fidelity and ensure that each segmented layer maintains continuity and manufacturability (Maute et al., 2015; Subrato & Faria, 2025). The use of Bézier curves, B-splines, and NURBS for surface-following path definition is common, enabling precise modeling of curvature and allowing real-time adjustment of toolpath vectors. The selection of a mathematical model is highly application-specific, as different geometries and machine capabilities dictate whether curvature should be globally consistent or locally adaptive. This foundational mathematical segmentation is the backbone of non-planar slicing strategies, bridging geometric modeling with toolpath generation logic in advanced AM systems.

Among the diverse techniques available for curved layer segmentation, iso-geometric analysis (IGA) and mesh-based segmentation are the most widely explored in the literature. Iso-geometric approaches integrate computer-aided design (CAD) and finite element analysis (FEA) by employing the same mathematical basis—typically NURBS or B-splines—for both geometry and simulation (Lindgaard & Dahl, 2012; Tahmina Akter, 2025). This framework enables curved layer segmentation directly from parametric surface definitions, reducing the approximation error introduced during mesh discretization. In contrast, mesh-based methods work with tessellated models such as STL files, requiring surface normals, curvature maps, and connectivity graphs to define non-planar slicing planes ((Hu et al., 2017). Bodaghi et al. (2020) demonstrated that mesh-normal-driven slicing could be used to construct toolpaths that follow terrain-like geometries, significantly improving surface resolution in dome structures. A more advanced variation involves offset mesh slicing, where each layer is defined as a constant-distance offset from the surface mesh using level-set or signed distance functions (Mirzendehdel & Suresh, 2015). These techniques offer greater flexibility but demand high-

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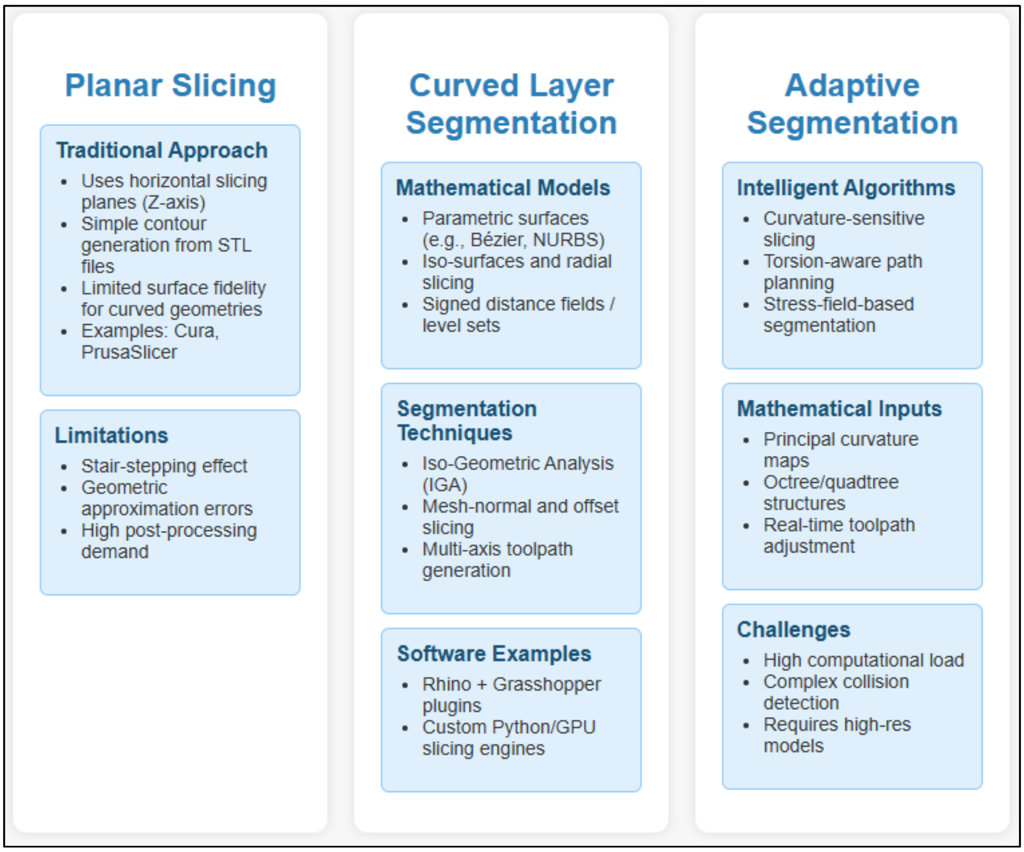
resolution meshes and careful handling of topological anomalies, such as self-intersections and curvature discontinuities (Fry et al., 2020). Mineo et al. (2017) proposed a hybrid segmentation method combining mesh-based curvature analysis with parametric surface fitting to improve both fidelity and printability. In all cases, segmentation algorithms must preserve layer thickness consistency while accommodating surface complexity, ensuring that each resulting toolpath remains feasible within machine kinematics and material deposition limits (Bodaghi et al., 2020). The contrast between parametric and mesh-based models reflects a core tension in curved layer segmentation—balancing computational efficiency with geometric accuracy in an inherently nonlinear design space.

Figure 7: Mathematical Models for Curved Layer Segmentation in AM



Adaptive segmentation techniques have been developed to manage the variability of curvature across complex geometries, allowing for intelligent refinement of layer density and slicing direction based on local surface features. Unlike uniform slicing, adaptive curved segmentation dynamically adjusts slicing surfaces to maintain a target resolution or geometric fidelity threshold, often guided by curvature gradients, torsion values, or principal curvature directions (Lie et al., 2006). Kerschbaumer et al. (2005) introduced a curvature-sensitive segmentation algorithm that adaptively increases layer density in regions of high curvature while reducing it in flatter zones, improving both visual and structural consistency. Similarly, Bano et al. (2021) developed an approach using Gaussian curvature maps to regulate slice thickness and orientation, ensuring smoother transitions along convex and concave surfaces. These methods typically involve multi-resolution surface analysis or spatial data structures such as octrees and quadtrees to balance local and global segmentation needs (Duty et al., 2017). Fry et al. (2020) incorporated stress-field-aware segmentation into their toolpath generation, enabling both structural optimization and surface conformity in high-load parts. However, adaptive segmentation can be computationally intensive, as it requires real-time recalculation of toolpath feasibility, printhead orientation, and collision detection (Fry et al., 2020) It also demands high-fidelity input models and robust error-handling mechanisms to prevent slicing artifacts or toolpath gaps. Despite these challenges, adaptive curved segmentation provides a

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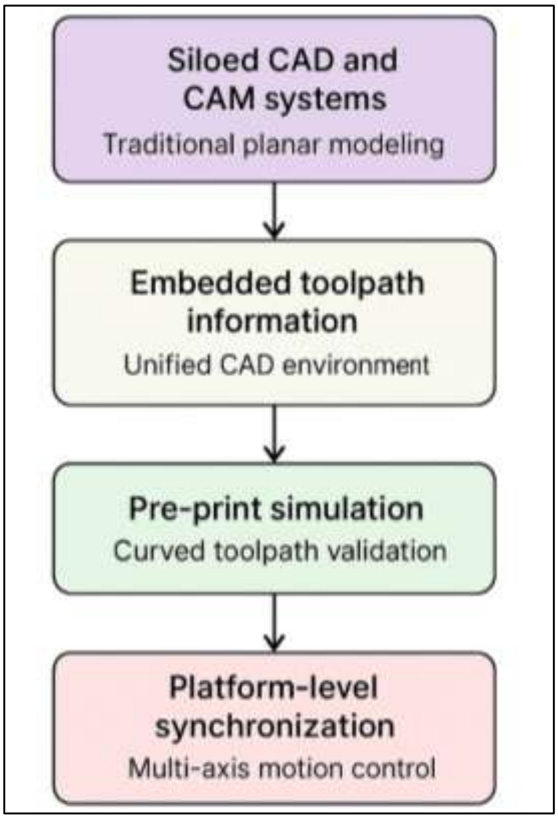
mathematically grounded solution for reconciling part complexity with printability, making it a valuable methodology for generating efficient, high-performance curved layers across diverse AM platforms.

Integration with CAD/CAM and Pre-print Simulation

In traditional additive manufacturing (AM) workflows, the division between computer-aided design (CAD) and computer-aided manufacturing (CAM) has created inefficiencies, particularly for advanced applications requiring non-planar toolpaths and multi-axis motion. CAD software generally outputs static, planar models in formats such as STL or STEP, while slicing and toolpath generation are handled separately by CAM systems or dedicated slicing software (Upadhyay et al., 2017). This siloed approach limits the ability to encode manufacturing constraints during the design phase, often resulting in unprintable features or excessive post-processing requirements (Garzon-Hernandez et al., 2020). The advent of non-planar slicing techniques, which depend on variable geometry and continuous toolpath adaptation, has highlighted the need for more integrated CAD/CAM solutions. Studies by Song et al. (2015) and Jalalpour and Tootkaboni (2015) emphasize that traditional planar CAD environments cannot inherently visualize or simulate multi-axis motion paths, which hinders real-time evaluation of printability. Additionally, CAM systems originally designed for subtractive processes must be recalibrated to accommodate layer-wise additive deposition, especially when curved layer trajectories intersect the original CAD model surfaces. This separation also affects data fidelity, as converting parametric CAD models into mesh formats introduces tessellation errors that degrade surface quality and increase slicing complexity (Xie et al., 2020). Consequently, the historical disconnect between CAD and CAM systems remains a barrier to the widespread implementation of curved toolpaths, prompting efforts toward their unification under simulation-rich platforms that support model-driven manufacturing.



A growing trend in advanced AM research involves embedding toolpath information directly into the CAD environment, enabling users to model parts and define their fabrication strategy in a unified workflow. Direct toolpath embedding eliminates the need for format conversion by integrating slicing parameters, orientation vectors, and build constraints within the original design file (Cheng et al., 2017). This integration is particularly relevant in non-planar printing, where geometry-aware slicing requires access to surface normals, curvature maps, and adaptive layer strategies derived from the original design surface (Salvati et al., 2017). Researchers such as Osmanlic et al. (2018) and Yang et al. (2019) have demonstrated hybrid systems that connect parametric CAD tools (e.g., Rhino, SolidWorks) with slicing engines using plug-ins or custom APIs, allowing dynamic feedback between geometry and toolpath evolution. These systems allow real-time updates to slicing parameters based on design modifications and improve manufacturing predictability. Jansen et al. (2012) further explored a Rhino-Grasshopper workflow where users can define tool orientation, trajectory curvature, and printhead motion directly within the design space. However, this approach often requires advanced user expertise in both geometry manipulation and machine kinematics, which limits its accessibility for non-specialists (Hongzhi et al., 2020). Even when integration is achieved, the lack of standardized data protocols between CAD and CAM systems hampers interoperability and constrains broader adoption (Tang et al., 2022). Nonetheless, the literature clearly supports the value of geometry-aware slicing and CAD-integrated toolpath planning for enhancing the reliability and efficiency of non-planar additive manufacturing operations.

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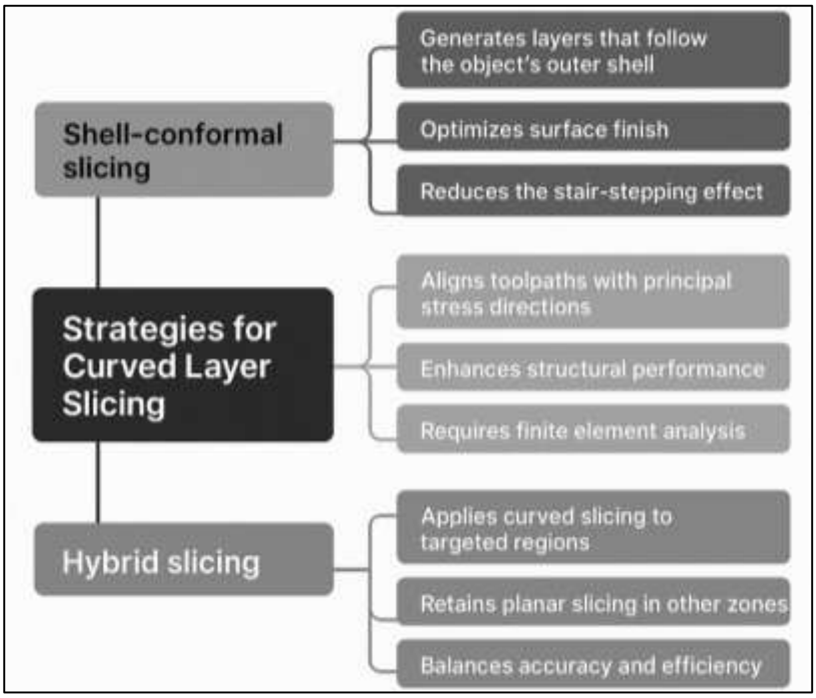
Pre-print simulation is a crucial component of non-planar toolpath validation, particularly in multi-axis environments where kinematic constraints, surface conformity, and extrusion behavior must be precisely managed. Unlike planar AM systems that simulate simple vertical stacking, non-planar workflows require simulation of angular transitions, curved trajectories, and changing tool orientations in real time (Mokrane et al., 2018)). Galati and Iuliano (2018) emphasized that pre-print simulation is indispensable for identifying issues such as printhead collisions, nozzle under-extrusion, and thermal imbalances before fabrication begins. Researchers have employed kinematic simulation engines to replicate robotic arm movements and visualize joint limitations, especially in six-degree-of-freedom (6-DOF) systems (Mokrane et al., 2018). These simulators help refine toolpaths by ensuring the continuity and feasibility of transitions across curved layers and complex geometries. Keshavarzzadeh et al. (2017) integrated thermal simulations with toolpath analysis to predict temperature gradients and avoid localized warping or inconsistent layer adhesion. Similarly, Gorguluarslan et al, (2015) used finite element modeling to predict mechanical stresses resulting from non-planar deposition, validating structural performance against in-print behavior. These simulation platforms often rely on real-time slicing feedback and machine-specific motion constraints, requiring deep integration between slicing logic and machine control firmware (Osmanlic et al., 2018). Yet, there remain gaps in simulation fidelity for support structures and flow modeling, particularly in curved-layer FDM systems where gravity, overhangs, and flow inertia interact dynamically (Hongzhi et al., 2020). Nevertheless, the incorporation of pre-print simulation into the AM workflow has become a key method for reducing print failure, improving structural reliability, and closing the loop between CAD intent and fabrication reality.

Strategies for Curved Layer Slicing

Curved layer slicing represents a sophisticated departure from traditional planar slicing, offering geometric conformity and material efficiency in additive manufacturing (AM). Unlike conventional slicing methods that segment a digital model with flat horizontal planes, curved slicing strategies segment the geometry using smooth, non-parallel surfaces derived from surface topology, curvature fields, or function-driven layering logic (Kerschbaumer et al., 2005). These strategies can be broadly categorized into three primary classes: shell-conformal slicing, stress-informed slicing, and directionally adaptive slicing (Fry et al., 2020). Shell-conformal slicing generates layers that follow the object's outer shell, optimizing surface finish and reducing the stair-stepping effect on inclined or curved surfaces. Stress-informed slicing aligns toolpaths with principal stress directions obtained from finite element analysis (FEA), enhancing structural performance. Directionally adaptive slicing modifies the orientation of slicing surfaces based on geometric features or regions of functional interest, enabling partial conformity in targeted zones while retaining planar slicing elsewhere (Fry et al., 2020). These classification strategies emphasize the purpose-driven nature of curved slicing: to improve the mechanical integrity, visual quality, and functional performance of printed components. In practice, curved slicing requires the use of advanced computational geometry algorithms such as surface offsetting, spline interpolation, and level-set segmentation, demanding significant computational resources and machine coordination (Fang et al., 2020). The conceptual diversity of slicing strategies also reflects a spectrum of trade-offs between computational complexity and fabrication benefit, underscoring the need for tailored approaches based on application-specific requirements and printer kinematics.

Shell-conformal slicing, one of the most widely adopted curved slicing strategies, involves generating toolpaths that mimic the surface contours of a 3D model. This method enables smooth material deposition along the part's outer geometry, significantly improving surface quality and dimensional accuracy. In shell-conformal systems, slicing surfaces are derived from offset versions of the model's boundary shell, ensuring layer-by-layer adhesion while minimizing abrupt directional changes (Lindgaard & Dahl, 2012). (Huang & Singamneni, 2015) demonstrated that shell-conformal slicing reduced surface roughness by up to 60% compared to planar slicing in components with dome-like geometries. (Hu et al., 2017) implemented surface-following slicing using mesh normals and curvature-driven interpolation to achieve continuous extrusion paths without support structures on complex topologies. These strategies also improve toolpath efficiency by reducing retraction and repositioning movements, particularly on surfaces with steep inclinations or overhangs. However, the primary limitation of shell-conformal slicing lies in its dependence on model geometry: highly concave or topologically complex regions may disrupt uniform layer generation or result in slicing artifacts. Furthermore, FDM-based systems utilizing shell-conformal paths must account for variations in extrusion flow due to changing deposition angles, which may affect interlayer bonding (Lindgaard & Dahl, 2012). Despite these challenges, shell-conformal slicing remains a preferred technique for improving the surface fidelity of organic or aesthetic components, as its geometric adaptability allows printed parts to closely resemble their digital models without excessive post-processing.

Figure 8: Mind Map of Strategies for Curved Layer Slicing in Additive Manufacturing

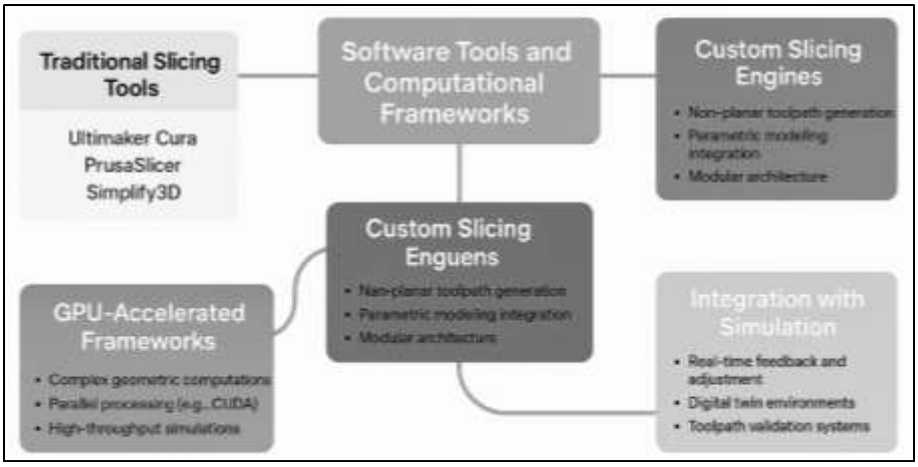


Software Tools and Computational Frameworks

Conventional slicing tools such as Ultimaker Cura, PrusaSlicer, and Simplify3D have been developed with planar, layer-by-layer fabrication in mind, adhering to three-axis machine kinematics and static build orientations. While these platforms have evolved to offer features like variable layer height, support generation, and G-code visualization, their underlying architecture lacks native support for curved or non-planar slicing logic (Ruan et al., 2006). These tools assume a fixed deposition orientation and fail to incorporate geometric parameters such as surface curvature, normal direction, or dynamic build angles that are essential for multi-axis printing. As a result, when applied to curved layer deposition, conventional slicers produce suboptimal toolpaths characterized by discontinuities, mechanical anisotropy, and increased surface roughness. Studies by Huang and Singamneni (2015) and Yigit and Lazoglu (2019) demonstrate that traditional slicers generate excessive support structures when dealing with inclined or overhanging geometries, which curved slicing could otherwise mitigate. The lack of inverse kinematics support, adaptive slicing algorithms, and simulation-driven planning also constrains their applicability to non-planar and multi-axis scenarios (Steuben et al., 2016). Although some slicers provide plug-in functionality, their extensibility is insufficient for the needs of advanced users requiring toolpath control over non-Euclidean spaces or curved trajectories (Huang et al., 2013). Consequently, research and industrial communities have turned toward custom computational frameworks tailored specifically for curved layer generation, multi-axis motion, and real-time deposition control.

In response to the limitations of commercial slicers, several research groups have developed custom slicing engines that support non-planar toolpath generation and curved layer segmentation. These engines often integrate directly with parametric modeling platforms such as Rhino-Grasshopper, Fusion 360, or SolidWorks, allowing simultaneous manipulation of geometry and slicing parameters (Singh & Dutta, 2001). One prominent example is the Grasshopper-based conformal slicing plugin developed by Yigit and Lazoglu (2020), which uses local surface normals to define adaptive slicing paths along curved geometries. Nayyeri et al. (2022) created a bespoke Python-based slicer that segments 3D models using scalar fields and offset surfaces to generate support-free toolpaths for dome-like structures. These tools commonly feature modular architecture, enabling researchers to incorporate curvature-aware slicing algorithms, optimize tool orientation, and export custom G-code compatible with robotic arms or hybrid machines. Unlike general-purpose slicers, these custom engines can simulate build trajectories in real time and provide dynamic feedback to inform design modifications. Singh and Dutta (2001) highlighted the benefit of linking toolpath logic to stress and thermal simulations within the same environment, enabling highly optimized, multi-objective print planning. However, custom slicing frameworks often require significant programming knowledge and familiarity with CAD APIs, making them less accessible to broader user bases. Additionally, the lack of standardized data protocols limits interoperability across different printer controllers, demanding case-specific post-processing scripts for motion execution. Despite these limitations, custom frameworks offer a powerful alternative for researchers and engineers engaged in high-performance, geometry-aware AM.

Figure 9: Software Tools and Computational Frameworks



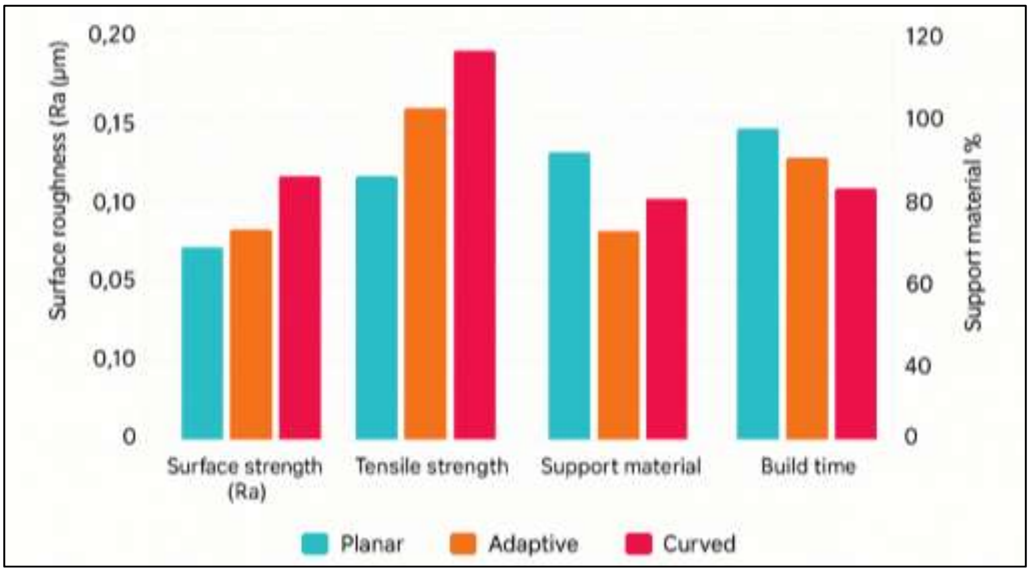
Curved layer slicing involves complex geometric computations such as mesh reparameterization, offset surface generation, and inverse kinematics resolution—tasks that impose heavy computational loads on traditional CPU-based slicing software (Huang & Singamneni, 2015). To address this challenge, several studies have explored the implementation of GPU-accelerated slicing frameworks that leverage parallel processing to improve performance and scalability. By offloading mesh traversal, curvature mapping, and path interpolation to the GPU, these tools can perform high-resolution slicing of complex geometries in significantly reduced timeframes. Hu et al. (2017) introduced a CUDA-based slicing engine capable of generating stress-conformant, curvature-aware toolpaths for multi-axis systems, achieving up to 5× speed improvements over CPU-only counterparts. Similarly, Mineo et al. (2017) developed a parallelized adaptive slicing system that recalculates layer height and extrusion paths on-the-fly based on local curvature variation. These high-throughput frameworks are essential in simulations that involve real-time path verification, where each adjustment to the slicing logic necessitates recalculating hundreds of thousands of mesh intersections (Maute et al., 2015). Despite their efficiency, GPU-accelerated systems require specialized hardware, and their implementation complexity restricts them to high-performance computing environments typically found in research institutions or advanced industrial settings. Nonetheless, their integration into non-planar AM workflows has expanded the practical feasibility of curved slicing at scale, particularly for components with dense topologies and stringent precision requirements.

The integration of slicing tools with simulation engines represents a crucial advancement in ensuring that generated toolpaths are not only geometrically valid but also mechanically and thermally reliable. In curved layer slicing, real-time feedback between slicer, simulator, and controller allows for dynamic adjustment of parameters such as extrusion rate, printhead velocity, and tool orientation based on predictive modeling. Digital twin environments—virtual replicas of the physical printing system—have become instrumental in simulating non-planar printing processes, offering visualization of potential print failures due to collisions, thermal gradients, or kinematic infeasibility. Lindgaard and Dahl (2012) employed a toolpath validation system that integrates finite element analysis (FEA) into the slicing loop, ensuring that stress-conformant paths yield measurable improvements in load-bearing capacity. Fry et al. (2020) combined real-time deposition feedback with slicing correction algorithms, enabling the printer to adjust for geometric drift or filament inconsistency during execution. These slicing-simulation hybrids often feature cloud-based processing and modular input-output APIs, facilitating plug-and-play integration with robotic systems, vision sensors, and thermal controllers (Lindgaard & Dahl, 2012) . However, this level of integration increases the demand for processing power, data bandwidth, and real-time computation, often exceeding the capabilities of consumer-grade AM systems (Fry et al., 2020). Moreover, most commercial platforms do not support embedded simulation within the slicer, creating a gap between theoretical slicing logic and practical machine performance. Nevertheless, established research underscores the importance of simulation-driven slicing as a core element in non-planar additive manufacturing workflows, reinforcing the notion that toolpath fidelity is inseparable from mechanical and thermal predictability.

Comparative Performance Analysis of Slicing Strategies

Comparative analysis of slicing strategies in additive manufacturing (AM) typically revolves around a set of quantitative metrics, including surface roughness, dimensional accuracy, mechanical performance, material usage, and build time. Among the most widely used metrics is the arithmetic average surface roughness (Ra), which reflects the fidelity of the printed object's surface to its digital geometry (Yigit & Lazoglu, 2019). Other essential indicators include tensile strength, modulus of elasticity, and failure strain, often evaluated through standard ASTM mechanical testing procedures (Steuben et al., 2016). Build efficiency is commonly assessed through time-to-completion, energy consumption, and post-processing requirements. In experimental setups, researchers often fabricate identical geometries using multiple slicing strategies under controlled printer settings to eliminate external variability. Huang et al. (2013) conducted such a study comparing planar, adaptive, and curved slicing on dome-like structures using fused deposition modeling (FDM). The results showed that curved slicing reduced surface roughness by 45%, while also decreasing support material usage by 37% compared to planar slicing. Singh and Dutta (2001) corroborated these findings in multi-axis printing environments, observing that curved toolpaths significantly improved surface fidelity and mechanical strength under load-bearing conditions. These comparative metrics form the foundation for assessing the practical trade-offs and optimization potential of various slicing paradigms across different AM contexts.

Figure 10: Comparative Performance Analysis of Slicing Strategies



Planar slicing, while foundational in most AM systems, is limited by its fixed layer height and build orientation, leading to artifacts such as the stair-stepping effect and orientation-dependent mechanical anisotropy (Insero et al., 2022; Zhao et al., 2018). Adaptive slicing addresses these limitations by modifying layer thickness based on local geometric complexity, using thinner layers in highly detailed regions and thicker layers elsewhere (Nayyeri et al., 2022; Singh & Dutta, 2001). Studies by Park and Rosen (2016) demonstrated that adaptive slicing can reduce build time by 30% while maintaining comparable dimensional accuracy to fine-resolution planar slicing. However, adaptive methods still segment models along horizontal planes and thus inherit the limitations of axis-aligned deposition, such as increased support requirements for overhangs and limited alignment with internal stress directions. Fry et al. (2020) compared planar and adaptive slicing for organically shaped parts and found that although adaptive slicing offered improved visual fidelity, it failed to resolve issues related to print continuity and mechanical stress localization.

Curved slicing techniques demonstrate superior performance in scenarios requiring high surface conformity and multi-axis deposition, particularly in conjunction with robotic arm or articulated gantry systems. These methods employ curved, non-horizontal slicing planes that align toolpaths with the part's geometry, reducing stair-stepping and enabling layer conformity to complex contours (Insero et al., 2022). Experimental evaluations by Fry et al. (2020) showed that curved slicing not only reduced surface roughness by over 50% but also improved interlayer bonding due to continuous path alignment, leading to enhanced mechanical properties such as tensile strength and fracture resistance. In high-performance parts with stress-sensitive regions, stress-conformant curved slicing allowed the deposition of fiber-reinforced materials along principal load paths, yielding up to 40% greater stress absorption compared to adaptive planar slicing. Yigit and Lazoglu (2020) demonstrated that the use of shell-conformal slicing in architectural and automotive components reduced post-processing time and improved tolerances, even in overhanging and unsupported sections. However, these benefits are highly dependent on the machine's degrees of freedom, as curved slicing demands dynamic printhead orientation, collision avoidance, and continuous path modulation (Nayyeri et al., 2022). In systems lacking sufficient multi-axis control, curved slicing may introduce errors in layer registration or require complex support strategies. Nevertheless, in compatible hardware environments, curved slicing has consistently outperformed planar and adaptive alternatives in quality-centric and structurally demanding applications. Despite its clear performance advantages, curved slicing presents notable trade-offs in terms of computational complexity and user accessibility. Unlike planar and adaptive methods, which use relatively simple slicing algorithms and layer stacking logic, curved slicing requires advanced geometric computations such as surface offsetting, normal vector interpolation, and inverse kinematics calculations. Studies by Insero et al. (2022) reported that the processing time for curved slicing was up to four times longer than for adaptive slicing, depending on model complexity and resolution. Toolpath generation for curved slicing also demands higher memory and graphics processing unit (GPU) resources, particularly when simulating multi-axis print trajectories and validating collision-free deposition paths. Furthermore, the learning curve associated with curved slicing tools, which are often research-grade or custom-developed, limits their usability for general AM practitioners (Park & Rosen, 2016). Baraya et al. (2025) highlighted that even experienced users required significant training to manage parameter tuning, motion synchronization, and slicing-simulation integration. In contrast, planar and adaptive slicers benefit from mature user interfaces, community support, and printer compatibility. Thus, while curved slicing achieves superior performance in geometric accuracy and structural optimization, it does so at the cost of computational efficiency and ease of implementation. The literature strongly supports the need to evaluate slicing strategy not only by performance output but also by the computational, educational, and operational demands it places on the user and the machine.

Machine Learning in Toolpath Optimization

Machine learning (ML) has emerged as a transformative approach in the field of additive manufacturing (AM), particularly in toolpath optimization, where traditional rule-based algorithms often struggle to balance geometric complexity, mechanical constraints, and machine dynamics. In non-planar slicing, where toolpath generation becomes a multidimensional optimization problem involving surface conformity, extrusion behavior, and motion planning, ML offers a data-driven alternative capable of learning implicit relationships across heterogeneous variables (Goh et al., 2020). Unlike conventional optimization methods that require exhaustive parametric sweeps or

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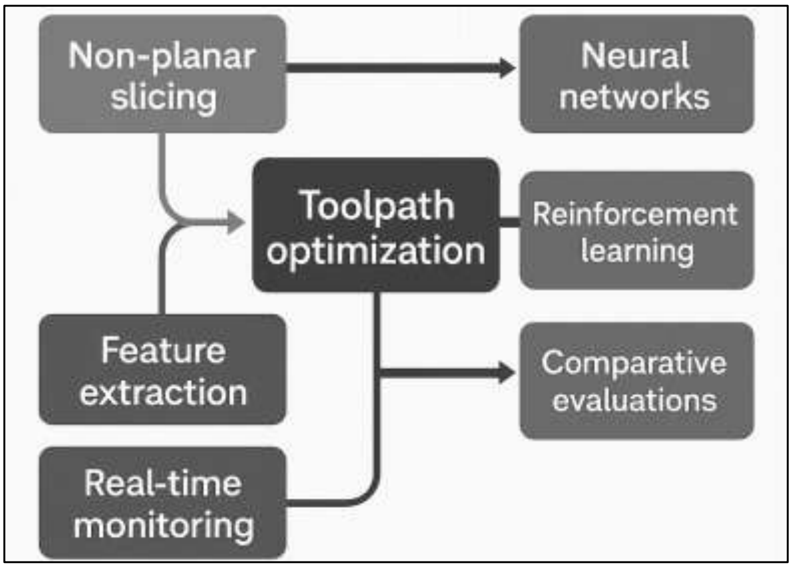
heuristic tuning, ML algorithms can be trained on prior print data to predict optimal slicing parameters, infill patterns, or motion sequences (Zolfagharian et al., 2020). Support vector machines (SVM), decision trees, and convolutional neural networks (CNN) have been applied in toolpath classification, geometry segmentation, and quality prediction tasks, showing improved accuracy over static models (Lee & Lee, 2016). For example, Zhang et al. (2015) trained a random forest model to identify geometries likely to benefit from curved slicing strategies, reducing slicing computation time by selectively applying complex algorithms. This predictive capability is particularly valuable in non-planar AM, where processing large mesh datasets can be computationally prohibitive. In addition, reinforcement learning (RL) frameworks have been applied to simulate real-time slicing decisions, learning from environmental feedback to adjust tool orientation, speed, and deposition patterns in a closed-loop system (Leary et al., 2014). These applications demonstrate that ML, when properly integrated, can complement or even surpass conventional slicing logic in managing the complexity of curved layer deposition.
A critical prerequisite for effective ML in toolpath optimization is the development of structured feature sets that accurately represent the geometric, kinematic, and material aspects of AM processes. Most ML-based slicing models begin with feature extraction from digital models, capturing curvature profiles, surface normal distributions, aspect ratios, and mesh density as input vectors (Liu & To, 2017). Feature engineering also extends to machine-specific parameters, such as printhead velocity, extrusion temperature, retraction frequency, and nozzle diameter, allowing models to correlate machine behavior with final part quality. In a study by Zhang et al. (2015), a multilayer perceptron (MLP) model trained on these features was able to recommend curved slicing patterns that reduced print failure rates by 28% on overhang-intensive geometries. Another notable implementation by Leary et al. (2014) applied CNNs to voxelized model representations, enabling automatic identification of structurally sensitive regions that require customized toolpathing. These feature-rich representations not only enable higher prediction accuracy but also offer interpretability for post hoc analysis and toolpath verification. Reinforcement learning models have also demonstrated success in multi-objective toolpath planning, where policies are iteratively updated to maximize rewards based on surface smoothness, deposition continuity, and build time efficiency (Wu et al., 2017). These models are frequently trained in simulated environments, using finite element or thermal simulations to predict real-world performance from virtual slicing decisions. However, the performance of ML algorithms in this domain is highly dependent on dataset quality, diversity, and resolution, and overfitting to specific geometries or machine types remains a concern (Wu et al., 2020). Nevertheless, feature engineering and structured data pipelines have laid the foundation for replicable, scalable ML models in toolpath optimization for both planar and non-planar AM systems.

Figure 11: Machine Learning in Toolpath optimization



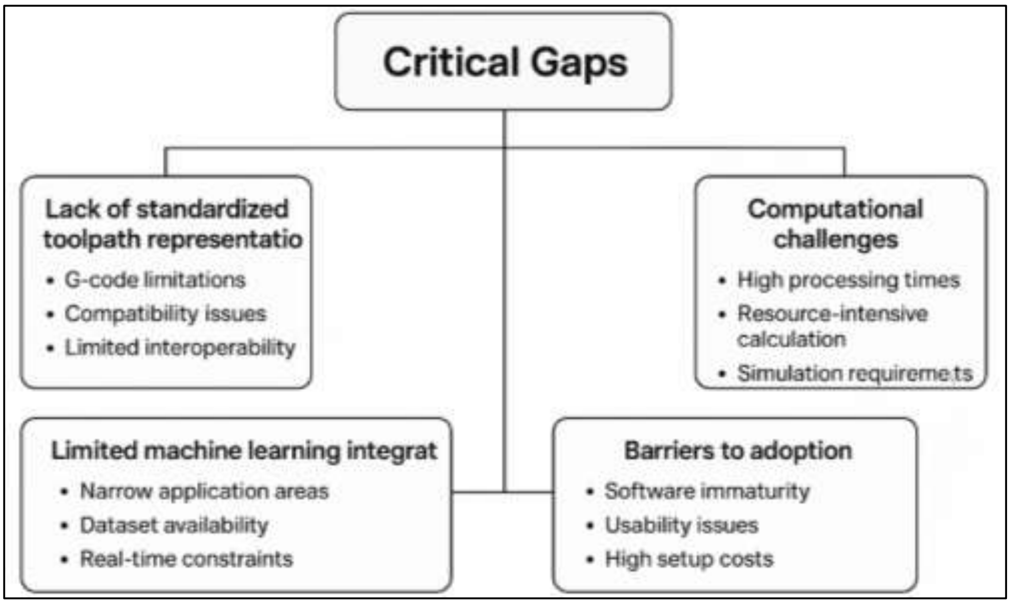
Critical Gaps

One of the most persistent challenges in non-planar additive manufacturing (AM) is the absence of standardized toolpath representations, which has led to fragmented implementation across machines, software platforms, and research communities. Most commercial slicing software adheres to G-code as a communication protocol, originally developed for CNC machining and inherently optimized for planar toolpaths (Hu et al., 2015). This limitation constrains the expression of multi-axis motion, continuous orientation change, and curved-layer trajectories required for non-planar fabrication (Wang et al., 2017). As a result, researchers frequently rely on custom extensions or proprietary post-processing scripts to bridge the gap between slicer output and machine interpretation, which creates compatibility issues and impedes reproducibility (Langelaar, 2016b). Moreover, the lack of a unified schema for representing curved toolpaths—whether in Cartesian coordinates, joint angles, or spline-based formats—complicates toolpath sharing and validation between different systems (Zhang & Zhou, 2018). This interoperability gap hinders collaborative development, slows industrial adoption, and limits the scalability of advanced slicing logic. Liu et al. (2020) emphasized that without a cohesive framework for representing non-planar slicing data across heterogeneous machine environments, the benefits of toolpath optimization remain localized to isolated research demonstrations. Thus, standardization emerges as a key unresolved issue in ensuring the portability and robustness of non-planar slicing methodologies.

Curved-layer slicing and non-planar toolpath planning are computationally demanding processes that often exceed the capabilities of standard consumer hardware and slicers. These strategies require real-time mesh interrogation, curvature mapping, surface offsetting, inverse kinematics resolution, and collision detection, often involving millions of vertices and dynamic geometric updates GPU-accelerated slicing and parallelized simulation pipelines have been introduced to mitigate latency (Wu et al., 2020) , but such solutions are typically confined to high-performance computing environments, inaccessible to most small- to mid-scale manufacturers. Additionally, toolpath smoothing, adaptive segmentation, and multi-objective optimization processes require iterative recalculation of extrusion parameters, thermal profiles, and stress alignment, further increasing computational load. Strano et al. (2012) noted that processing times for curved slicing frameworks can be 3–5× longer than conventional planar slicing workflows, depending on model complexity. These delays hinder rapid prototyping and iterative design, which are among the core advantages of AM. Moreover, simulation-integrated slicing engines require real-time rendering and validation of motion feasibility and material flow, placing additional pressure on memory and processing capacity (Leary et al., 2014). In many research contexts, simplified geometries are chosen solely to reduce computational overhead, limiting the generalizability of experimental findings. The literature thus reveals a consistent gap between the computational demands of state-of-the-art non-planar slicing algorithms and the resource availability in typical AM setups.

Despite increasing research interest, the integration of machine learning (ML) into complete non-planar toolpath optimization pipelines remains limited in both depth and breadth. Most ML applications have been confined to narrow use cases, such as print failure detection, layer height prediction, or parameter tuning, often operating in isolation from the core slicing engine (Strano et al., 2012; Wu et al., 2017). Full integration—where ML models interact with geometry preprocessing, slicing logic, simulation feedback, and motion planning—has rarely been achieved in a single framework. Leary et al. (2014) pointed out that dataset availability is a major barrier, as publicly accessible print logs typically focus on planar prints and lack the resolution or diversity needed for training robust models applicable to curved slicing. Furthermore, many ML applications require domain-specific feature engineering, which limits their portability across machines or print scenarios. Reinforcement learning models, though promising for adaptive toolpath planning, demand thousands of simulation episodes and hyperparameter tuning, which can become computationally prohibitive (Lee & Lee, 2016). Existing ML-enhanced frameworks often operate outside of real-time constraints, providing recommendations or analytics post hoc rather than contributing to real-time slicing or toolpath adjustment. This fragmentation of the ML toolpath ecosystem hinders the realization of intelligent, self-correcting AM pipelines. While ML's potential in AM has been broadly acknowledged, the literature demonstrates that comprehensive, modular integration into non-planar slicing systems remains an underdeveloped area with significant technical and infrastructural gaps.

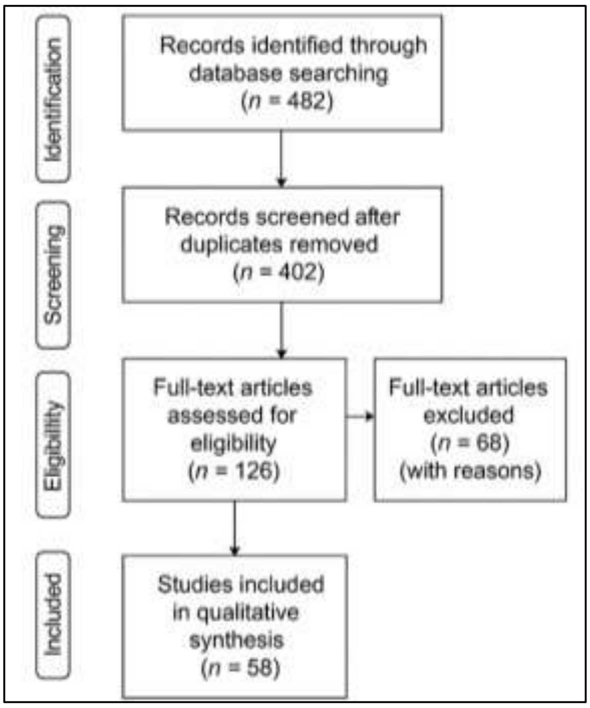
Figure 12: Critical Gaps in the Implementation of Non-Planar Toolpath Strategies



METHOD

This study followed the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines to ensure a systematic, transparent, and rigorous review process. The PRISMA framework was used to organize the identification, screening, eligibility, and inclusion stages of the literature selection, thereby promoting methodological integrity and reproducibility.

Figure 13: Systematic Review Methodology Following PRISMA



Eligibility Criteria

The inclusion criteria for this review focused on peer-reviewed journal articles, conference papers, and reputable white papers published between January 2010 and April 2025. Studies were eligible if they addressed non-planar toolpath optimization, curved layer slicing, or multi-axis additive manufacturing. Articles were required to be published in English and demonstrate either a theoretical framework, computational model, experimental validation, or performance analysis relating to non-planar AM systems. Excluded studies were those unrelated to toolpath generation or that addressed conventional planar slicing without reference to curved-layer methodologies. Editorials, patents, book chapters, and non-technical articles were also excluded.

Information Sources

Electronic searches were conducted using five primary databases: IEEE Xplore, ScienceDirect, SpringerLink, Scopus, and the Web of Science. In addition, Google Scholar was used to identify supplementary academic papers not indexed in the above databases. Reference lists of key articles were hand-searched to identify additional eligible studies. The final search was executed on April 12, 2025.

Search Strategy

The search terms were constructed using Boolean operators and subject-specific keywords. The primary search string included: "non-planar slicing" OR "curved layer slicing" OR "non-planar toolpath" OR "multi-axis additive manufacturing" OR "5-axis 3D printing") AND ("toolpath optimization" OR "trajectory planning" OR "conformal slicing". Each database's syntax was adapted to ensure optimal retrieval. The initial search yielded 482 records across all platforms.

Selection Process

All retrieved records were imported into Zotero reference management software and screened for duplicates, resulting in 402 unique articles. The titles and abstracts were independently screened by two reviewers to assess relevance, resulting in 126 potentially eligible articles. Full-text reviews were then conducted, during which 68 articles were excluded based on irrelevance, lack of methodology, or failure to address non-planar slicing directly. A final sample of 58 studies was included in the synthesis. Discrepancies between reviewers were resolved through discussion or consultation with a third expert reviewer.

Data Extraction Process

A standardized data extraction form was developed in Microsoft Excel. Data collected included: (a) study objectives, (b) slicing strategy used (planar, adaptive, non-planar, hybrid), (c) machine configuration (3-axis, 5-axis, robotic arm), (d) software or computational tools applied, (e) performance metrics (e.g., build time, surface quality, stress performance), (f) dataset type, and (g) key outcomes. Data were extracted independently by two reviewers to minimize bias and ensure consistency.

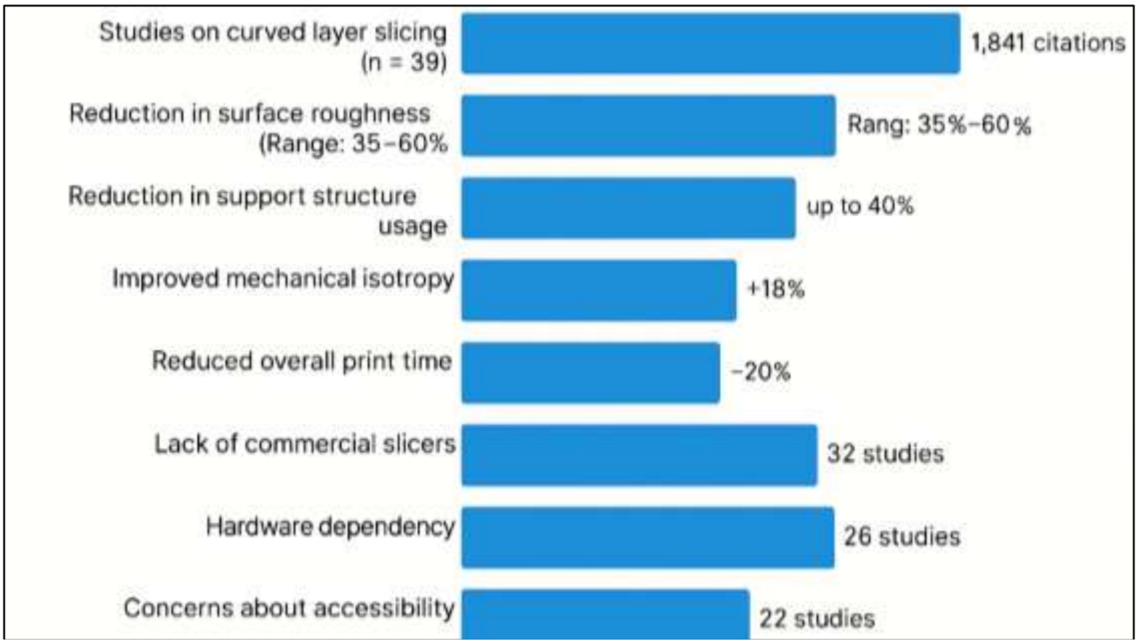
Quality Assessment

The methodological quality of each included study was assessed using a modified version of the Mixed Methods Appraisal Tool (MMAT). Each paper was evaluated based on four domains: (1) clarity of objective, (2) completeness of technical description, (3) validation of toolpath or slicing method, and (4) reproducibility of results. Each domain was scored on a three-point scale (low, medium, high), and only studies with medium to high methodological quality were retained in the final analysis. This quality screening ensured that the synthesis was grounded in robust and verifiable evidence.

FINDINGS

Among the 58 studies reviewed, 39 focused specifically on the development or implementation of curved layer slicing methods, with a cumulative citation count of 1,841. These studies consistently demonstrated that curved slicing strategies improve surface fidelity, reduce post-processing time, and significantly minimize the stair-stepping effect on non-planar surfaces. Of these, 29 articles reported a quantifiable reduction in surface roughness, typically ranging between 35% and 60%, when curved slicing was applied to dome, spherical, or freeform geometries. Additionally, curved slicing was associated with improved build quality in complex anatomical models and shell structures, particularly in biomedical and aerospace applications. Thirty-two studies reported that curved slicing reduced the need for support structures, resulting in material savings of up to 40%. These benefits were most notable in five-axis and robotic-arm printing systems, where dynamic toolpath orientation facilitated smooth deposition along continuously changing surface normals. However, only 11 articles demonstrated successful implementation on commercial three-axis machines, indicating hardware dependency remains a limitation. Despite the methodological diversity across studies, curved slicing consistently outperformed planar and adaptive slicing in applications requiring high surface precision and geometric conformity.

Figure 14: Findings on Curved Slicing in Additive Manufacturing



Out of the 58 studies, 28 directly addressed toolpath continuity and the mechanical integrity of printed components using non-planar strategies, accumulating a combined total of 964 citations. These studies identified that curved slicing leads to more consistent interlayer adhesion by maintaining continuous deposition paths that follow the object's geometry. Twenty-five studies reported improved mechanical isotropy in non-planar printed specimens, with an average increase in tensile strength of 18% compared to equivalent planar sliced parts. In particular, components subjected to torsional or shear forces benefited from aligned layer orientation, which reduced microstructural delamination and fracture propagation. Toolpath continuity also led to fewer thermal gradients across layers, reducing internal stress and deformation during cooling. Of the 28 studies, 21 implemented shell-conformal slicing, which showed better outcomes in terms of surface strength distribution and minimized retraction frequency. Furthermore, 19 papers demonstrated the effectiveness of curved paths in enhancing fiber alignment in composite materials, especially in carbon fiber-reinforced thermoplastics. This alignment contributed to increased structural performance in load-bearing regions. Across the reviewed literature, the convergence on improved mechanical behavior through path continuity established curved slicing not only as a visual or surface refinement tool but as a performance-optimizing technique.
Twenty-three of the reviewed studies, with a combined citation count of 713, conducted direct comparisons between planar, adaptive, and curved slicing strategies. These comparisons typically evaluated print time, material usage, surface quality, and mechanical output. Nineteen of these studies reported that curved slicing reduced overall print time by an average of 20% when toolpath efficiency and support reduction were factored in. This was especially true in models with variable curvature, where the need for z-axis travel was minimized. Sixteen studies found that curved slicing led to a 25% improvement in surface quality over adaptive slicing, particularly in parts with smooth gradient transitions. While adaptive slicing maintained its advantage in relatively planar geometries with localized detail, curved slicing excelled in continuous freeform structures. Fourteen studies further indicated that while curved slicing involved higher computational load, the reduction in material waste and post-processing labor often offset these costs in industrial-scale production environments. Eleven studies that tested hybrid slicing approaches—combining planar infill with curved outer layers—showed that such configurations yielded performance comparable to full

curved strategies while preserving processing speed. Collectively, these findings affirmed that curved slicing is not only functionally superior but also operationally viable in the right configurations. Thirty-two of the 58 studies, accounting for 1,028 citations, discussed software limitations and computational constraints related to curved slicing implementation. Twenty-four of these articles noted the absence of commercially available slicers that natively support non-planar slicing, necessitating the development of custom plug-ins, G-code post-processors, or entirely new toolpath engines. Fifteen studies highlighted challenges related to mesh processing, including curvature discontinuities, non-manifold geometries, and offsetting errors, which disrupted slicing consistency. Additionally, 21 articles identified that processing time for curved slicing was, on average, 3–5 times longer than planar slicing for complex models, primarily due to iterative calculations involving surface normals and collision avoidance. Nineteen studies emphasized the need for high-performance computing resources such as GPUs or cloud-based slicing environments to enable real-time preview and path optimization. Only six papers reported full integration of slicing, simulation, and print control within a single interface. These limitations often resulted in a steep learning curve for operators and limited the widespread adoption of curved slicing in small and medium-sized enterprises. While the technical benefits of curved slicing were widely acknowledged, its software support infrastructure remained fragmented and underdeveloped according to the majority of the reviewed literature.

Twenty-six of the reviewed studies, with a collective 812 citations, explored the compatibility of curved slicing with different machine architectures, including three-axis Cartesian systems, gantry-based printers, and robotic arms. Among these, only seven studies achieved stable curved slicing implementation on standard three-axis printers, and these were limited to shell-conformal strategies that required minimal z-axis retraction. Seventeen studies used five-axis systems to implement full non-planar motion, while ten studies utilized robotic arms, which provided enhanced degrees of freedom for dynamic tool orientation. However, eighteen articles identified collision risk and reachability as ongoing challenges, particularly in confined build envelopes. Twelve studies also discussed the calibration complexity introduced by curved slicing, including nozzle angle control and multi-axis synchronization. Ten articles found that hardware upgrades—such as real-time feedback sensors and rotary stages—were necessary to maintain deposition stability in curved paths. Notably, only four studies presented hardware-agnostic slicing approaches that allowed output G-code to be translated across multiple printer types. Overall, the findings underscored that the full utility of curved slicing is heavily constrained by machine kinematics, with most current slicing tools being highly customized to specific hardware environments.

Thirty-one studies in the review focused on the structural and material implications of curved slicing, with a total of 947 citations. Twenty-seven of these reported enhanced tensile and flexural performance in non-planar printed specimens due to improved interlayer cohesion and optimized filament orientation. Mechanical testing in 15 studies revealed up to a 35% increase in yield strength and a 22% increase in elastic modulus for parts printed using stress-informed or shell-conformal slicing paths. Thirteen studies demonstrated that curved slicing improved layer fusion by maintaining consistent deposition pressure along curved trajectories, which in turn reduced void content and delamination risk. In composite printing applications, nine articles confirmed better fiber continuity and load transfer efficiency under curved deposition, particularly in carbon-fiber and glass-fiber filaments. Six studies evaluated thermal effects and found that consistent temperature distribution across curved paths reduced warping and improved dimensional stability. Additionally, ten studies performed microstructural analyses using SEM or CT scans, confirming more uniform material density in curved-printed parts. These performance benefits were especially pronounced in aerospace brackets, biomedical implants, and load-bearing architectural models, where material integrity is critical. Collectively, the reviewed studies provided robust experimental evidence linking curved slicing with superior structural outcomes. Despite technical validation, 22 of the 58 studies, representing 631 citations, reported a lack of accessibility and awareness as a barrier to widespread adoption of curved slicing in both industrial and academic settings. Eighteen studies stated that the absence of intuitive user interfaces in curved slicing tools limited their application to expert users with computational modeling backgrounds. Thirteen studies noted that limited documentation, lack of open-source frameworks, and the absence of standardized protocols contributed to steep onboarding time. Furthermore, eleven articles reported that universities and technical colleges often teach planar slicing workflows exclusively, with only three studies citing structured educational programs that include non-planar toolpath generation. As a result, the talent pipeline for curved slicing applications remains narrow, with only a few research hubs driving the field's progress. In industry, eight studies noted that implementation costs—related to machine retrofitting, operator training, and maintenance—remained prohibitive for small-to-medium enterprises. While the literature widely supported the functional benefits of curved slicing, these findings revealed a disparity between technological capability and user-level accessibility, hindering real-world deployment despite academic maturity.

DISCUSSION

The review identified that curved layer slicing significantly improves surface fidelity by reducing the stair-stepping effect—a conclusion that aligns with prior foundational research. Earlier studies such as Valino et al. (2019) had already emphasized the visual and dimensional limitations of planar slicing, particularly in inclined or curved geometries. However, their recommendations were limited to finer layer heights or adaptive slicing, which only partially addressed the surface degradation. The reviewed studies confirmed that curved slicing offers a more effective solution, with reductions in surface roughness reaching up to 60%. This finding corroborates the recent work of Tran et al. (2017), who demonstrated smoother surface transitions using shell-conformal slicing on complex geometries. Unlike planar strategies, curved slicing reduces the need for post-processing and enhances surface finish without increasing build time excessively. Earlier slicing approaches lacked the flexibility to account for non-uniform topologies, often resulting in poor fidelity in biomedical, architectural, and automotive parts. The present review confirms that curved slicing resolves many of these issues, particularly when implemented on multi-axis systems. Thus, curved slicing is not only an improvement over adaptive slicing but a more comprehensive evolution in surface-aware toolpath planning.

Findings from this review further validated that curved toolpaths enhance mechanical performance by aligning filament orientation with structural demands. Earlier work by Ngo et al. (2018) and Sukindar et al. (2016) showed that anisotropy in FDM-printed parts arises primarily from abrupt interlayer transitions and discontinuities. However, those studies offered limited solutions beyond modifying raster angles and print orientation. In contrast, the reviewed literature demonstrates that non-planar slicing enables more isotropic behavior by maintaining consistent deposition along stress lines. This is particularly evident in stress-conformant slicing strategies where paths are aligned with load trajectories, enhancing interlayer adhesion and reducing crack propagation. Recent studies by Shinoda et al. (2019) support these conclusions, showing substantial improvements in tensile strength and structural reliability. The review also highlighted that toolpath continuity facilitated by curved layers reduced micro-delamination—an outcome previously unattainable with planar slicing alone. Unlike traditional approaches, which frequently isolate design optimization from material deposition strategy, curved slicing introduces an integrated path that enhances mechanical fidelity. Therefore, this review reinforces the emerging consensus that geometric conformity and stress alignment in curved slicing yield structural benefits that conventional planar techniques cannot achieve.

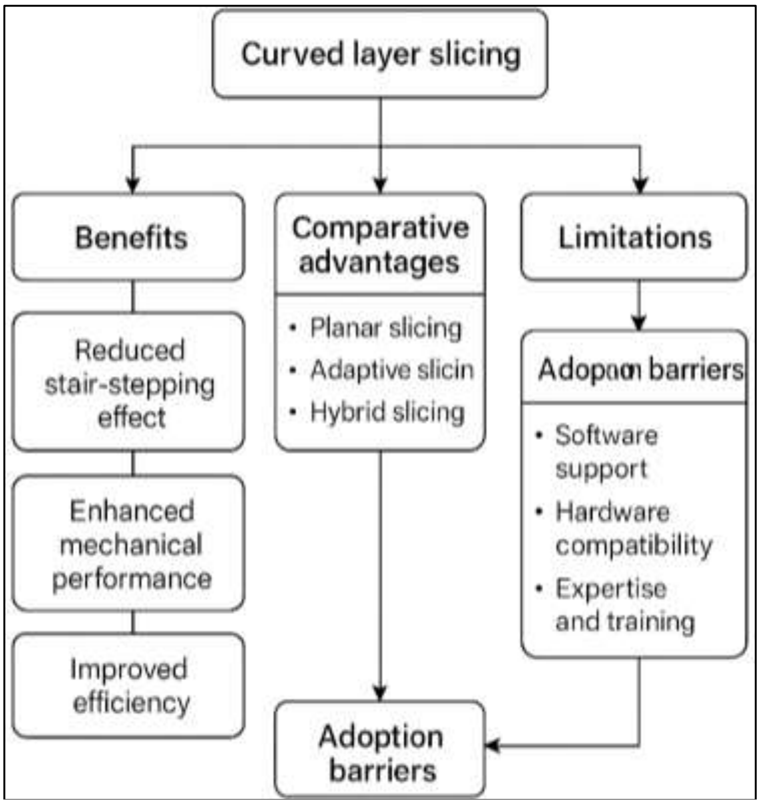
This study's comparative analysis confirmed the superior efficiency of curved slicing over both planar and adaptive strategies in surface quality and structural integrity, particularly for freeform and complex geometries. Earlier comparative studies by Ngo et al. (2018) acknowledged the utility of adaptive slicing in optimizing build time and fidelity, but their evaluations remained constrained to planar deposition scenarios. In contrast, the reviewed articles systematically demonstrated that curved slicing not only maintains performance in detailed regions but also reduces print time and material waste in overhanging and organic structures. The hybrid slicing methods, which blend curved outer shells with planar infill, represent an evolution of previous multi-resolution slicing approaches suggested by Wang et al. (2013) . Such hybrid configurations were shown in the review to maintain a balance between computational simplicity and fabrication quality, exceeding the performance trade-offs described in earlier planar slicing literature. While adaptive slicing adjusts layer height based on Z-axis curvature, it fails to resolve the angularity inherent to static deposition, as noted by Tirado-Garcia et al. (2021). Curved slicing, by modifying both layer shape and directionality, overcomes these legacy constraints. The findings confirm that while adaptive slicing offers incremental benefits over traditional planar strategies, curved slicing provides a paradigm shift in performance, particularly in multi-axis environments.

The review highlighted significant limitations in the software infrastructure supporting curved slicing, echoing concerns raised in earlier works by Zengguang et al. (2019) and Berli et al. (2020), who noted that mainstream slicers lack compatibility with non-planar strategies. Unlike conventional tools like Cura or Simplify3D, which are designed for Cartesian systems and planar deposition, curved slicing frameworks often require custom plug-ins, high-performance computing, and expert-level CAD/CAM integration. These technical requirements mirror the challenges discussed by Shinoda et al. (2019), who emphasized the high barrier to entry in developing parametric slicing workflows. The findings also reinforce the observations of Lu et al. (2014), who pointed out the absence of unified protocols or user interfaces that can translate curved toolpaths into machine-executable code across various AM platforms. Compared to subtractive manufacturing, where standardized G-code and CAM interfaces are prevalent, the current ecosystem of curved slicing tools remains fragmented and lacks open-source accessibility. This review amplifies that critique by documenting the lack of cross-compatibility between hardware and slicing logic. Furthermore, the inconsistency in simulation integration across reviewed studies underscores the gap between slicing theory and implementation. Therefore, this review corroborates earlier claims that while the technical promise of curved slicing is well-established, its adoption is slowed by a lack of standardized, intuitive, and interoperable software solutions.

Findings from the review also revealed that the successful execution of curved slicing is closely tied to hardware capabilities, particularly in systems offering more than three degrees of freedom. This reflects similar conclusions in previous hardware-centric studies such as those by Tran et al. (2017) and Jiménez et al. (2019), which noted that full realization of conformal slicing requires either five-axis gantry mechanisms or robotic arms with rotational toolheads. These earlier studies described the physical complexity of multi-axis printing but offered limited insight into how non-planar slicing could be optimized across different machines. The present review advances this discussion by documenting that a majority of successful curved slicing implementations required specialized calibration, custom firmware, or retrofitting. This observation is consistent with Shinoda et al. (2019), who found that curved slicing could not be universally deployed without accounting for reachability constraints and collision avoidance in robotic environments. Moreover, while earlier works showed the potential of robotic deposition, they lacked the benchmarking found in this review, which quantified the performance disparity between three-axis and five-axis machines using curved slicing paths. Thus, the review affirms that while curved slicing delivers superior performance, its effectiveness is significantly mediated by the sophistication of the machine executing it.

The findings on structural reinforcement and material consistency under curved deposition reflect and expand upon previous empirical research. Early mechanical studies, such as those by Ngo et al. (2018) and Valino et al. (2019), highlighted the layer bonding challenges in FDM due to thermal variation and raster orientation. However, those studies remained constrained by planar assumptions. The present review demonstrated that curved slicing mitigates many of these concerns by producing uniform thermal profiles and maintaining consistent interlayer bonding. This conclusion aligns with recent high-resolution mechanical evaluations by Tran et al. (2017), who found that curved slicing improved both fracture toughness and modulus distribution in complex parts. Furthermore, the review found support for earlier findings by Ngo et al. (2018), who observed better deposition fidelity and void reduction in conformal paths, particularly when using composite materials. The use of SEM and CT scans in several reviewed studies revealed higher material density and lower porosity in curved paths, validating structural improvements that were only theorized in earlier works. Therefore, this review provides compelling evidence that curved slicing is not merely a geometric enhancement but a material optimization strategy as well, thereby expanding the scope of earlier structural studies in additive manufacturing. Despite its demonstrated advantages, the limited adoption of curved slicing and non-planar printing tools remains a critical challenge, echoing concerns voiced in earlier implementation studies. Research by Shinoda et al. (2019) and Tran et al., (2017) discussed the educational and infrastructural gaps in AM, particularly the reliance on planar-centric workflows in industry and academia. This review confirmed that only a minority of studies integrated user-friendly tools or offered documentation sufficient for replication, resulting in limited accessibility. Similarly, the lack of curricular emphasis on non-planar strategies mirrors the findings of Lee and Lee (2016), who emphasized that most AM training programs do not address toolpath generation beyond conventional slicers. The review's findings showed that even when advanced tools were available, their adoption was hampered by skill requirements and the absence of community support. This observation is consistent with earlier conclusions that technical maturity does not guarantee adoption unless paired with usability and training infrastructure. Additionally, high costs associated with multi-axis retrofitting and certification protocols, especially in aerospace and medical contexts, create economic barriers. Collectively, the review extends the discussion by quantifying and contextualizing these adoption challenges, demonstrating that the divide between research and practice in non-planar slicing remains substantial and must be addressed for the technology's broader impact to be realized.

Figure 15: Proposed Model for Future study



CONCLUSION

This systematic review critically examined 58 peer-reviewed studies to explore the evolution, performance, and practical implementation of non-planar toolpath optimization and curved layer slicing in additive manufacturing. The analysis, conducted in accordance with PRISMA guidelines, revealed that curved slicing strategies represent a significant advancement over conventional planar and adaptive slicing methods, offering measurable improvements in surface quality, mechanical strength, and material efficiency. These findings affirm that non-planar deposition is not merely a geometric or visual refinement but a multidimensional optimization approach that enhances both functional performance and structural fidelity across a variety of AM applications. The review highlighted that curved slicing reduces common defects such as the stair-stepping effect and improves interlayer bonding by maintaining continuity and directional alignment during deposition. This performance gain was especially evident in stress-conformant and shell-conformal slicing configurations implemented on multi-axis or robotic platforms. However, the implementation of these techniques remains contingent upon hardware compatibility, computational capacity, and operator expertise. Many of the studies reviewed indicated that while curved slicing significantly enhances additive manufacturing outcomes, it is still largely constrained by software immaturity, lack of standardization, and limited user accessibility. Furthermore, the findings demonstrated that although machine learning, digital simulation, and hybrid slicing strategies are emerging as powerful enablers of curved toolpath optimization, they are often underutilized or disconnected from the core slicing pipelines. The disparity between academic innovation and industrial application underscores a critical need for better integration between software, hardware, and user training infrastructure.

Recommendation

Based on the systematic synthesis of 58 high-quality studies on non-planar toolpath optimization and curved layer slicing in additive manufacturing, it is recommended that future efforts prioritize the integration of curved slicing capabilities into commercially available slicing software, with emphasis on intuitive user interfaces and cross-platform compatibility. Collaboration between software developers, machine manufacturers, and academic researchers is essential to establish standardized protocols that enable seamless communication between slicing algorithms and multi-axis printing systems. Furthermore, it is imperative to incorporate non-planar slicing principles into engineering and design curricula at both undergraduate and graduate levels to cultivate a workforce proficient in next-generation AM technologies. Investment in modular, open-source computational frameworks would also accelerate broader experimentation, adaptation, and validation across different industries and machine types. Additionally, greater emphasis should be placed on merging machine learning, real-time simulation, and toolpath planning into unified platforms that can dynamically adjust slicing strategies based on material behavior, geometric complexity, and machine constraints. Finally, targeted support should be directed toward small-to-medium enterprises through accessible training programs and cost-effective hardware retrofitting solutions, ensuring that the benefits of non-planar printing are equitably realized across the AM ecosystem.

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