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Procedia CIRP 136 (2025) 284–289

www.elsevier.com/locate/procedia

35th CIRP Design 2025

Non-planar 3D printing – Enhancing Design Potentials by Advanced Slicing Algorithms and Path Planning

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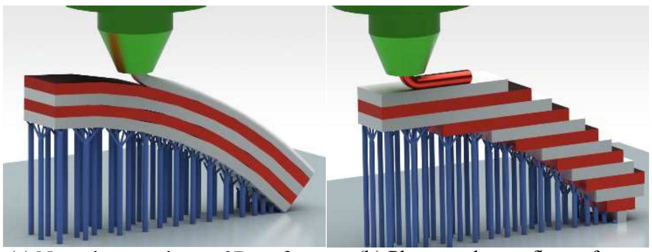
Abstract

In non-planar 3D printing, the material is no longer restricted to pre-planned, flat movements, but print layers can be freely aligned in three-dimensional space. This results in challenges for path planning and control while significantly improving the mechanical properties of components. Considering recent research results and challenges in non-planar 3D printing, this paper makes two key contributions. First, we investigate to what extent conventional 3D printers (Prusa MK4) can effectively perform non-planar 3D printing and how slicing and path generation can be performed on an algorithmic level. Second, we examine fundamental relationships between the mechanical properties of the resulting part and parameters of non-planar 3D printing (layer orientation, layer thickness, etc.) to identify key design potentials.

Keywords: *Additive Manufacturing; Non-Planar 3D Printing; Advanced Slicing Algorithm; Process Parameters; Design Guideline*

1. Introduction and Motivation

There is an increasing utilization of additive manufacturing (AM) across different industry branches and products [1]. Aside from rapid prototyping, there is a strong focus on the manufacturing of functional parts [2]. Fused deposition modeling (FDM) is one of the most widely used AM technologies due to its simplicity and efficiency. Highly complex parts are created based on simultaneous two-dimensional movement of the nozzle layer by layer [3]; see Figure 1(b). This leads to significant limitations with regard to mechanical properties and strength [4] as well as surface quality [5], hindering a wide range of industrial applications [3]. Non-planar 3D printing (NP-3DP) is a technology to improve the properties of printed parts, specifically in anisotropic materials. Here, layers are realized on a three-dimensional surface rather than flat planes [6]; see Figure 1(a). The increasing degree freedom in layer orientation results in improved mechanical properties [7] and surface quality [8] as well as increased geometrical accuracy [9]. Thus, enabling applications as final parts for various use cases.



(a) Non-planar path on a 3D surface (b) Planar path on a flat surface

Fig. 1. Illustration of non-planar versus planar 3D printing

Research in the field of advanced printing technologies, including 4D and 5D printing, is evolving [10]. While 4D printing [11] deals with the deformation and shape-changing behavior of specific materials after printing with energy sources, 5D printing [12] investigates three-dimensional

10.1016/j.procir.2025.08.050

printing for linear movement plus two dimensions for rotary. As a broad term, non-planar 3D printing include 5D printing but does not strictly address five degrees of freedom.

A core challenge in NP-3DP is the design of algorithms that are able to produce an advanced path according to the design features [7-9]. Although some breakthroughs have been made towards understanding the effect of various parameters of slicing techniques [6], in-depth understanding is needed on how these non-planar advanced paths [13] can be used within the design process and how these enhance the mechanical properties of the printed objects. Thus, the motivation of this research is to explore the potentials of NP-3DP to tackle design limitations, improve load-bearing capacities, and enhance anisotropy control considering specific design needs. Therefore, the research objective of this contribution is to investigate the effect of different advanced path strategies on the mechanical properties of the printed parts by non-planar 3D printing as well as to explore limitations of this method. This results in the following research question: *What is the influence of different trajectories on mechanical properties in both planar and non-planar 3D printing?*

The paper is structured as follows: The basics and our motivation are reflected in section 1. In section 2, existing research is reviewed to identify earlier slicing algorithms and considered process parameters. In section 3, the method used to answer the research questions and boundary conditions is explained, followed by the findings from our experiments. The last section contains the discussion of limitations as well as conclusions and an outlook on future research.

Nomenclature

FDM	Fused Deposition Modelling
NP-3DP	Non-planar 3D Printing
P-3DP	Planar 3D Printing
CLFDM	Curved Layer Fused Deposition Modelling
PLA	Polylactic Acid
RSS	Reference Slicing Surface
DIC	Digital Image Correlation

2. Background and State of the Art

Limitations of established P-3DP, like the stair-stepping effect and the inability to change orientations of material layers, are addressed by various research in the field of NP-3DP, e.g. [6]. In the following sections, general benefits, advanced slicing algorithms, and investigations of process parameters are reviewed. The key findings are summarized in Figure 2.

2.1. Benefits of Non-planar 3D Printing

The stair-stepping effect is a basic limitation of P-3DP and occurs on surfaces with a low slope and affects the smoothness of the surface [8]. It is proven that by NP-3DP geometrical accuracy can be increased [9]. Research indicates that in low inclinations of surfaces (even in simple geometries), both flatness and angularity are improved significantly, while in high inclinations only flatness is enhanced. Promising benefits of NP-3DP [14] and its eco-friendliness [15] drive researchers to take advantage of both NP-3DP and composites such as reinforced carbon fiber PETG [16] to achieve higher mechanical properties. The combination of two materials (regular PTEG and carbon fiber-reinforced PETG) and two methods of printing (planar and non-planar) was compared with regard to the performance. Thrust and impact loading tests have been performed for the application of producing propellers for drones. Here, carbon fiber-reinforced PETG material printed by the non-planar method demonstrates the highest mechanical properties. Similarly in [17], samples of carbon fiber and glass fiber are manufactured for a 3-point bending test. It was found that for both materials, the bending performance on non-planar samples is significantly higher than planar slicing.

2.2. Advanced Slicing Algorithms for Non-planar 3D Printing

Firstly, adaptive slicing was introduced to solve problems such as the stair-stepping effect [18]. This method consists of increasing the number of layers in specific areas where this effect occurs significantly. However, this approach is not capable of completely eliminating this effect. Moreover, it increases the printing time and does not have a positive effect on part strength. Curved layer fused deposition modeling (CLFDM) deposits the material along a curved path, demonstrating an enhanced solution to overcome technical constraints in planar FDM, such as anisotropic strength limitations [19]. The curve-following nature of non-planar 3D printing increases surface smoothness and results in better mechanical properties [20]. In [20] the authors use a model-based simulation to explore NP-3DP. Although their findings do not indicate the need for the nozzle to be perpendicular to the curved path, in a real experimental setup, dynamic adjustment of the nozzle is necessary to maintain high printing quality [21]. A customized adhesion test is performed to compare the bonding strength of layers in the planar and non-planar methods. The finding shows that when there is a deviation in the distance between the nozzle and printing, it lowers bonding strength and leads to a rough surface with inconsistency in printing. Lacking an advanced slicing algorithm is one of the major challenges in NP-3DP. In [8], the benefits of the non-planar method, in particular layer geometry correction, and limitations such as design restrictions of parts using normal 3D printers are discussed. The focus of this research work is on the advancement of generating a complex algorithm able to identify areas in the part where NP-3DP should be applied while being capable of detecting collisions. Enabling the potential to use both planar and non-planar would reduce the complexity of path generation and collision risk. However, this research only considers adding a non-planar layer for the last top layer, which reduces surface roughness. In [22], an algorithm capable of generating trajectories with multi-axis movement of the printer nozzle is developed and tested. The algorithm works based on a reference slicing surface (RSS), which uses a 3D surface as the reference, and with the offsetting of this surface along normal directions, multiple paths are generated.

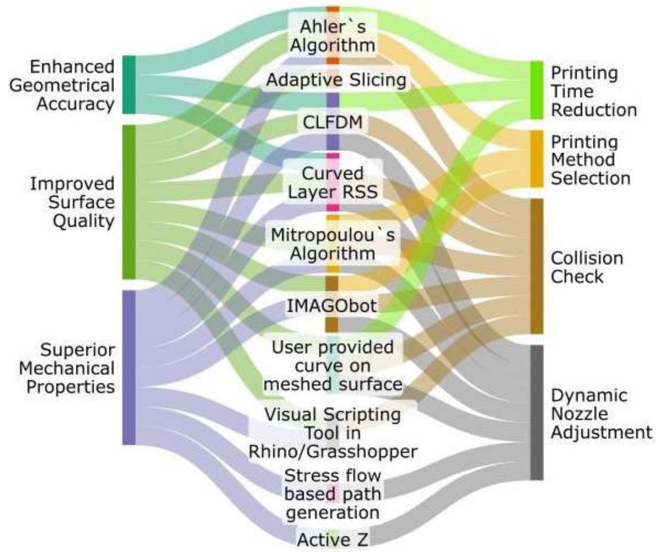


Fig. 2. Classification of existing algorithms and their properties

The restriction of this algorithm is that only limited designs can be realized. A recently advanced model [23] led to overcoming these challenges and is capable of generating complex trajectories suitable for 5-axis movement. IMAGObot [23] introduces a higher ability to handle complex geometries and ease for the user for modifications. The study [7] evaluates the possibility of optimizing printed component strength by generating tool paths along stress directions. A stress analysis is performed with various samples, and the slicing and path planning are carried out accordingly. The authors declare achievement of outstanding mechanical properties using liquid crystal polymer: greater failure strength and higher stiffness compared to the traditional planar slicing method. This approach generally would be assumed to achieve the highest strength based on every design and its stress analysis.

2.3. Investigations of Process Parameter

In [24], different influencing parameters of the non-planar method are introduced, such as air gap and layer thickness impacting bending test results in sinusoidal layers. The results show that a smaller air gap and optimized layer thickness significantly increase flexural strength by enhancing part density and bonding between layers.

The introduced benefits and slicing algorithms, as well as processes considered in current research work, are summarized in Figure 2. It is also pointed out that properties (left-hand side) and process parameters (right-hand side) are frequently addressed in current research. It can be concluded that most algorithms are capable of generating advanced trajectories that lead to improvements in surface roughness and mechanical properties. However, it is still a remaining question either how effective the algorithms are specifically in terms of enhancing mechanical properties or the flexibility provided by these algorithms for generating various paths in the desired direction.

3. Methodology

The following section introduces the methods to answer the research questions, focusing on the slicing technique and different paths. In order to investigate the influence of different trajectories on the mechanical properties in both P and NP-3DP, four different unidirectional trajectories are used; see Figure 3. The samples are printed in both planar and non-planar methods with the polylactic acid (PLA) using a Prusa Mk4 3D printer. The conventional path generation is conducted by adjusting the printing angle on the Prusa Slicer to achieve the desired direction of paths. Similar to the paths generated by conventional slicing, in the same direction, non-planar trajectories, see Figure 3, are generated. For the planar method, a rectilinear pattern is chosen with 100% infill [25]. In addition, the fill angle is varied from 0 to 90 degrees to investigate the effect of different path orientations. For non-planar path generation, Siemens NX CAM software is used. *Zig-Zag* pattern [26] in different angles, see Figure 3, are applied for non-planar samples. For adaptive specimen, the *Follow Periphery* pattern [26] is applied for non-planar sample, while for planar sample the *Concentric* pattern is used. The pattern used for each pair of planar and non-planar strategies in certain path orientations is identical. However, only the terms for calling a pattern differ in different software. The term adaptive is used in this work because the paths generated by this pattern are adaptable based on design features. Printing parameters are given in Table 1.

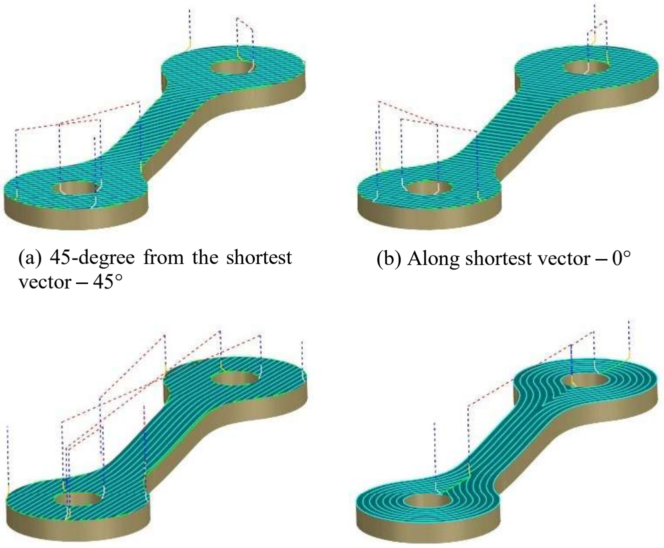
Table 1. Printing process parameters

Parameters	Value
Nozzle diameter	0.4 mm
Nozzle temperature	220°C
Bed temperature	70°C
Printing speed	120 mm/s
Infill density	100%
Layer thickness	0.2 mm
Number of perimeters	2
Perimeter speed	45 mm/s
Number of solid layers	0

In non-planar path planning, support structures are generated with a planar strategy. Afterward, samples are made using the non-planar method. Here we applied the general algorithm used in CNC milling machines. The G-codes are generated with Siemens NX CAM software according to ISO 6983. These G-codes only contain the motion coordinates. To adapt the outputted G-codes to a 3D printer, we implemented a Python program* to calculate the distance between each G-code line and added a parameter called E. This parameter controls the amount of material extruded at every defined distance. Manual modification of G-codes is inevitable in our path planning strategy. The slicing algorithm used in our work is in line with [22], offsetting the layers based on the reference layer according to layer thickness. Although this approach cannot be

* The code is available under: github.com/ArashAfshari/Non-planar-3D-Printing

applied to highly complex geometries, it is a simple procedure to build samples with NP-3DP. The extracted algorithm is shown in Table 2.



(a) 45-degree from the shortest vector – 45°
(b) Along shortest vector – 0°
(c) Along longest vector – 90°
(d) Design-based adaptive path

Fig. 3. Illustration of different trajectories in NP-3DP

The tensile and bending tests are performed for both planar and non-planar printed samples for the evaluation of mechanical properties using a loading speed of 0.01 mm/s. For every direction in both tests, two samples were produced to increase reliability. A Zwick/Roell GmbH testing machine is used for both tests with up to 10kN applied force integrated with a three-dimensional digital image correlation (DIC) system ARAMIS 12M (Carl Zeiss GOM Metrology GmbH). Two cameras capture images of the sample surface to assess strain distribution and crack propagation during the test.

(a) Tensile test
(b) Bending test

Fig. 4. Illustration of testing setup

4. Results and Discussions

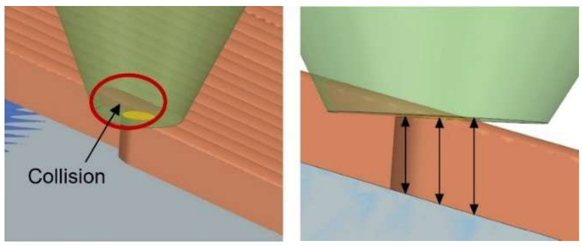
This section presents the implementation of the NP-3DP outcome on the improvement of conventional 3D printing slicing errors, mechanical properties, and design perspective, as well as restrictions on path generation. The algorithm extracted from our work is represented in Table 2. This algorithm can be applied for various 3D printers as well as robotic arms. High accuracy of G-code paths along with precise control of material extrusion allows this algorithm to handle non-planar layers effectively. Additionally, it can facilitate performing hybrid additive manufacturing combined of both additive and cutting methods.

Table 2. Algorithm applied for NP-3DP

```
Algorithm 1:
Open G-code file (only contains motions)
Set initial variables (layer thickness and number of layers)
Set layer height
    While current_layer < total_height
    current_layer= base_height + (current_layer *layer_thickness).
Process Each Line in G-code for Current Layer
For each line in G_code_lines:
    Identify Move Type:
        If: Process Extruding Move
            Extract the X, Y coordinates and update the Z coordinate to current_layer
            Calculate the distance d from previous_point to (X, Y, current_z)
            Compute E_value = d * E_factor
            Append E{E_value} to the line
            Update previous_point to (X, Y, current_layer)
        Else: Process Non-Extruding Move
            Update the Z coordinate to current_layer and update previous_point without adding an E value
Increase current_layer by 1
```

4.1. Printing quality and limitations of path planning

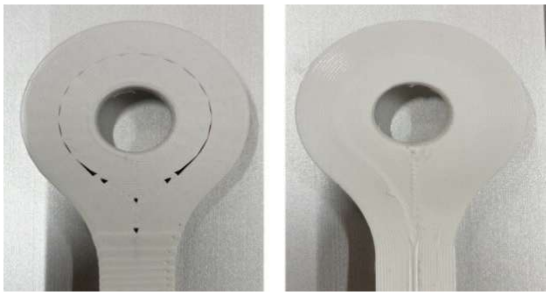
Our simulation with Siemens NX software shows that even in low-slope curves and surfaces, there would be two main issues; see Figure 5. First, a collision of the nozzle with the printing path, and second, a distance problem that affects layer adhesion. In both of the mentioned cases, printing quality is reduced. Although in this work the focus is on performing NP-3DP with accessible commercial equipment, for maintaining high printing quality the nozzle angle should be oriented perpendicular to the path [21].



(a) Collision of the nozzle with the printed layer
(b) Layer distance uncertainty

Fig. 5. Illustration of errors in printing non-planar layer using 3 axis 3D printer

Our experiment demonstrates that while the printing path is unidirectional, serious slicing problems can occur. Normally, 3D printing is done with a 90-degree rotation of the path in each top layer. This technique compensates for the errors in generating paths in one direction to ensure achieving high-quality parts. Nevertheless, it is still a challenge while proceeding with P-3DP. Non-planar trajectories overcome this limitation by providing the flexibility to obtain any desired direction; see Figure 6.

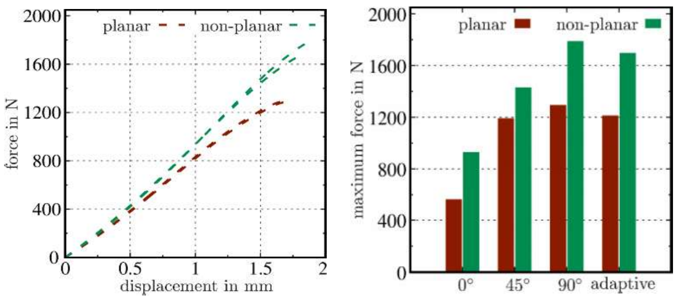


(a) Slicing error in P-3DP (b) Refined slicing in NP-3DP

Fig. 6. Illustration of optimization for an object printed in both planar and non-planar

4.2. Effect on mechanical properties

The outcome of the performed test demonstrates that improvement is achieved from the transition of planar to non-planar 3D printing even though the directions of the paths are the same. Figure 7(a) represents the higher tensile load-bearing capacity of NP-3DP over P-3DP by the increase rate of 40%. The steeper slope of the NP-3DP indicates enhanced stiffness and elastic modulus under stresses are also evident. In addition, Figure 7(b) shows the improvement of enduring higher forces before reaching a failure with samples in which their filament is bonded in different directions in NP-3DP. This evidently represents in all directions the mechanical properties are improved in the non-planar method. We observed that 45-degree samples are highly prone to crack generation without having a perimeter. Therefore, we applied 2 perimeters, and then printing the infill starts. In addition, the motion of the nozzle between extruding and non-extruding moves, can cause a negative impact on the bonding between layers [21], [27].

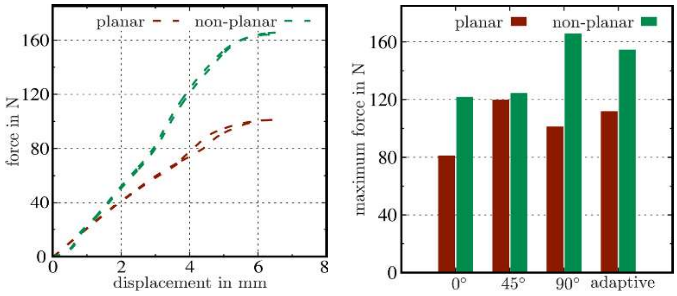


(a) For 90° specimen (b) For all specimens

Fig. 7. Results of tensile tests for samples printed in planar and non-planar methods

The bending test results show the non-planar 3D-printed sample with trajectories through the longest vector (90 degrees) can bear nearly 60% more load than the same sample printed in the planar method; see Figure 8(a). Similar to the tensile testing, the elevated slope of the NP-3DP method results in higher mechanical properties through increased stress. Indeed, in all directions, samples classified by NP-3DP exhibit higher performance while performing bending loads; see Figure 8(b).

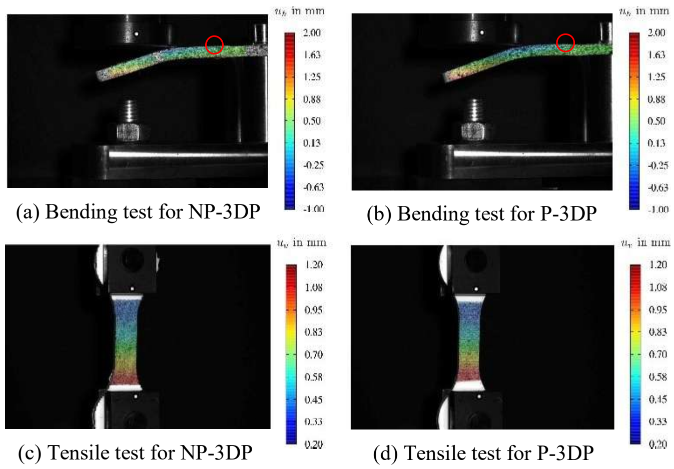
The analysis of the captured images from tensile and bending testing confirms the higher mechanical properties of NP-3DP and the reliability of our work; see Figure 9. For bending tests, the displacement of NP-3DP samples is lower than for P-3DP as the colors are lighter, indicating a higher stiffness; see Figure 8(a) as well.



(a) For 90° specimen (b) For all specimens

Fig. 8. Bending load-bearing capacity of samples printed in planar and non-planar method

The crack initiation in bending tests is defined by the red circle on the top right corner of Figures 9 (a) and (b). By analyzing the location of the crack for all samples under tensile and bending loads, we find out that for each test the crack position in samples is the same. This highlights the authenticity and reproducibility of our work.



(a) Bending test for NP-3DP (b) Bending test for P-3DP

(c) Tensile test for NP-3DP (d) Tensile test for P-3DP

Fig. 9. Displacement visualization of 90° specimen

4.3. Implications of design potentials

Our observation in this research shows that the surface quality of the non-planar strategy is significantly enhanced compared to conventional methods, and fewer finishing efforts are required. This improvement is primarily due to the full elimination of the stair-stepping effect [8]. Therefore, the surfaces created are smoother and more coherent because of the curve-following nature of NP-3DP [19]. This level of surface refinement permits a higher degree of ergonomic optimization, as designs can be more closely aligned with natural forms and user comfort. In addition, less reliance on support structures and higher surface smoothness, in particular in overhang areas, represents greater design freedom where the designers can focus on creativity and functionality without being concerned about printing quality. This capability can increase the implementation of generative design and topology optimization, enabling the creation of more innovative and efficient components. The choice of using non-planar or planar methods enables the designers to vary material properties such as rigidity in a specific area of the design and elasticity in another; see Figures 7 and 8. This ability allows for a deeper understanding of how advanced planar and non-planar printing paths interact with heterogeneous mechanical properties, enabling the refinement of design performance outcomes. This knowledge permits the creation of components where rigidity and flexibility are allocated based on performance requirements. Indeed, it unlocks the potential of advancement in multi-functional designs and multi-material printing.

5. Conclusion and Future work

In our work, we explored the potential of applying non-planar 3D printing in Prusa MK4 as well as the limitations of this method and new possibilities. NP-3DP shows significant improvement and flexibility in path generation and slicing, resulting in higher mechanical properties. This capability enables new design potentials where objects can be lighter, stronger, and more sustainable. Further improvement of our proposed algorithm will focus on handling more complex geometries. Moreover, by generating a specific post-processor integrated with the nozzle extrusion control codes, we would be able to reduce manual efforts of path planning significantly. Even though non-planar 3D printing has its own implementation challenges, for instance, difficulties of advanced path planning and complexity of the 3D printing process, it has a high potential for optimizing component quality and tackling existing challenges. Further investigation, therefore, will include different infill patterns such as the Hilbert curve [28].

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