

Research Status of Approaches to Reduce the Stair-Step Effect in 3D Printing

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Abstract. The stair-step effect is an inherent defect in 3D printing technology caused by the layer-by-layer additive manufacturing principle. It severely impairs the surface precision and mechanical properties of printed components, thereby emerging as a critical bottleneck that restricts the advancement and application of 3D printing in high-precision domains. To summarize the existing research on reducing the stair-step effect, this paper mainly focuses the current state of studies regarding adaptive slicing algorithms and printing orientation optimization, while also reviewing approaches related to nozzle design and post-processing repair techniques. This paper presents a detailed overview of the current research status of approaches and provides a synthesis and critical evaluation of the aforementioned approaches.

Keywords: 3D printing, Stair-case effect, STL,

1 Introduction

3D printing, also called additive manufacturing, is a technology that fabricates components via a layer-by-layer material deposition process. And it constitutes a critical component of the Fourth Industrial Revolution [1]. Owing to its extremely high design and manufacturing flexibility, 3D printing is currently widely adopted in diverse fields—from small-scale toy components in daily life to large-sized mechanical parts for aerospace applications, all of which involve the 3D printing technology. However, this technology still faces multiple intractable challenges, including optimizing printing efficiency, minimizing support material usage, and—the focus of this study—reducing the stair-case effect.

The stair-case effect in 3D printing refers to the surface roughness or dimensional deviation induced by the layer-by-layer fabrication process, also known as the sawtooth effect or terrace phenomenon. As adjacent sliced layers exhibit misaligned boundaries during stacking [2], a micro-stepped topography is formed, where the edge of each layer is slightly discernible on the object surface[3].

As an inherent characteristic of the layer-by-layer additive manufacturing process [4], this phenomenon induces multiple adverse impacts: it impairs the surface quality of fabricated components [5-7], and further influences their mechanical properties; it will cause dimensional inaccuracies that compromise the functional reliability of devices, with some even failing to meet operational requirements due to severe staircase effect-induced deviations. For example, in the aerospace field, surface staircases on core components with complex curved surfaces

increase fluid drag and reduce operational efficiency; in the biomedical field, stepped structures on artificial joints and implants may induce tissue friction-induced damage and compromise biocompatibility.

Currently, extensive research efforts have been dedicated to reducing the staircase effect in 3D printing. For example, Zhu et al. proposed an adaptive slicing algorithm based on the normal vectors of triangular facets in STL files: this algorithm reduces the staircase effect while preserving model features by automatically adjusting layer thickness according to the dihedral angle at sharp edges and vertex complexity [8]. Lu et al. derived a volume error calculation formula induced by the stair-case effect based on an analysis of Fused Deposition Modeling (FDM) process characteristics, and further proposed an adaptive slicing algorithm after their research [9].

This paper systematically reviews the research progress on reducing the stair-case effect in 3D printing recently. From the four perspectives of adaptive slicing algorithms, print orientation optimization, nozzle design optimization and repair, the principles and current application status of various strategies are analyzed. The challenges of existing research are summarized, and future research directions are prospected, with the aim of providing a reference for research and industrial applications in related fields.

2 Adaptive Slicing

Adaptive slicing relies on the STL model as its core data source and analytical foundation. The STL model serves as the data carrier for adaptive slicing, with its primary function being to convert complex three-dimensional models into discrete geometric information recognizable by 3D printers.

2.1 Introduction to STL Model

A STL model encapsulates extensive data on triangular facets, including the coordinate data of three vertices and the normal vector coordinates of the facet's plane. A complete 3D geometry can be reconstructed by linking all triangular facets in 3D space[6]; this method of splicing is analogous to tiling tiles to form complex curved surface.

Adaptive slicing dynamically adjusts layer thickness based on local surface variations of the STL model's contour, thereby reducing the stair-case effect on the printed part, enhancing its dimensional accuracy[7], and approximating the theoretical model geometry.

While numerous adaptive slicing algorithms exist, their fundamental principle uniformly relies on connecting the intersection points of the cutting plane and triangular facets into closed contours based on topological relationships[6].

2.2 Current Status of Methodological Research

Zhu et al. proposed an adaptive slicing algorithm that uses normal vectors of triangular facets in STL files as the computational basis, mitigates the staircase effect, and preserves model features. The algorithm determines layer thickness solely based on triangular facet normal vectors, automatically adjusting the layer thickness according to the dihedral angle at sharp edges and the complexity of vertices[8].

As shown in Figure 1, this study conducted comparative experiments using a Totoro-shaped 3D printed part as the test artifact, and compared it with traditional adaptive slicing and layer-thickness-aware adaptive slicing. In contrast to traditional adaptive slicing, the proposed approach preserves model features with a minimal number of layers. In contrast to layer-thickness-aware adaptive slicing, although the layer count increases moderately, the approach achieves superior identification and subdivision of feature points in the model's mid-section.

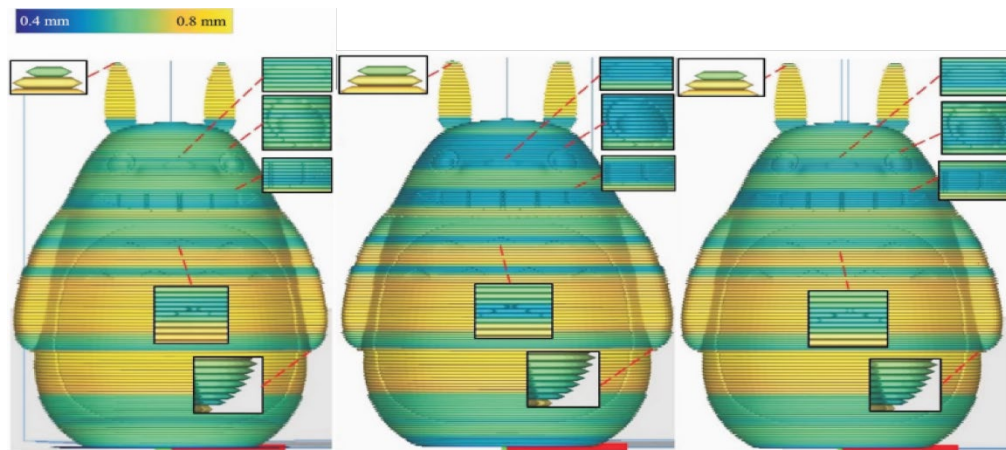


Fig. 1. Print the layered rendering of the Totoro model[8].

The algorithm uses the sharp edges and the complex points as the model feature, which can identify the model detail feature well. However, the algorithm does not give the specific identification method of the sharp edges and the complex point.

Based on the analysis of the characteristics, Lu Ning et al. derived the calculation formula for the volume error resulted from the stair-case effect. And they proposed a new adaptive layering algorithm based on optimal volume error[9].

In the experiment, this algorithm was compared with the equal-thickness layering slicing. The experiment shows this method successfully reduces the stair-case effect of the printed product and the contour detail recovery accuracy is good. However, this approach still needs further investigation into the integration of multi-objective optimization techniques to simultaneously address these interrelated requirements.

An adaptive slicing technique was presented by Ahmed Elayeb et al. to increase the printed device's precision. After data has been extracted, this method identifies the intersection points of two planes ----the STL mesh and the original layer slicing plane, so as to adjust the layer thickness based on the local surface curvature[10].

This method maintains uniform layer thickness in homogeneous regions while cutting high-curvature surfaces into thin layers. Although minimizing layer height can reduce dimensional errors, the key challenge lies in striking a balance between feature quality and print time.

This algorithm can achieve the improvement of printing time efficiency by attentively selecting the range of layer thickness. However, besides the layer thickness, many other parameters can affect the step effect, such as the direction of the spinneret, the spinneret speed, and the

temperature. Therefore, further research on multi-objective optimization methods is needed to simultaneously meet these interrelated requirements.

In addition to the above three methods, there are many other algorithms. Here, only a brief introduction will be given without further elaboration. For instance, Wu Yan et al. introduced a correction coefficient on the basis of NTASM to adaptively reduce the layer thickness of model feature details[11].

3 Print Orientation Optimization

The magnitude of the stair-stepping effect is dependent on the build orientation. Specifically, a more pronounced tilt of the printed component correlates with a more severe stair-stepping effect. For overhanging surfaces, there exists a critical minimum overhang angle below which structural fabrication is infeasible without inducing excessive geometric distortion[12]. A smaller overhang angle corresponds to a more significant stair-stepping effect; notably, when the overhang angle exceeds a threshold value[13], the stair-stepping effect intensifies drastically. And at this time, The material will collapse or deform under the gravity before curing, and the superposition of stair-stepping and overhang-induced collapse substantially reduces the surface quality of the fabricated part.

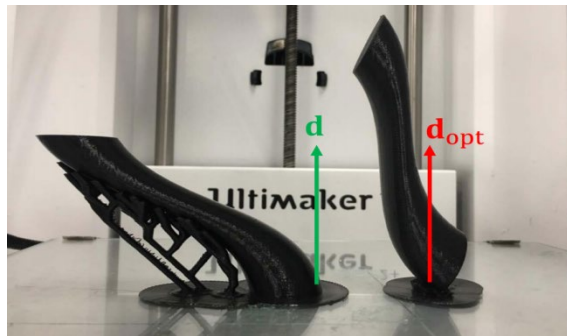


Fig. 2. Use different print directions

As shown in Figure 2, the two distinct construction orientations yield different surface qualities. The step effect produced when d is the printing direction is significantly greater than that when d_{opt} is used. Thus, by minimizing volume error, the optimal printing direction d_{opt} can be determined.

Torbjørn L. Leirmo et al. proposed a new optimization method that minimizes shape errors based on some geometric features. The new approach generates continuous solution spaces by deriving individual expressions for each feature combination[14].

The methodology developed by the study establishes a mathematical framework for solving optimal orientation problems. It mathematically identifies the optimal construction direction by modeling the solution space as a continuous function within a closed domain. However, certain objects cannot be adequately represented by such mathematical functions, and their decomposition into massive geometric components inevitably complicates computational processes.

To address increasingly complex geometries, the methodology developed by Antonio Bacciaglia and colleagues provides an effective solution. This approach is particularly suitable for industrial applications requiring rapid processing of intricate geometries to determine optimal orientations[15]. By implementing ray tracing exclusively on the discretized triangular mesh of the model surface, it dramatically reduces computational time. It eliminates the tedious repeated test, thus shortening the time to market, reducing the workload of operators, and improving the accuracy and final quality of parts.

4 Other Optimization Methods

As the core component of 3D printing systems, the nozzle's structure critically determines melt extrusion velocity[16]. Its design, material selection, and manufacturing processes significantly influence print quality. Optimizing nozzles effectively mitigates step effects. The primary focus of nozzle optimization research lies in achieving precise extrusion control, with numerous studies dedicated to this critical aspect[4].

Jan Bem and colleagues proposed a novel extrusion nozzle for fused deposition modeling 3D printing, equipping a adjustable orifice to realize adaptive control of the extrusion for enhanced printability[17].

The nozzle design has great potential in the future. It could make a big difference in some fields such as improving local control of mechanical properties and material efficiency, which can help improve the overall quality of 3D printing. However, the long-term durability of the most important part of the nozzle, the silicone sleeve, is a difficult problem to solve.

Sun Zixuan et al. proposed a strategy to repair the step effect gap in the FDM 3D printing of inclined surfaces and curved surfaces based on the characteristics of the printing material in the flowable and non-completely solidified state[18].

It was determined that the partial solidification time of the surface layer of PLA printed on stair-stepping-affected planes is approximately 0.2 seconds, confirming the residual plasticity of extruded filaments for a short period post-extrusion from the nozzle. Under optimized process conditions provided in the experiment, the maximum repair efficiency for stair-stepping effects reached 98%. This study further analyzed the specific impacts of key process parameters—including layer height, printing speed, extrusion speed, and printing temperature—on material flowability, validating that the proposed gap-filling strategy enables robust stair-stepping mitigation across diverse printing scenarios.

5 Deficiencies and Development Trends

The stair-case effect is an inherent characteristic of 3D printing, so it is impossible to be eliminated. The best approach is to minimize the step effect as much as possible to reduce its impact on print quality. From the summary and analysis of the current research results, the present research has made many significant achievements in the weakening of the step effect in 3D printing, but it still faces challenges such as insufficient compatibility with multiple materials, poor adaptability to complex components, and excessively long printing time.

Future research on reducing stair-case effects in 3D printing could focus on multiple dimensions. For instance, developing new algorithms to enhance printing precision while reducing computational complexity for time optimization; integrating AI technologies to evolve toward intelligent adaptive systems; and refining multi-axis printing techniques to enable more flexible nozzle tilting, thereby improving print quality while minimizing support structures. Furthermore, intelligent optimization of process parameters can substantially enhance the mitigation of stair-stepping effects.

6 Conclusion

This paper systematically reviews some recent research progress of 3D printing to reduce the stair-case effect. It analyzes the principle and application status of various methods from the aspects of adaptive slicing algorithm, printing direction optimization, nozzle optimization and repair, and also makes a prospect of some shortcomings. It has great significance to promote the breakthrough of 3D printing technology to high precision and high surface quality by reviewing the research progress of the current technical paths to improve the step effect and analyzing different methods.

In the future, we should strengthen the combination of 3D printing and artificial intelligence technology, emphasize the adaptive intelligent control of printing parameters, the optimization of printing time and the improvement of materials to improve the compatibility of multi-materials.

References

- [1] Dilberoglu, U. M., Gharehpapagh, B., Yaman, U., Dolen, M.: The Role of Additive Manufacturing in the Era of Industry 4.0. *Procedia Manuf.* 11, pp. 545–554 (2017)
- [2] Wenbin, H., Tsui, L. Y., Haiqing, G.: A study of the staircase effect induced by material shrinkage in rapid prototyping. *Rapid Prototyp. J.* 11, pp. 82–89 (2005)
- [3] Tavares, T. M., Ganga, G. M. D., Filho, M. G., Rodrigues, V. P.: The benefits and barriers of additive manufacturing for circular economy: A framework proposal. *Sustain. Prod. Consum.* 37, pp. 369–388 (2023)
- [4] Lao, W., Li, M., Tjahjowidodo, T.: Variable-geometry nozzle for surface quality enhancement in 3D concrete printing. *Addit. Manuf.* 37, p. 101638 (2021)
- [5] Tang, P., Zhao, X., Shi, H., Hu, B., Ding, J., Yang, B., Xu, W.: A review of multi-axis additive manufacturing: Potential, opportunity and challenge. *Addit. Manuf.* 83, p. 104075 (2024)
- [6] Yi, X., Peng, H., Liang, Y., et al.: Research on the Optimization Slicing Algorithm of STL Models in Additive Manufacturing. *Foundry Technol.* 43(12), pp. 1073–1078 (2022)
- [7] Yi, Y., Li, Y., Liu, B., et al.: 3D printing adaptive layering algorithm preserving STL model feature details. *J. Xi'an Jiaotong Univ.* 57(08), pp. 105–114 (2023)
- [8] Zhu, M., Dang, Y., Gao, S., et al.: 3D printing adaptive layering algorithm with vector-preserving model characteristics using the patch method. *J. Xi'an Jiaotong Univ.* 55(08), pp. 50–58 (2021)
- [9] Lv, N., Ouyang, X., Qiao, Y.: Adaptive Layering Algorithm for FDM-3D Printing Based on Optimal Volume Error. *Micromachines.* 13, p. 836 (2022)

- [10] Elayeb, A., Tlija, M., Eltaief, A., Louhichi, B., Zemzemi, F.: Minimizing Dimensional Defects in FFF Using a Novel Adaptive Slicing Method Based on Local Shape Complexity. *J. Manuf. Mater. Process.* 8, p. 59 (2024)
- [11] Wu, Y., Hu, J., Chen, X., Sun, R., He, C., Gao, H.: Adaptive hierarchical optimization method for feature details of 3D printing models and experimental study. *Manuf. Technol. Mach. Tool.* (1), pp. 28–32 (2025)
- [12] Maconachie, T., Leary, M., Lozanovski, B., Zhang, X., Qian, M., Faruque, O., Brandt, M.: SLM lattice structures: Properties, performance, applications and challenges. *Mater. Des.* 183, p. 108137 (2019)
- [13] Cong, S., Gu, H., Wei, C., Zhang, M., Cheng, D., Qian, L., et al.: Advancements and challenges in overhang structure fabrication during laser powder bed fusion: a comprehensive review. *Virtual Phys. Prototyp.* 20(1). (2025)
- [14] Leirimo, T. L., Semeniuta, O.: Minimizing form errors in additive manufacturing with part build orientation: An optimization method for continuous solution spaces. *Open Eng.* 12(1), pp. 227–244 (2022)
- [15] Bacciaglia, A., Liverani, A., Ceruti, A.: Efficient part orientation algorithm for additive manufacturing in industrial applications. *Int. J. Adv. Manuf. Technol.* 133, pp. 5443–5462 (2024)
- [16] Wang, J., Hu, H., Liu, Z., Shi, Y., Huang, Y.: Optimization of 3D Printing Nozzle Parameters and the Optimal Combination of 3D Printer Process Parameters for Engineering Plastics with High Melting Points and Large Thermal Expansion Coefficients. *Materials.* 18, p. 500 (2025)
- [17] Bém, J., Suder, J., Mikkola, A., Kot, T., Maslowski, J., Babjak, J., Mihola, M.: Variable-Orifice-Size Nozzle for 3D Printing. *J. Manuf. Mater. Process.* 9, p. 308 (2025)
- [18] Sun, Z., Wang, Y., Li, F., Chen, Y., Zhang, C.: Research on Repair Strategies Based on 3D Printing with Step Effect in Non-fully Solidified Materials. *J. Ordnance Equip. Eng.* 46(2), pp. 294–302 (2025)