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International Journal of Computer Science and Information Technology
ISSN: 3005-9682 (Print), ISSN: 3005-7140 (Online) | Volume 6, Number 1, Year 2025
DOI: https://doi.org/10.62051/ijcsit.v6n1.10
Journal homepage: https://wepub.org/index.php/IJCSIT/index

Path Planning Techniques for Additive Manufacturing: A Review

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ABSTRACT

Path planning plays a pivotal role in additive manufacturing by determining the movement of the toolhead during material deposition, which directly affects print quality, material usage, manufacturing efficiency, and functional performance. This review systematically examines recent developments in path planning strategies across various AM processes. We categorize existing approaches based on their primary objectives, including enhancing print quality, reducing time and material consumption, and achieving specific printing properties such as mechanical strength, aesthetics, or thermal/electrical performance. Emerging trends such as energy-aware path planning, multi-objective optimization, and learning-based strategies are also discussed. Finally, we identify current challenges and outline promising research directions, including generalizable planning frameworks, trade-off analysis between objectives, and standardized benchmarking. This review aims to serve as a valuable reference for researchers and practitioners seeking to optimize AM processes through innovative path planning techniques.

KEYWORDS

Additive Manufacturing; Path Planning; Multi-objective Optimization

1. INTRODUCTION

Additive Manufacturing technology—also known as rapid prototyping, 3D printing, or solid freeform fabrication—has been developing for more than 30 years [1]. This technology has shown great potential in a series of industries such as construction [2], automobiles [3], biomedicine [4] and aerospace [5]. The AM process differs from conventional subtractive manufacturing; while traditional methods remove material, AM builds components additively, point by point and layer by layer, from the bottom up [6]. Currently, AM technologies are mainly classified into seven categories: vat photopolymerization, powder bed fusion, binder jetting, material jetting, sheet lamination, material extrusion, and directed energy deposition [7]. In manufacturing, the strategy for designing the build path is referred to as path planning. Path planning is crucial in AM, as different path strategies can affect surface roughness, dimensional accuracy, and material properties. Moreover, different paths imply different movement strategies for the corresponding print head (e.g. the nozzle in Fused Deposition Modeling (FDM) or the laser in Directed Energy Deposition (DED), resulting in varying durations required to complete the same component. Therefore, better path planning strategies can lead to improved manufacturing characteristics, higher quality, or shorter production times. Many papers have already been published on this topic. As a rapidly evolving manufacturing technology, new AM techniques are being developed and are likely to continue advancing in the future.

In the 3D printing process, the infill path of the model is a pre-defined trajectory, along which the printer's nozzle is guided by motors to deposit material layer by layer, ultimately forming a solid model. In the process of infill path planning, the total infill path length should be minimized, along with reductions in acceleration changes along the path, jumps between paths, and the number of nozzle starts and stops. A well-designed infill path can save printing material, reduce printing time, and improve surface accuracy and printing efficiency. The currently available path planning strategies can be categorized into three groups: improving print quality, saving material/time, and achieving targeted printing performance. "Improving print quality" refers to the development of path planning strategies in AM aimed at enhancing surface quality, shape accuracy, and infill distribution quality. "Saving material/time" refers to the development of path planning strategies in AM to reduce overall manufacturing time or material consumption. "Achieving targeted printing performance" refers to the formulation of path planning strategies in AM to attain improved mechanical, topological, or functional properties. Before going into detailed explanations, some commonly used path patterns are introduced first. Figure 1 shows the corresponding basic path patterns that are widely used today. Most improved path planning strategies are based on these fundamental patterns. These patterns are widely employed in AM to fill the layers of sliced 3D models and can be easily selected in popular slicing software such as Cura and Slic3r.

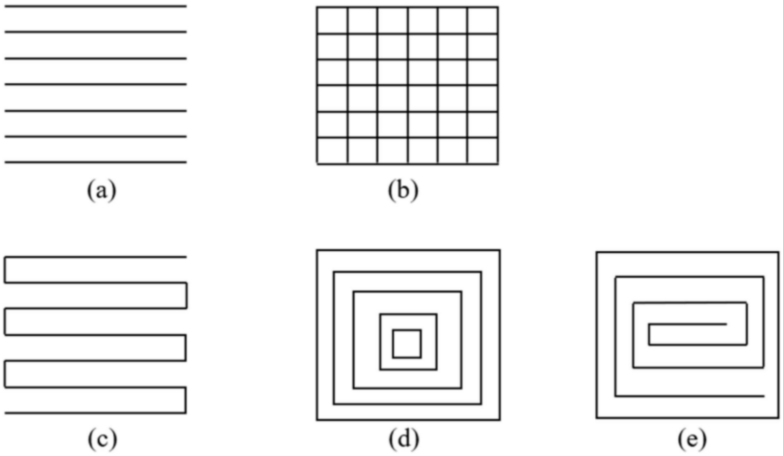

Figure 1. Basic path patterns. (a) Raster path (b) Grid path (c) Zigzag path (d) Contour offset path (e) Spiral path

A 3D model can be manufactured using many different path planning strategies, and Figure 2 illustrates just two examples. As shown, the surface quality on Surface 1 in Figure 2 may vary between these two different path planning strategies, as well as the shape accuracy and infill distribution quality.

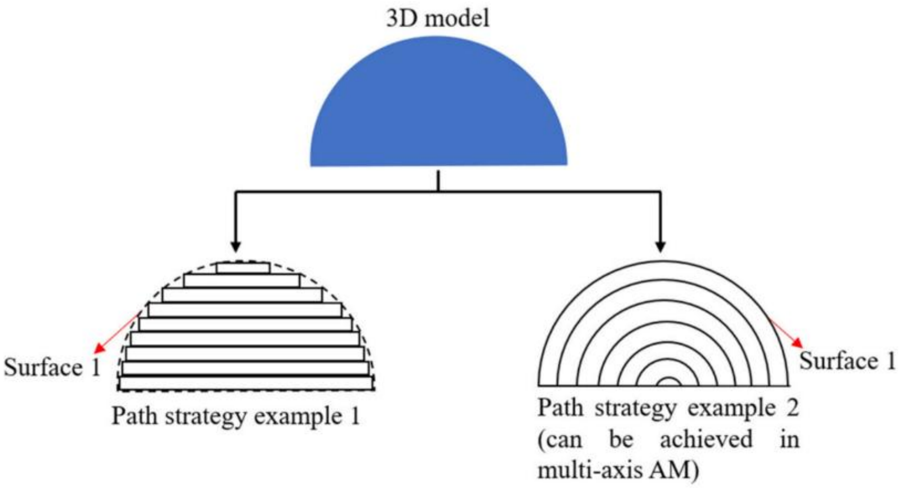

Figure 2. Path planning affecting Surface quality

2. RESEARCH STATUS AND MAIN TECHNOLOGIES

2.1. Improve Print Quality

Improving print quality has long been a central objective in the study of path planning for additive manufacturing. During the actual printing process, the path planning strategy determines the material deposition method, sequence, and the geometric trajectory of the toolpath, all of which significantly influence key quality indicators such as surface finish, geometric accuracy, and mechanical performance of the printed parts. In recent years, various path generation and optimization algorithms have been proposed to specifically address typical issues such as the staircase effect, contour deviation, and corner inaccuracies. This section provides a systematic review of existing path planning strategies and their technical approaches to enhancing print quality, with a focus on surface quality and shape accuracy.

2.1.1. Surface quality.

Jin et al. [8] proposed representing layer contours with closed Non-Uniform Rational B-Splines (NURBS) curves to preserve the surface accuracy of 3D part models. Building on this approach, they developed a hybrid adaptive path generation algorithm aimed at optimizing surface quality by generating precise contour paths and thereby reducing surface errors in additive manufacturing (AM). Figure 3 illustrates an example of contour paths produced using their method. Furthermore, Jin et al. introduced a surface-layer path planning technique specifically tailored for conventional Fused Deposition Modeling (FDM) processes, in which paths are guided along curved layers to enhance printed surface finish. Similarly, Ezaire et al. [9] proposed a curved-layer path planning strategy that employs volumetric coverage printing paths for material extrusion AM to further improve surface quality. In addition, Jansen et al. [10] developed two path planning methods—path projection and the parent-child method—for five-degree-of-freedom (5DOF) and six-degree-of-freedom (6DOF) material extrusion AM systems. These methods effectively mitigate the staircase effect (shape deviation), thereby achieving superior surface quality.

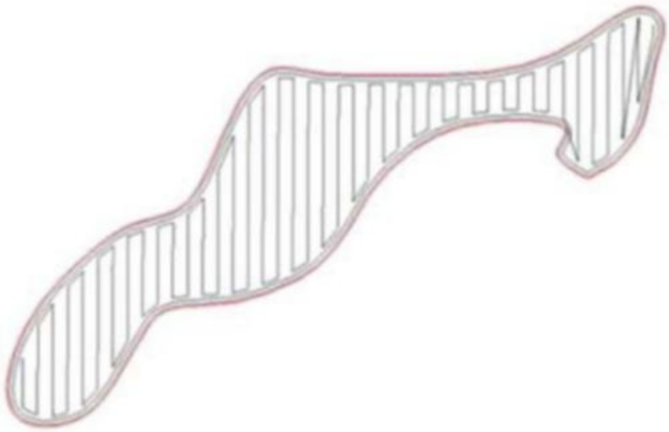

Figure 3. an example of the generated contour paths.

2.1.2. Shape Accuracy.

Routhu et al. [11] improved zigzag and offset path patterns by adjusting laser scanning speed to reduce height variations during the laser powder-based metal deposition process, thereby enhancing shape accuracy. Jin et al. developed a three-step path planning strategy to achieve precision manufacturing in Fused Deposition Modeling (FDM). Communal et al. [12] proposed a path planning method that specifically addresses the shape accuracy at the corners of each layer in material extrusion AM. Figure 4 illustrates their successful fabrication of high-quality 90° and 30° corners. Liu et al. introduced a composite path planning approach that incorporates a sharp-corner correction strategy to further improve the shape accuracy of parts fabricated through wire and arc AM. Giberti et al. proposed a Bézier curve-based path planning algorithm designed to ensure velocity control and uniform speed distribution of extruded material in binder jetting AM, thus enhancing the geometric fidelity of printed parts. Finally, Ding et al. [13] developed an automatic path planning method for wire and arc AM that effectively achieves high shape accuracy in manufactured components.

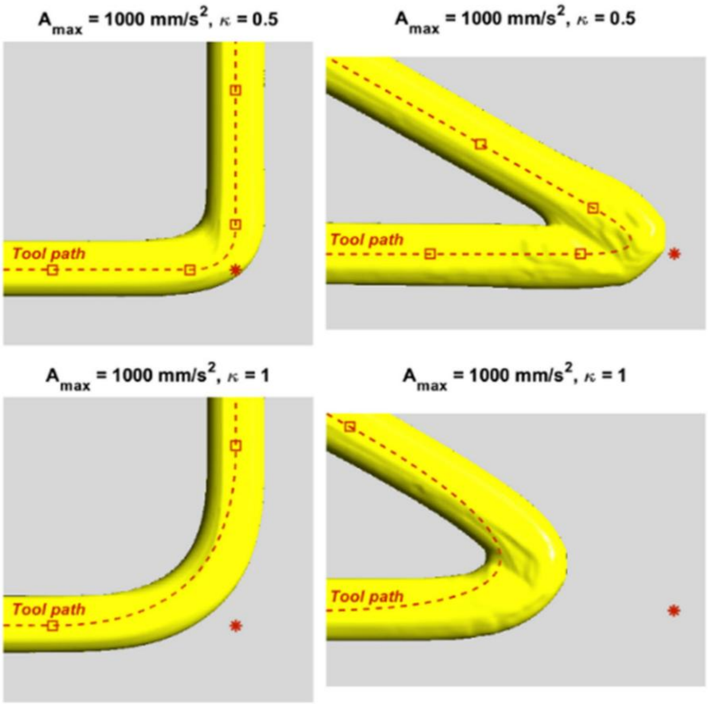

Figure 4. successfully fabricated 90° and 30° angles

2.2. Filling Distribution Quality

Eiliat and Urbanic [14] proposed a modern path planning strategy to determine the optimal infill path for achieving void-free structures with improved distribution quality. Building on this objective, Xiong et al. [15] developed a variable bead width path planning method for wire and arc additive manufacturing (WAAM), enabling bead width adjustments during fabrication to eliminate voids. In contrast, conventional constant-offset path strategies often leave voids in the center of layers. By adopting an adaptive offset path, Xiong et al.'s approach effectively produces parts with uniform, void-free infill.

Kumar and Maji also proposed a path planning method for WAAM that optimizes path width and bead overlap to minimize void formation. However, their strategy does not account for variable bead widths during the printing process. Wang et al. introduced two distinct approaches for WAAM: a cylindrical path planning strategy for fabricating rotary parts (such as propeller blades) without internal voids, and a sequential path planning strategy based on a water-filling principle that relocates intersecting areas to the outer contour, ensuring uniform compaction of the inner regions.

Michel et al. proposed a modular path planning (MPP) strategy, which incorporates feature-based modular design into the traditional layer-by-layer process, achieving uniform and defect-free deposition in wire and arc AM. Ding et al. [16] introduced a mid-axis transformation (MAT)-based path planning method, allowing material deposition along multiple directions to prevent voids, and subsequently developed a specialized MAT strategy for thin-walled structures with enhanced infill quality. Ren et al. combined contour-parallel patterns with adaptive zigzag patterns to achieve void-free metal deposition in AM parts. Similarly, Han et al. employed grouping and mapping algorithms to generate paths based on optimized zigzag and contour layouts, achieving improved void-free infill in FDM processes. Jin et al. [17] further developed an FDM path generation strategy that adaptively selects optimal path inclinations, effectively reducing sharp corners within layers and enhancing overall infill quality.

2.3. Improving Efficiency

2.3.1. Material Saving.

Jansen et al. [18] proposed two path planning methods for five-degree-of-freedom (5DOF) and six-degree-of-freedom (6DOF) material extrusion AM systems, enabling successful manufacturing without the need for support structures and thereby significantly reducing material waste. Figure 5 shows the machine and representative parts fabricated using their approaches. Similarly, Zhao et al. introduced a non-planar path planning strategy that minimizes support material usage in robot-based material extrusion AM. Nguyen et al. developed a heuristic path planning method that achieves support-free fabrication, further contributing to material conservation.

In addition, Ding et al. proposed a mid-axis transformation (MAT) based path planning technique for wire and arc AM, which also reduces material consumption by enabling efficient multi-directional deposition. Thompson and Yoon devised a path planning algorithm to optimize the XY stage movement in aerosol printing (material jetting), allowing for arbitrary printing trajectories and controlled speeds while minimizing material waste.

Moreover, a path planning method was developed for an eight-axis direct energy deposition system, facilitating the fabrication of complex rotary parts without the need for support structures. Zhang and Liou further contributed by developing an automatic path planning strategy for five-axis laser-assisted AM, successfully reducing support material requirements.

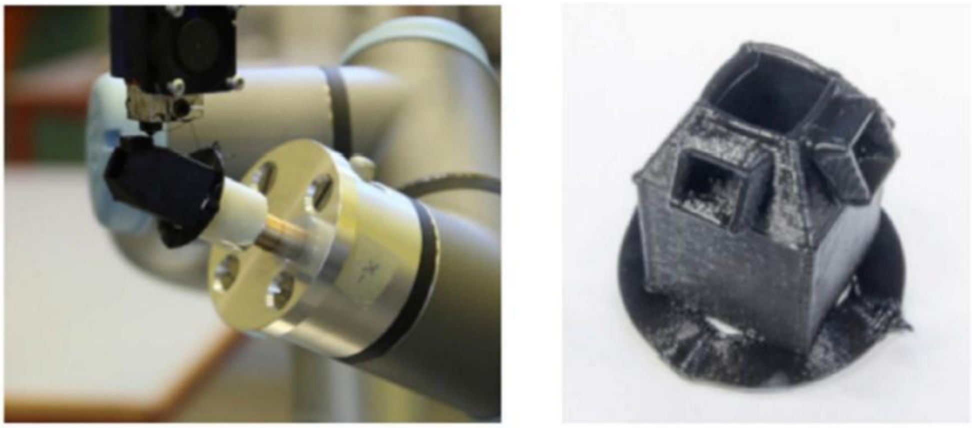

Figure 5. 5DOF AM machine (left) and the product without any support (right)

2.3.2. Time Efficiency.

Bui [19] proposed a path planning strategy for multi-head material extrusion AM, where multiple print heads can work together without collisions, thereby reducing manufacturing time. Their strategy is based on multiple print heads printing the same material. Expanding upon multi-nozzle coordination, Choi and Zhu [20] introduced a dynamic priority-based path planning strategy for multi-material extrusion AM, optimizing toolpaths for different materials and avoiding nozzle collisions to enhance production efficiency. To minimize non-productive movements, Volpato et al. proposed a combined heuristic path planning method aimed at reducing the total extruder travel distance in material extrusion AM. Similarly, Ganganath et al. introduced a speed-optimized path planning strategy using triangular and trapezoidal velocity profiles to decrease transition times between printing segments.

Fleming et al. developed a continuous path planning strategy that reduces unnecessary nozzle movements by approximately 20% by minimizing the distance between successive infill curves and layers. The use of closed Non-Uniform Rational B-Splines (NURBS) for path generation has also been shown to shorten build times through analytical modeling. A path planning strategy ensures a single continuous movement of the print head to complete printing in material extrusion AM. The use of the Hilbert curve as a path pattern is shown in Figure 6a. Luo and Tseng proposed a path planning strategy for multi-part production in FDM. They aimed to reduce the path length between parts to decrease manufacturing time. Jiang introduced a multi-layer path strategy to save manufacturing time. Zai and Chen presented a porous path planning strategy for successfully manufacturing porous structures in material extrusion AM. Figure 6b shows the results of the paths they generated, which are also shown in the figure. Their strategy found the optimal feasible path to save time when printing porous structures. Dreifus et al. proposed a path planning strategy based on the Chinese Postman Problem, which is particularly suitable for manufacturing grid structures and can minimize the total manufacturing time in material extrusion AM. Coupek et al. proposed a path planning method for seven-axis material extrusion AM that avoids the use of support structures, saving both material and processing time. Figure 6c shows the successful manufacturing using their strategy on their seven-axis FDM machine. McQueen et al. proposed an efficient path planning strategy for material extrusion AM with two robotic arms, allowing both arms to work together to save manufacturing time. Shembekar et al. proposed a collision-free path planning strategy for a six-degree-of-freedom material extrusion AM system, which can save material usage and manufacturing time. Cai and Choi developed a group-based path planning strategy for a multi-robot material extrusion AM system. Their strategy ensures collision-free printing between the print heads, thereby saving the total manufacturing time when all robot heads work together.

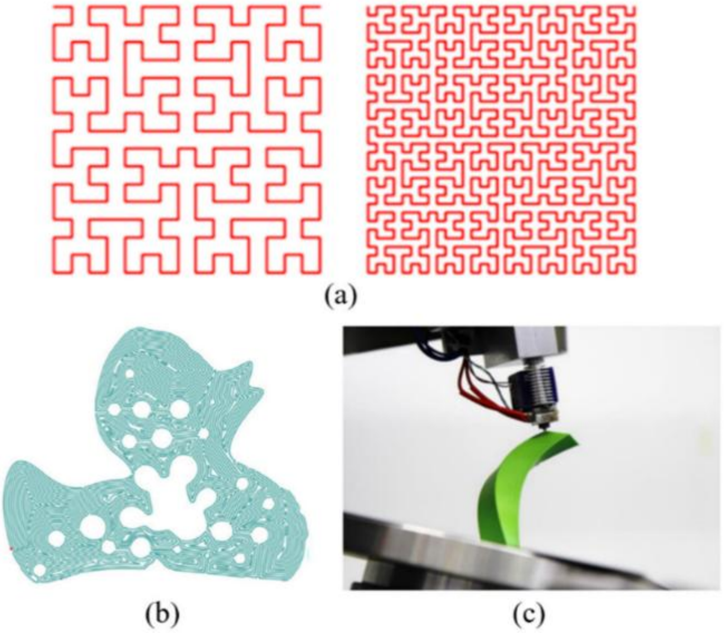

Figure 6. (a) Hilbert curve path pattern generated by (b) porous structure path generation example (c) Path planning strategy successfully manufactured

2.4. Achieve The Target Printing Attribute

Li et al. [21] developed an innovative path planning strategy for printing continuous carbon fiber-reinforced composites with complex geometries and high mechanical performance in material extrusion AM. Similarly, Asif [22] also proposed another strategy with the same objective in material extrusion AM. Kraljić and Kamnik developed a path planning strategy that enhances the bonding between tracks, thereby improving the strength of printed parts in 6DOF material extrusion AM. Li et al. proposed a path planning strategy for manufacturing topology-optimized lightweight parts in FDM. They also introduced a path planning strategy along the main stress direction of the part to enhance the structural performance of FDM printed parts. The wave path planning was developed by

Jin et al. to improve the structural strength of printed parts in FDM. Lin et al. [23] proposed a maze-like path planning strategy for manufacturing isotropic components in FDM. Jin et al. developed a path planning strategy for successfully manufacturing thin-walled parts with good quality in FDM. Ma et al. also proposed an adaptive path planning method with varying thicknesses for the successful manufacturing of thin-walled parts. Eliseeva et al. developed a path planning strategy for successfully manufacturing functionally graded compositions in a multi-material direct energy deposition system. Deuser et al. [24] also proposed a path planning method that successfully prints functionally graded compositions, but in a material extrusion AM system with three print heads. Ozbolat and Khoda proposed a simulation-based path planning strategy to determine the order of material deposition in AM, successfully manufacturing hollow porous structures with functionally graded materials. Zhu and Yu developed a path planning strategy based on a dexel-based spatiotemporal modeling method, which ensures collision-free movement of the print head while using multiple print heads for multi-material printing in FDM. We previously proposed a support interface path planning strategy for easily removing parts after manufacturing in a direct energy deposition process [25].

3. SUMMARY

As mentioned above, a significant amount of research has been conducted on path planning strategies aimed at saving material or manufacturing time. However, there is limited research considering the energy consumption of different path planning strategies. As the world becomes more focused on sustainability, the attention on sustainable manufacturing has significantly increased. AM can become more sustainable and environmentally friendly in the future through path planning. Research proposes new path planning strategies: (1) Saving more energy is a meaningful research topic for the future. (2) A comprehensive path planning strategy that can handle all objectives, combine them, and modify them into new path planning strategies to achieve corresponding goals. Additionally, while current path planning strategies are typically only applicable to specific AM technologies, in the future, a path planning strategy may be developed that can be used for many AM technologies rather than just one. (3) A path planning platform can be developed in the future. This platform can automatically help select the optimal path planning strategy based on the required input properties. The platform should be aware of all the advantages and disadvantages of each path planning strategy, as well as which path planning strategy is used for which AM technology. Then, when inputting the objectives, the corresponding available strategies and the recommended best strategy will pop up, along with their advantages and disadvantages. (4) As mentioned earlier, when adopting improved path planning strategies for specific objectives, other attributes or qualities may deteriorate. For example, when trying to improve the strength of printed parts using different path patterns, the part's dimensional changes and/or build time may also be altered. These trade-offs can be studied in the future. The trade-offs depend on the specific requirements of the customer. (5) Currently, it is not possible to distinguish which path planning strategy is better than another because these strategies are used in research with different parts/models. A benchmark model with all the necessary features can be developed in the future to compare different path planning strategies. Once this benchmark model is available and all upcoming research can be based on it, it will be possible to know which path planning strategy is better for certain objectives (e.g. surface roughness). This will provide useful information for choosing which path planning strategy to adopt in the future. (6) With the development of AM systems, new AM technologies are constantly emerging. Hybrid AM systems, which combine additive and subtractive processes with multi-axis machining, are among these new developments. Therefore, conducting path planning research for these novel advanced AM systems is a necessary condition for the further development of AM systems. (7) Machine learning and integrated path planning strategies can be developed in the future [26]. Machine learning is one of the fastest-growing technology fields today. It is a subset of artificial intelligence, primarily focused on using algorithms and statistical models to make decisions without specific programming. Typically, machine learning can be applied in areas such as medical diagnostics, image processing, prediction, classification, and more. Recently, research on using machine learning in AM has been published for AM process optimization, dimensional accuracy analysis, manufacturing defect detection, and material performance prediction. However, machine learning has not yet been applied to improving path planning strategies. In fact, machine learning is very powerful in planning strategies. Liu et al. [26] used machine learning to select the optimal driving path with the shortest path length. Figure 10a shows the problem map in their study, where the black grid indicates areas with obstacles. The starting point is A, and the ending point is B. In their study, machine learning effectively solved this problem. Similarly, in the path planning problem of AM, machine learning can also be used to obtain the optimal path and printing sequence. All the printing paths in the AM manufacturing process can be divided into points (Figure 7b), and the printing order of the points can be determined through machine learning.

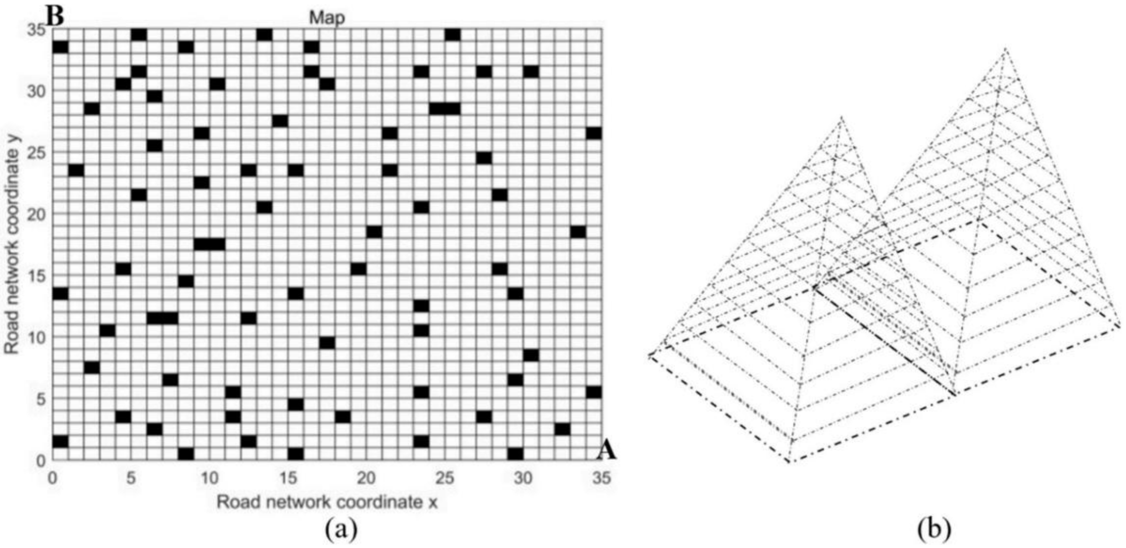

Figure 7. (a) Problem diagram of selecting the best path (b) Using machine learning to divide the 3D model into path selection points

Path planning is a crucial aspect of AM , as it directly impacts the final printing performance and quality. Most of the research in AM has focused on improving the AM process, developing new AM technologies, and exploring new applications of AM based on commonly used path strategies. However, many researchers are still trying to improve AM with different objectives by developing new path planning strategies. This paper focuses on the path planning strategies presented in these publications. The review covers aspects such as improving print quality, saving materials and time, and achieving target printing performance. A summary table provides a guide for selecting the appropriate path planning strategy in future AM manufacturing based on specific goals. There remains a substantial amount of research on path planning that can be conducted in the future. A future path planning platform could intelligently recommend optimal strategies based on desired objectives and application-specific constraints. A benchmark model designed to test the performance of path planning strategies could be created. Trade-offs between different manufacturing attributes could be considered as a factor in the future path planning design process. Finally, machine learning could become a powerful method for further improving path planning strategies.

REFERENCES

[1] Jiang, J.; Lou, J.; Hu, G. Effect of support on printed properties in fused deposition modelling processes. Virtual Phys. Prototyp. 2019, 14, 308–315.

[2] Adam Pajonk, et al. Multi-material additive manufacturing in architecture and construction: a review, J Build Eng, 45 (2022), Article 103603.

[3] R. Leal, et al. Additive manufacturing tooling for the automotive industry, Int J Adv Manuf Technol, 92 (2017), pp. 1671-1676.

[4] Filipa A.M.M. Gonçalves, et al. The potential of unsaturated polyesters in biomedicine and tissue engineering: synthesis, structure-properties relationships and additive manufacturing, Prog Polym Sci, 68 (2017), pp. 1-34.

[5] Byron Blakey-Milner, et al. Metal additive manufacturing in aerospace: a review, Mater Des, 209 (2021), Article 110008.

[6] Jiang, J.; Xu, X.; Stringer, J. Optimisation of multi-part production in additive manufacturing for reducing support waste. Virtual Phys. Prototyp. 2019, 14, 219–228.

[7] Gao, W.; Zhang, Y.; Ramanujan, D.; Ramani, K.; Chen, Y.; Williams, C.B.; Wang, C.C.L.; Shin, Y.C.; Zhang, S.; Zavattieri, P.D. The status, challenges, and future of additive manufacturing in engineering. Comput. Des.2015, 69, 65–89.

[8] Jin, G.; Li, W.; Tsai, C.; Wang, L. Adaptive tool-path generation of rapid prototyping for complex product models. J. Manuf. Syst. 2011, 30, 154–164.

[9] Ezair, B.; Fuhrmann, S.; Elber, G. Volumetric covering print-paths for additive manufacturing of 3D models. Comput. Des. 2018, 100, 1–13.

[10] Jensen, M.L.; Mahshid, R.; D'Angelo, G.; Walther, J.U.; Kiewning, M.K.; Spangenberg, J.; Hansen, H.N.; Pedersen, D.B. Toolpath Strategies for 5DOF and 6DOF Extrusion-Based Additive Manufacturing. Appl. Sci. 2019, 9, 4168.

[11] Routhu, S.; Kanakanala, D.; Ruan, J.; Liu, X.F.; Liou, F. 2-D Path Planning for Direct Laser Deposition Process. In Proceedings ofthe Volume 1: 36th Design Automation Conference, Parts A and B; ASME International: New York, NY, USA, 2010; pp. 415–423.

[12] Comminal, R.; Serdeczny, M.P.; Pedersen, D.B.; Spangenberg, J. Motion planning and numerical simulation of material deposition at corners in extrusion additive manufacturing. Addit. Manuf. 2019, 29, 100753.

[13] Ding, D.; Pan, Z.; Cuiuri, D.; Li, H. A tool-path generation strategy for wire and arc additive manufacturing. Int. J. Adv. Manuf. Technol. 2014, 73, 173–183.

[14] Eiliat, H.; Urbanic, J. Visualizing, analyzing, and managing voids in the material extrusion process. Int. J. Adv. Manuf. Technol. 2018, 96, 4095–4109

[15] Xiong, Y.; Park, S.-I.; Padmanathan, S.; Dharmawan, A.G.; Foong, S.; Rosen, D.W.; Soh, G.S. Process planning for adaptive contour parallel toolpath in additive manufacturing with variable bead width. Int. J. Adv. Manuf. Technol. 2019, 105, 4159–4170

[16] Ding, D.; Pan, Z.; Cuiuri, D.; Li, H.; Van Duin, S.; Larkin, N. Bead modelling and implementation of adaptive MAT path in wire and arc additive manufacturing. Robot. Comput. Manuf. 2016, 39, 32–42.

[17] Jin, Y.-A.; He, Y.; Xue, G.-H.; Fu, J.-Z. A parallel-based path generation method for fused deposition modeling. Int. J. Adv. Manuf. Technol. 2014, 77, 927–937.

[18] Jensen, M.L.; Mahshid, R.; D'Angelo, G.; Walther, J.U.; Kiewning, M.K.; Spangenberg, J.; Hansen, H.N.; Pedersen, D.B. Toolpath Strategies for 5DOF and 6DOF Extrusion-Based Additive Manufacturing. Appl. Sci. 2019, 9, 4168.

[19] Bui, H.; Pierson, H.A.; Nurre, S.G.; Sullivan, K.M. Tool Path Planning Optimization for Multi-Tool Additive Manufacturing. Procedia Manuf. 2019, 39, 457–464.

[20] Choi, S.; Zhu, W. A dynamic priority-based approach to concurrent toolpath planning for multi-material layered manufacturing. Comput. Des. 2010, 42, 1095–1107.

[21] Li, N.; Link, G.; Wang, T.; Ramopoulos, V.; Neumaier, D.; Hofele, J.; Walter, M.; Jelonnek, J. Path-designed 3D printing for topological optimized continuous carbon fibre reinforced composite structures. Compos. Part B Eng. 2020, 182, 107612.

[22] Asif, S. Modelling and Path Planning for Additive Manufacturing of Continuous Fiber Composites; Sabanci University: Istanbul, Turkey, 2018.

[23] Lin, S.; Xia, L.; Ma, G.; Zhou, S.; Xie, Y.M. A maze-like path generation scheme for fused deposition modeling. Int. J. Adv. Manuf. Technol. 2019, 104, 1509–1519.

[24] Deuser, B.; Tang, L.; Geldmeier, J.; Landers, R.G.; Leu, M.C. Process planning and control for functionally graded material fabrication using freeze-form extrusion fabrication. In Solid Freeform Fabrication Symposium; Department of Mechanical and Aerospace Engineering Missouri University of Science and Technology: Rolla, MO, USA, 2011.

[25] Jiang, J.; Weng, F.; Gao, S.; Stringer, J.; Xu, X.; Guo, P. A support interface method for easy part removal in directed energy deposition. Manuf. Lett. 2019, 20, 30–33.

[26] Li, Z.; Zhang, Z.; Shi, J.; Wu, D. Prediction of surface roughness in extrusion-based additive manufacturing with machine learning. Robot. Comput. Manuf. 2019, 57, 488–495.