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Optimization of tool-path generation for material extrusion-based additive manufacturing technology☆

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Abstract

In this study, we propose a tool-path generation approach for material extrusion-based additive manufacturing (AM) that considers the machining efficiency and fabrication precision, which are inherent drawbacks of general AM techniques compared with conventional manufacturing methods. The proposed approach aims to tackle the generation of direction-parallel tool-paths for the interior filling of simple connected areas, which comprises three main steps: (1) determining the inclination of reference lines; (2) generating and grouping tool-path segments into individual sub-paths; and (3) linking sub-paths based on specific requirements. These three modules interact to affect the efficiency and precision of AM significantly. In order to find an optimal inclination, we first analyze the impacts on the fabrication efficiency and manufacturing accuracy with different inclinations. A comparatively accurate building time model is developed subsequently to obtain the optimal tool-path inclination, but without compromising the machining precision, based on the analysis of a geometrical accuracy model. The proposed approach employs different inclinations in distinct layers according to specific manufacturing scenarios and technological requirements. After determining the reference lines, the tool-path segments are selected and grouped based on some characteristics (e.g., the number of intersections between reference lines and boundaries) to make up individual sub-paths, which are then connected to a zigzag-shaped path with short line segment connections. In the module for sub-path linking, some strategies are introduced to decrease the number of useless tool-paths, i.e., uncut paths, which could jeopardize the manufacturing quality by frequently turning the print head on and off. In addition, parametric curves are used to link the final sub-paths to avoid deceleration/acceleration processes in the end/starting parts of the sub-paths. The proposed approach has been used in practice to generate tool-paths for a wide range of models and the results verify its effectiveness and obvious advantages.

Keywords: Additive manufacturing; Inclination determination; Sub-path linking; Tool-path generation

1. Introduction

Additive manufacturing (AM) is a material additive process, which is fundamentally different from conventional subtractive manufacturing processes [1]. AM fabricates a physical object from a CAD model layer by layer, which is more convenient and rapid than other manufacturing approaches. Recently, a wide variety of AM technology applications have emerged in diverse fields, such as architecture, biomedical engineering, and product development [2]. Given its advantages in terms of time and cost savings, AM technology is expected to be an important industry in the near future.

In general, AM technology is characterized by its high efficiency due to the reduction of a product's development period. However, the manufacturing process is not as rapid as desired because of the layer-based fabricating procedure. Thus, building a complex part usually requires several hours, which is unacceptable in most current manufacturing scenarios. Han [3] noted that reducing the building time is now an important issue that affects the development of AM technology. A wide range of deposition strategies has been proposed by many researchers to increase the manufacturing speed. From adaptive slicing to post-processing, an inherent weakness of AM technology that these methods

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cannot avoid is that this technique is essentially a start–stop process, which deposits layers sequentially [4]. In addition, the transition between patches in each layer can degrade the building efficiency greatly and this has also attracted much attention. These issues are obvious and serious in some specific AM technologies based on material extrusion.

To further enhance the effectiveness and efficiency, tool-path planning has gradually become a major feature of process planning for AM technology. A desirable deposition tool-path could improve the precision, surface quality, and strength of prototypes, but it may also reduce the building time and forming material requirements [5]. In general, two main tool-path planning strategies are employed in AM technology: contour-parallel paths and direction-parallel paths [6]. A contour-parallel tool-path employs successive offsets of the boundary curves as tool-path elements, where each successive offset can be obtained using a classical Voronoi diagram approach, whereas a direction-parallel tool-path contains a large number of line segments, which are parallel to a specified inclination. These two strategies have distinct characteristics in terms of the deposition quality and efficiency [7]. Although the contour-parallel tool-path has been studied using various algorithms for several years, the most common tool-path strategy employed in current research is the direction-parallel path because of its practical advantages in terms of easy visualization and high-speed machining [8].

Two key issues in tool-path planning for material extrusion-based AM technology are the boundary filling strategy and tool sequencing strategy [9]. The boundary filling strategy mainly addresses the problems of filling up a patch of internal area continuously without halting the manufacturing process, which has been studied widely in various fields of AM as well as conventional milling manufacturing. The tool sequencing strategy represents the connection of sub-paths in an appropriate order. The fabrication efficiency is the main consideration when determining the sequences of sub-paths because distinct sequencing strategies result in different lengths for the final tool-path to jump from the end of one sub-path to the starting point of another sub-path. Because the time required to execute each jump is almost proportional to the jump distance, minimizing the jump distance is the objective when optimizing the sequencing strategy [10]. In the present study, we focus on tool-path generation in AM technology based on material extrusion, where we aim to obtain the desirable fabrication efficiency and satisfactory precision.

Few studies have addressed the reduction of the process time in AM technology from the perspective of tool-path optimization. Because the tool-path strategy is closely associated with the fabrication quality, most initial research into tool-paths was restricted to issues related to the manufacturing quality. Han et al. [3] proposed a deposition planning approach based on a grouping and mapping algorithm. First, they analyzed the causes of overfilling and underfilling during fused deposition manufacturing (FDM) and they tried to alleviate their occurrence by optimizing the tool-path. Kao et al. [11] presented a shape optimization algorithm, which was implemented to allow high-quality spiral deposition paths to be produced based on its skeleton. Yang et al. [12] introduced an equidistant path generation algorithm to improve the fabrication efficiency and surface quality. Later, Yang [5] and Wah [10] transformed tool-path optimization in AM technology into a classical NP-complete problem and they employed a genetic algorithm to obtain a solution. Jin [13] proposed a mixed tool-path generation algorithm that generated contour tool-paths along the boundary and the offset curves of each sliced layer were used to preserve the geometrical accuracy, where the zigzag tool-paths of the internal area of the layer were employed to simplify the computing processes and to speed up fabrication. However, they did not provide details of how to connect each of the path segments, which we address in the present study.

Tool-path planning for AM is an essential but complex issue, which fundamentally affects the fabrication quality and efficiency. To plan the tool-path effectively and scientifically, we propose a tool-path optimization method that generates more reasonable and appropriate tool-paths for material extrusion-based AM technologies in different scenarios. This method is characterized by a full consideration of the forming quality and deposition efficiency, according to the specific requirements when addressing distinct problems, rather than considering one feature alone. Three main stages are involved in the proposed tool-path generation approach: determining the inclination, generating the tool-path for each sub-region, and connecting the individual sub-paths. This process is illustrated in Fig. 1. The proposed tool-path planning method can be adjusted adaptively to different fabrication requirements and it can improve the deposition quality by employing parametric curves to connect sub-paths, in contrast to previous approaches.

2. Related work

2.1. Generation of tool-paths in AM

The tool-path required for material extrusion in AM is a predefined trajectory along which the nozzle is driven to deposit fabrication material and to form the surface layer by layer. Because the deposition quality features (e.g., surface roughness, dimensional accuracy, and part strength) are influenced by the tool-path, as well as some other processing parameters, many efforts have been made to optimize tool-path planning. In fact, the tool-path planning process in material extrusion-based AM is similar to that of conventional milling in pocket areas. Therefore, various types of tool-path patterns from milling can be introduced into AM, such as zigzags, contours, spirals, and some other filling patterns.

At present, contour-parallel-based and direction-parallel-based filling strategies are mainly employed in AM, which have their own advantages and disadvantages. The contour-parallel tool-path comprises a series of contours, which run parallel to the boundaries of the two-dimensional cross-sections yielded by slicing [14], thus this type of fabrication accuracy is greater and more satisfactory. However, its main problem is the implementation of the offset algorithm, which is computationally expensive and complex. The shapes of the boundaries tend to be comparatively complex in AM, especially with multi-cavity structures. Furthermore, in some circumstances, contour-parallel-based tool-paths may yield more uncut tool-paths, which have negative