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A non-retraction path planning approach for extrusion-based additive manufacturing

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ABSTRACT

Notwithstanding the widespread use and large number of advantages over traditional subtractive manufacturing techniques, the application of additive manufacturing technologies is currently limited by the undesirable fabricating efficiency, which has attracted attentions from a wide range of areas, such as fabrication method, material improvement, and algorithm optimization. As a critical step in the process planning of additive manufacturing, path planning plays a significant role in affecting the build time by means of determining the paths for the printing head's movement. So a novel path filling pattern for the deposition of extrusion–based additive manufacturing is developed in this paper, mainly to avoid the retraction during the deposition process, and hence the time moving along these retracting paths can be saved and the discontinuous deposition can be avoided as well. On the basis of analysis and discussion of the reason behind the occurrence of retraction in the deposition process, a path planning strategy called "go and back" is presented to avoid the retraction issue. The "go and back" strategy can be adopted to generate a continuous extruder path for simple areas with the start point being connected to the end point. So a sliced layer can be decomposed into several simple areas and the sub-paths for each area are generated based on the proposed strategy. All of these obtainable sub-paths can be connected into a continuous path with proper selection of the start point. By doing this, separated sub-paths are joined with each other to decrease the number of the startup and shutdown process for the extruder, which is beneficial for the enhancement of the deposition quality and the efficiency. Additionally, some methodologies are proposed to further optimize the generated non-retraction paths. At last, several cases are used to test and verify the developed methodology and the comparisons with conventional path filling patterns are conducted. The results show that the proposed approach can effectively reduce the retraction motions and is especially beneficial for the high efficient additive manufacturing without compromise on the part resistance.

1. Introduction

1.1. Additive manufacturing

Additive manufacturing (AM), also referred to as layered manufacturing (LM) or rapid prototyping (RP), is a fundamentally different fabrication process from conventional manufacturing methods by integrating computer aided design, material science and computer numerical control to fabricate physical prototypes from virtual CAD models layer by layer [4]. The recent decades have witnessed the rapid development of AM technologies which have been gradually employed in a wide range of applications, such as prototype fabrication, product development, biomedical engineering, electronical devices, and architecture, etc. [45]. Additionally, the capability of producing customized parts has also stimulated the interest of public in this technology. AM offers huge potential in many applications by reducing the development period and eliminating some stages of conventional fabrication methods, as well as building parts without geometric constraints. These advantages have brought in a surge of research interest in AM from many disciplines to bring its all potentialities into full play [37].

After nearly three decades of research, development, and use, a variety of AM technologies are available from the market and more potential techniques for AM are being developed by researchers with the introduction of new technologies, methods, materials, applications, and business models [44]. There are currently seven categories of AM classified by ASTM International Committee F42 based on the forming processes: material extrusion (e.g. Fused Deposition Modeling, FDM), material binding (using inkjet printing process to deposit material),

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binder jetting (using inkjet printing process to deposit liquid bonding agent), sheet lamination (e.g. Laminated Object Manufacturing, LOM), vat photopolymerization (e.g. Stereolithography Apparatus, SLA), powder bed fusion (e.g. Selective Laser Sintering, SLS) and directed energy deposition (e.g. Direct Metal Deposition, DMD). Besides, it is believable that new processes would be developed in the near future that do not fit into any categorization. Although the joining details and the forming equipments of different AM processes differ from each other considerably, they share some common aspects, such as the pre-process on virtual models before practical fabrication, the deficiencies of the fabricated parts, and the issue of long producing time.

Similarly to other manufacturing methods, AM has its own shortcomings and limitations in terms of the quality of manufactured parts and the fabrication efficiency. So far, many efforts have been devoted to improving the part performance and enhancing the fabrication efficiency. In the aspect of part quality, surface roughness and dimensional accuracy are two primary topics that have been studied and investigated. Before proposing specific approaches and methods to address the surface roughness, the surface profile of additively manufactured parts should be modeled firstly and then adopted to analyze the relation between various parameters and the surface finish [1,19,5]. The established surface models can assist in improving the surface quality by the optimization of process parameters [24,34] and post-processing strategies [28,31]. Likewise, the dimensional accuracy has also attracted many attentions from researchers; various studies have been carried out to investigate the process parameters which affect the part deviation during the whole fabrication process. Fahad et al. [11] developed a new benchmarking part to evaluate the accuracy and repeatability of AM processes by considering certain features and dimensions to ensure that the operation capabilities were fully evaluated. As the dimensional accuracy is affected by a variety of factors, some approaches were proposed and adopted to obtain the influence on the part accuracy exerted by process parameters, such as grey Taguchi method [35] and artificial neural networks [29], and finally to minimize the deviation in the fabrication process. Besides, the error compensation is an effective method to improve the dimensional accuracy. For example, Tong et al. [40,41] proposed a parametric error modeling and software error compensation method to address and evaluate the volumetric accuracy of the AM machines inspired by the techniques used for the parametric evaluation of coordinate measuring machines and machine tool systems, and the testing results of proposed strategies showed a significant improvement in dimensional accuracy of built parts. At the same time, they [39] utilized another method to compensate the error by correcting both the STL and sliced file.

With regard to the fabrication efficiency, although AM has long been labeled as a technique that can shorten the production period, it is not always true and the fabrication process is not as rapid as desired actually. The fact that the time for fabricating **n** objects is **n** times as much as that for one object in AM brings in that the current AM systems are becoming unacceptably slow with the increasing size and complexity of parts being fabricated [6]. So, the drawbacks of AM in fabrication efficiency becomes much more prominent when the objects to be produced turn from small cubic inches or thin wall features to parts with large sliced cross-sections. The fundamental reason is that the methodology of building a part in AM essentially consists of a sequence of steps which are necessary and cannot be neglected. The layer-based forming method leads to a mutually contradictory relationship between the surface quality and the build time. Specifically, a large layer thickness can reduce the number of the sliced layers, and hence shorten the fabrication time, but the surface quality would be deteriorated due to stair-step effect; though a smaller layer thickness can improve the surface finish, the fabrication efficiency would be affected inevitably. This problem becomes more serious when it comes to the extrusion-based additive manufacturing, where the semi-solid filament is deposited line by line to form a layer.

Some works have been done to fasten the fabrication process based on the aforementioned reasons. Besides the development and modification of the forming process to decrease the time consumed on one layer, like the continuous liquid interface production (CLIP) technique developed by Tumbleston et al. [42], another feasible methodology applied in the optimization during the process planning, such as build orientation selection [48], support reduction [2] and path optimization [17], is very effective and important. As the time traveling along a path is the basic component of the whole fabrication time, minimization of the traveling time for each layer by path optimization is thus essential to minimize the time needed for completing the fabrication of a part. The aim of this paper is to minimize the fabrication time by decreasing the number of the start-stop processes appearing in retracting paths, mainly for but not limit to, extrusion-based additive manufacturing.

1.2. Extrusion-based additive manufacturing

Among the most widely used and rapidly developing AM technologies, a typical and well-known technique is the extrusion-based additive manufacturing [43]. In this process, the material is fed into an extruder by the motor driving force or the pneumatic force, and melted (no need in some cases) in a liquefier to be extruded from a nozzle, which is controlled by a moving platform in the horizontal plane when the extruded material is squeezed and deposited on the build plate line by line based on the pre-designed paths to form a surface. The deposited surface would solidify rapidly when the material leaves the extruder and exposes to the atmosphere with much lower temperature and moisture. At the same time, the nozzle and build platform can be moved in the vertical direction relatively to enable the nozzle to be lifted by the distance of layer thickness to deposit upper layers, and finally to produce complex 3D objects.

The extrusion-based additive manufacturing technology has achieved great improvements in respect of model data processing, material property, part performance, and fabrication efficiency after a lot of works have been exerted. In the aspect of data processing, Kai et al. [20,21] presented an improved interface between 3D models and AM systems based on the analysis and investigations of existing file formats for AM. The proposed new file format support the STL format by removing redundant information in the original STL file and adding topological information to balance storage and processing costs. Starly et al. [36] pointed out that direct slicing from CAD models may overcome inherent disadvantages of using STL format in terms of the process accuracy, ease of file management, and incorporation of multiple materials. So they developed a direct slicing algorithm for the STEP-formatted NURBS geometric representation. Koc et al. [23] presented a method of biarc curve fitting technique to improve the accuracy of STL files, as well as to reduce the file size for AM. In the fabrication technique and employed material, Lee et al. [25] installed a spindle and a low-cost FDM extruder on each end of a rotary axis in a five-axis machine tool to fully realize the advantages of AM and conventional subtractive manufacturing and to improve the part accuracy which is usually uncertain in AM due to the uneven shrinkage and residual stresses. The materials for extrusion-based AM have been extended from the early thermoplastics to many types of functional materials, such as liquid metals, foods, drugs, and biocompatible materials. The adoption of these materials in extrusion-based AM enables this technology to be used in many new areas, like soft components as flexible sensors for electronical devices [3] and biological soft tissues [30]. With regard to part performance and fabrication efficiency, the related studies and researches have been mentioned in the last section.

1.3. Process planning

Process planning of additive manufacturing technology is a bridge between virtual 3D models and AM machines by transferring the digital

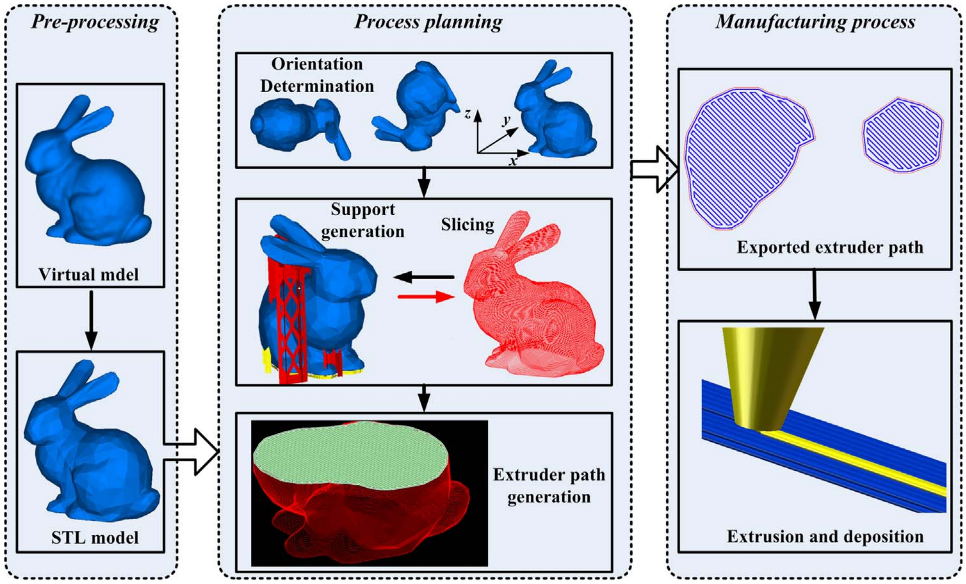


Fig. 1. An illustration of the process planning in AM process.

models into the language or codes that can be recognized by the hardware. The process planning of different AM technologies usually has similar procedures and mainly consists of four steps: build orientation determination, support generation, slicing and extruder path planning [18]. Take the extrusion-based AM as an example, four steps are illustrated in Fig. 1. The build orientation refers to the location and direction of the part to be sliced and deposited, so the orientation directly affects the number of sliced layers and thus determines the build time. Besides, a suitable part deposition orientation can improve part accuracy and surface finish by affecting the orientation of surfaces and support structures needed for building the part [32]. As so many aspects are affected by the part orientation, a number of factors and parameters are supposed to be considered in deciding the part orientation. Actually, under a certain situation, one factor should be dominant in obtaining an optimal orientation. With the determined slicing and deposition orientation, some overhang features are recognized for subsequent generation of some additional structures that acts as the support and would be removed after the fabrication [15]. As a critical step for the process planning, the support plays an important role in guaranteeing smooth and successful fabrication process. At the same time, several technical factors should be taken into account in the support generation,, like the material consumption, build time, and surface finish. As the objects to be fabricated become increasingly complex and intricate, more flexible and robust support generation methodologies are required. The next step is slicing which refers to a process where a set of paralleling planes that are perpendicular to the part orientation are adopted to intersect with the virtual model, and the obtained intersecting boundaries on the part surface can be used for the extruder path planning. A crucial parameter in the slicing procedure is the distance between slicing planes (i. e. layer thickness) as it would affect the build time and surface quality significantly. A desirable method is using the adaptive slicing strategy to target better part quality together with less production time [13]. The extruder path is the planned trajectory for the extruder to deposit the material and fill the certain area layer by layer. The path planning affects the fabrication efficiency and filling accuracy mainly from two aspects: the contour filling strategy and the linking method between sub-paths. The contour filling strategy refers to how to fill up the interior area of a contour, while the linking method is more about determining the sequence of the sub-paths on one layer which determine the idle time consumed in traveling these useless linking paths. Despite many efforts have been concentrated on the path generation, there are still several problems need to be solved to further improve the part quality and enhance the build efficiency. For example, the filling quality near sharp corners of the path is unsatisfied due to serious overfill and underfill issues. In filling relatively complex cross sections with some holes, too many retractions appear during the deposition process and would affect the fabrication efficiency and filling performance together.

1.4. Research objective

It is obvious that the extruder path generation for extrusion-based additive manufacturing is important but requires further improvement, especially in the fabrication efficiency for relatively complex objects. In this paper, a non-retraction extruder path planning method is applied to determine the motion trajectory of the extruder by avoiding the idle time moving along liking paths between sub-paths, and thus shorten the fabrication time. First, we analyze the fundamental reason behind the emergence of retraction in the deposition and propose a “go and back” strategy to avoid the retraction by placing the start and end points for each simple region next to each other. As the start and end points are close to each other, they can be connected to a deposition path of its adjacent regions by properly selecting the location of the start point. We call the area satisfying these conditions as simple area. Based on this, an input connected region is decomposed into several simple areas and the extruder path is generated for each basic area. Then all the sub-paths are combined into a continuous path by traversing all the start and end points of all the sub-paths. To enhance the deposition performance, the obtained continuous extruder path is further optimized from some aspects. At last, some cases with different geometrical characteristics and complexity are adopted for verification and demonstration of the new fill pattern and the results show that the proposed methodology is very suitable and useful for the extrusion-based AM.

2. Background and related work

In the process planning of AM, 3D parts are sliced into a number of slices which define the boundaries for the path planning. Different path patterns have been developed to fill the defined area of each layer with several path elements, which can be deposited continuously with only one startup and shutdown process. The planned paths are supposed to cover all the areas to be filled uniformly and fully.

As for the extrusion-based AM, the path can be defined as the trajectory along which the extruder is guided to deposit material at specific regions layer by layer. Actually, the extruder path in extrusion-based AM is similar with the tool path in conventional milling of pocket areas, which is achieved by material removal layer by layer. Hence, the strategies in planning the tool path for pocket milling can be utilized in the extrusion-based AM, such as zigzag, contours, spiral and some other patterns. Different patterns have their own merits and limitations in terms of the fabrication efficiency and filling quality.

Currently, contour parallel-based and direction parallel-based (raster scanning and zigzag) paths are two most popular patterns applied in the extrusion-based AM with their own pros and cons respectively [9]. The contour parallel paths are comprised of a series of contours parallel to the input boundaries of 2D slices from the slicing procedure, so few sharp turns appear in the planned paths that is beneficial for improving the fabrication accuracy [33]. However, as the input contours can be very complex, the path generation may be very difficult in the implementation of the offset algorithm, which is computationally expensive [26]. In contrast, direction parallel paths utilize a number of line segments that are parallel to an initially selected reference line to fill up the interior area, and is simpler to implement than the contour parallel paths [22]. At the same time, filling the direction parallel paths can be very fast due to the linear movements along line segments. The main problem of this filling pattern is the compromise of filling accuracy since there are many sharp turns that would affect the deposition process. So the contour parallel pattern is suggested to be used for filling the boundaries in order to guarantee good surface accuracy and smoothness, while the direction parallel paths are used for the interior regions for achieving acceptable fabrication efficiency. A common problem for these two general filling patterns is the discontinuity issue when the sliced cross section has some holes, which is very common in fabricating complex models.

Spiral path pattern is another option for filling the pocket area in conventional CNC milling, and has been widely used [12]. The spiral path is continuous and thus provides better deposition conditions than direction parallel paths in the extrusion-based AM. Even though the spiral path pattern is more difficult to construct and generate due to the complicated intersection calculations of the offset, its advantages enable it to have an important status in path planning [46]. However, the discontinuity between sub-paths is still a problem for spiral paths.

In order to conquer the discontinuity issue in the filling path, some works have been done. In the direction parallel path, Tang et al. [38] pointed out that the tool retraction motion was an important issue in zigzag pocket machining and they proposed an optimization method combining both the local and global minimization of the number of retractions in the resulted paths to solve this problem. As for contour parallel path, Park et al. [33] presented a contour parallel offset tool-path linking algorithm, to guarantee that no tool-retractions were required in the machining process. Besides, Zhang et al. [27] proposed a simple and effective contour- parallel tool-path linking method by constructing a tool-path region tree for the offset operation and linking the corresponding points and virtual corresponding points to generate the sub paths. At last, the obtained sub-paths were merged to enable tool-path with no retraction. Elber et al. [10] presented a scheme to construct C_1 continuous toolpath for 5-axis pocketing by forming out circular segments of maximally inscribed sizes and linear segments connecting these circular segments. The obtained tool path was continuous and good for high speed machining.

In the area of AM, Dwivedi and Kovacevic [8] proposed a method to generate a continuous path for material deposition. They applied a subdivision of a 2D polygonal section into a set of monotone polygons, and the path for each individual sub-region was generated with a closed zigzag path. At last, these closed zigzag paths were joined to each other to get the final torch path, which was also a closed loop. At the same time, this method could be used to improve the toolpath for CNC milling by reducing the number of idle paths. Ding et al. [7] presented a similar but more practical method to generate optimal tool-paths for the wire and arc additive manufacturing. They firstly used a divide-and-conquer strategy to decompose 2D geometries into a group of convex polygons and a continuous tool-path is generated for each polygon after an optimal scan direction is identified. Finally, all separated sub-paths were connected to form a close curve. The experiments and implementation of their path planning strategy showed better surface accuracy than other existing methods. Recently, Zhao et al. [47] developed an interesting and novel kind of filling patterns, called connected Fermat spirals, which could fill a connected 2D region with a single continuous path. This new type of filling path could join all the decomposed sub-regions along a graph traversal with a special geometric property. The results from their studies demonstrated that this new method would lead to efficient and high-quality layered fabrication.

Based on the above review of current path planning strategies, two key factors are required to be considered in the path planning for extrusion-based AM. The first is the continuity of the planned path according to the needs from the technical characteristics of extrusion-based AM. Both the fabrication efficiency and the filling quality would be better with less number of the retracting paths. Besides, the influence on the deposition quality exerted by the geometries of the path should be considered, for example, the sharp corners in the paths should be avoided, the gap between path segments should be uniform, etc. A new extruder path generation algorithm is developed in this paper to satisfy these two requirements.

3. Non-retraction path planning methodology

In this section, an extruder path planning algorithm to generate a continuous path without retraction for a singly-connected region is described. Before talking about the algorithm in detail, we first analyze the reason behind the occurrence of retraction motions in general path patterns. Then, we present a strategy informally named as “go and back” to solve this problem. Finally, we explain how to employ the proposed method to generate extruder paths for arbitrary connected areas without the retracting paths.

3.1. Problem analysis

As illustrated in Fig. 2, two general path patterns (direction parallel and contour parallel) are adopted to fill a square with two holes inside. We can see that at least three path elements for filling the whole area with the zigzag pattern, while much more sets of contours or spirals are required when using the contour parallel path patterns. One continuous path is termed as a sub-path which can be deposited once without any retraction motions. It is obvious that there is no room any more for the optimization of reducing the number of sub-paths with general path patterns. The reason is that a sub-path might go into a dead end once the starting point of this sub-path has been specified and the extruder has to leave the dead end and travel to the start point of another sub-path to restart the deposition work. As the path space is well defined based on the deposition conditions, the end of a sub-path is unknown or even random in advance of generating all the path elements within this area, not to mention the connection between the current sub-path and other unfilled sub-paths. This harsh reality leads to the difficulty in optimizing the extruder paths globally and a greedy algorithm is the second best method to link all the sub-paths. So, the resulted extruder path for a connected region usually consists of several path elements which are connected with each other with retracting paths.

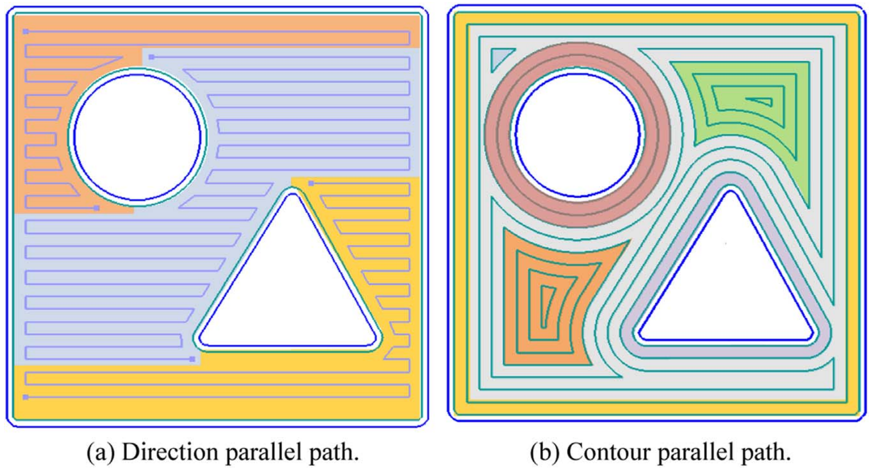


Fig. 2. Illustration of two general path patterns.

3.2. "Go and back" strategy

In order to address this issue, a strategy called "go and back" is presented to generate the sub-paths which have the following two properties. The first property is that the end point of a sub-path can be located at the start point after its start point has been chosen, so the generated sub-path can be connected into a continuous and closed path. Another property is the selection of the start point is arbitrary along the closed loop of the sub-path, and this property is perfectly useful for the connection between adjacent sub-paths. Fig. 3 shows the comparison between the general filling paths and the paths generated with the "go and back" strategy. We can explain the "go and back" strategy with a more straightforward way: unlike the general zigzag or spiral paths that tend to travel towards one direction (perpendicular to the reference line with regard to direction parallel paths, while inwards or outwards for contour parallel paths), our new path patterns contains two path elements: outgoing path and returning path which have opposite directions with each other for either direction parallel or contour parallel path patterns. The returning path would go back to the start point along one side of the outgoing paths and fill the areas that have not been filled by the outgoing path. With this method, the start point and the end point of the deposition path can be located at a same point and the region to be filled can be covered perfectly with the outgoing path and the returning path. So we name this approach as "go and back" strategy originating from the "outgoing" path and the "returning" path. We can see from Fig. 3 that the deposition results are desirable in terms of the coalescence between adjacent deposited strands and the surface quality.

The generation of these two path elements can be realized with three steps. The first step is to generate a reference path within the region to be filled according to the desired path patterns as shown in Fig. 4(a). It should be noted that the path space of the reference path is twice as large as the practical space $\boldsymbol{w}$ in the filling paths. Meanwhile, the distance between the reference path and the input boundary is the path space $\boldsymbol{w}$. Subsequently, the generated reference path is bolded symmetrically until the thickness is increased to the desired path space $\boldsymbol{w}$, as illustrated in Fig. 4(b) At last, the edge of the bolded lines is extracted and the two path elements could be specified after the start

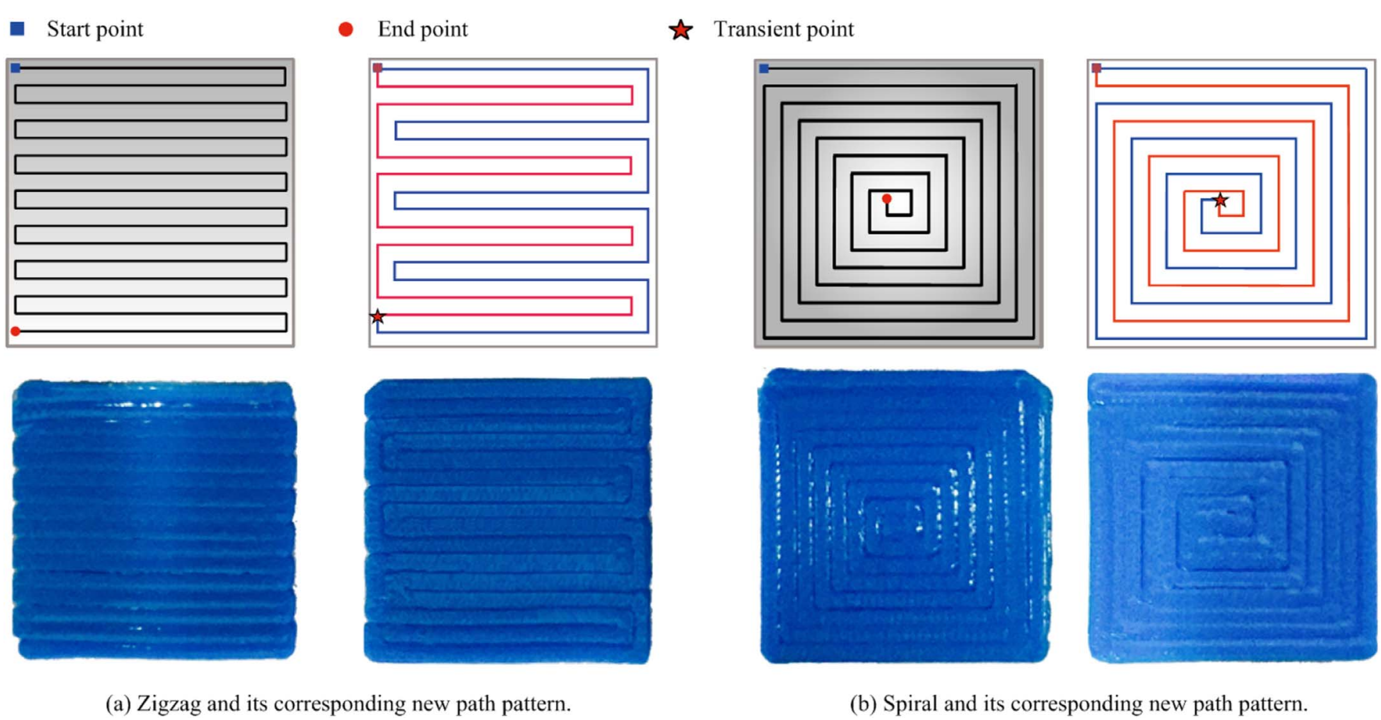
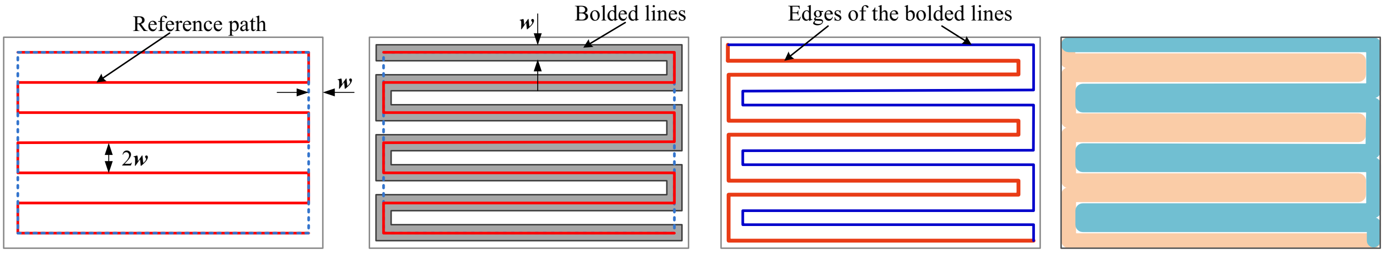


Fig. 3. Comparison between general path and the path pattern generated with "go and back" strategy.



(a) Generation of reference path. (b) Generation of bolded lines. (c) Generation of filling path. (d) Simulation of filling result.

Fig. 4. Generation of a sub-path with the "go and back" strategy.

point has been selected at one point on the extracted edge as shown in Fig. 4(c). This is the generation process of a sub-path with the "go and back" strategy and the obtained sub-path is closed. Fig. 4(d) is the simulation of the filling results using the generated paths. This strategy is also applicable to the contour parallel path patterns. The only difference in contour parallel path is that the reference path is bolded by two offset processes (inwards and outwards respectively) with $\boldsymbol{w}/2$ as the offset distance.

3.3. Generation of non-retraction path

Based on the aforementioned ideas for the construction of sub-paths, we develop a new approach to generate a continuous deposition path for connected areas. As the sub-path generated with the "go and back" strategy is closed and the start point can be chosen at the location of any point along the closed loop theoretically, the adjacent sub-paths can be linked if the start points of these two sub-paths are selected properly. Therefore, the extruder path generation method proposed in this paper is comprised of two steps: generation of sub-paths for the connected area, and the connection between them with proper selection of their start points.

3.3.1. Polygon decomposition and sub-path generation

Before generating the closed sub-path, the geometry of input connected region needs to be analyzed at first. Obviously, it is unlikely to fill an arbitrarily connected area with only one sub-path. So, the input connected area is required to be decomposed into a set of basic areas that can be filled with one sub-path. The purpose of the decomposition is to make the implementation of the sub-path generation accomplishable. Actually, there are many available approaches and algorithms for the decomposition of polygons, different ones would lead to different results. Similar to the basic filling path patterns, we utilize two basic approaches for the decomposition of the connected areas: direction parallel and contour parallel methods. These two methods would be discussed in detail respectively.

In the direction parallel-based decomposition process, several steps are involved as illustrated in the flowchart of Fig. 5. As the input 3D models for the process planning are commonly tessellated STL format, the sliced boundaries are a group of polygons consisting of many line segments. A main task for the direction parallel-based method is the determination of the inclination angle for the reference line which is used to analyze the geometry of polygons. In the selection of the inclination angle, several factors need to be considered, such as the number of sub-regions, the relation between adjacent layers, and so on. With the input polygon and the corresponding reference line, a recursive judgment is adopted to traverse through all the line segments of the polygon. If either of two conditions is satisfied by a line segment, a dividing line is added. Specifically, if a line segment is parallel to the reference line, a dividing line is added that is parallel to the reference line and goes through that line segment; another case is the vertex of a line segment is a local extreme point along the direction that is perpendicular to the reference line. This case can be judged from whether two adjacent vertexes (left and right) of current vertex are on

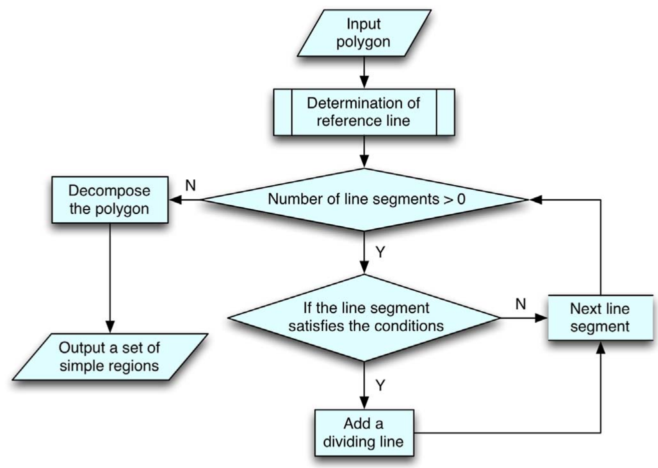


Fig. 5. The flowchart of the direction parallel-based polygon decomposition method.

the same side of a line that is parallel to the reference line and goes through current vertex. If so, this line is added as a dividing line.

After all the line segments have been analyzed and the dividing lines are added, the input polygon is decomposed according to these dividing lines and its own geometries. First, the polygon is decomposed into $n-1$ parts based on the positions of dividing lines, where n is the number of the dividing lines. Second, each part is divided into $m-1$ sub-regions based on the intersections between the reference line and the polygon, where m is the number of intersections. After these two steps, the input polygon is decomposed into M sub-regions, where M is

$$M = \sum_{i=1}^{n-1} (m_i - 1) \tag{1}$$

However, some of the obtained sub-regions can be merged into its adjacent regions if they meet two requirements: the first is they share two common boundaries of the input polygon, and they also have one common edge at the same time. All the regions satisfy the above two conditions are merged with each other to reduce the number of sub-regions which is beneficial. So, the final number of the sub-regions N is smaller than M.

The above direction parallel-based decomposition method is illustrated in Fig. 6. With the obtained sub-regions, the sub-path (either direction parallel or contour parallel-based path) for each region can be generated with the "go and back" strategy.

With respect to the contour parallel-based decomposition method, we develop a similar algorithm to that in [33] to divide the connected areas. The developed approach uses three steps to achieve the sub-regions and their corresponding sub-paths as illustrated in Fig. 7.

Step 1: Generate the offset contours by offsetting the input polygons by a distance of desired path space $\boldsymbol{w}$.

The input connected polygons area usually comprised of several boundaries, including the outer boundaries and the inner boundaries, as shown in Fig. 7(a). Generally, the outer boundary is defined as various line segments in counter-clockwise (CCW), while the inner

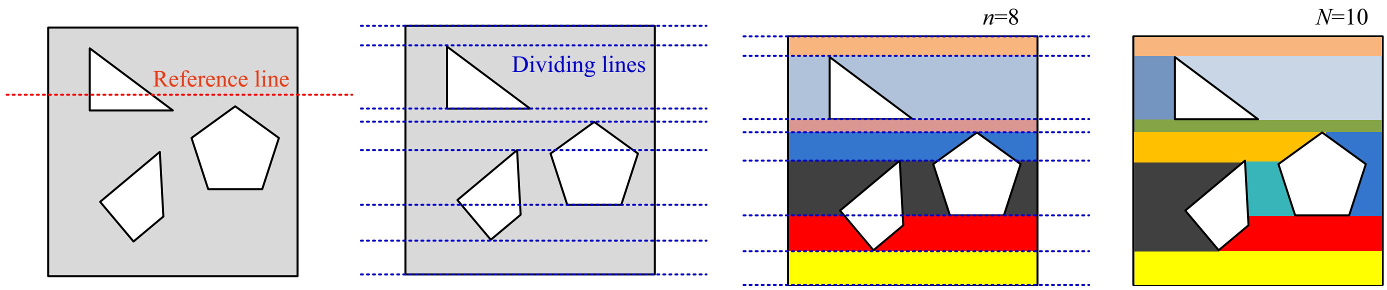


Fig. 6. The illustration of the direction parallel-based polygon decomposition method.

boundary is in clockwise (CW) for easy recognition. A set of offset contours are obtained by repeated offsetting of the boundaries with the distance of path width $\boldsymbol{w}$ as the offset distance. Note that the offset distance of the first offset contours is half of the path width $\boldsymbol{w}$ considering the practical deposition. The offsetting results are shown in Fig. 7(b).

Step 2: Clarify the relationship between the offset contours.

When generating the offset contours, each contour is obtained from its parent contours, so the parent/child relationship between them can be used to build a tree which represents the mutual relation between offset contours. Here, it should be noted that one parent contour may have more than one children contour, and vice versa. Based on the parent and child relationship, it is easy to construct a tree consisting of all the offset contours. The construction process is started from the input boundaries, including the outer and inner ones. As shown in Fig. 7(c), all the offset contours are numbered based on the information available during the offsetting operations. The input boundaries are named as **B1**, **B2**,...**B*i*** and their subsequent child contours are named as **B*i*−1**, **B*i*−2**,...**B*i*-*j*** until one child contour has several children, the names are changed to **B*i*-*j*−1**, **B*i*-*j*−2**... **B*i*-*j*-*k***, etc. As the input connected polygon must have only one outer boundary while the number of inner boundaries is unknown, we analyze the offset contours form the outer boundary towards into the interior. Based on the containing and contained analysis, the relationship tree is built up as shown in Fig. 7(d), and the color of each node is the same as that in Fig. 7(c) for easy visualization. With the relationship tree, all the generated offset contours can be classified into several parts as shown in Fig. 7(d).

Step 3: Generate the sub path based on the offset contours and the established relationship.

The offset contours within each part should be rerouted into a continuous path. The method is illustrated in Fig. 7(e), the adjacent contours are connected by cutting these two contours with a couple of parallel lines whose distance is the path space $\boldsymbol{w}$. When the number of contours in one part is more than two, three parallel line are adopted to intersect with the three contours and the intersections are used to connect the three contours, and the same method is employed when the number of the offset contours increases.

3.3.2. Sub-paths connection

After all the sub-paths have been generated in the connected area, the following task is to connect these sub-paths to form one single continuous path. The developed linking methods for both the direction parallel-based and contour parallel-based sub-regions are similar. An adjacent relation graph is required to be constructed based on their relatively geometrical locations at first. In the direction parallel-based decomposition method, the relation graph is built up with a top down sequence along the direction perpendicular to the reference line as shown in Fig. 8. While the relation graph can be directly generated from the relationship tree that has been established in the former step when handling with the contour parallel-based sub regions as shown in Fig. 9. With the relation graph, a linking sequence diagram can be generated based on the adjacent relationship between sub regions. As long as two sub-regions are neighbors and share common boundaries, they can be connected. This is the basic rule for the connection. With this rule, all the sub-paths are linked one by one.

In the direction parallel-based method, two sub-regions that are neighbors in the relation graph obtained from the resulted sub-regions can be linked into a continuous path by cutting two neighboring path elements and reconnecting them respectively, as illustrated in Fig. 9. As the neighboring sub-paths are in the upper and lower relation while not the left and right relation, different situations that would appear have been listed in Fig. 9. It is easy to link all the neighboring sub-paths with this approach.

In the contour parallel-based method, the linking diagram built from the relation graph can be used to connect all the sub-paths with the similar strategy to that in linking sub-paths in direction parallel-based method. As illustrated in Fig. 10(b), the linking diagram represents the mutual relationship between sub-regions and the paths in linked parts can be connected into a continuous closed path. The rerouted result is shown in Fig. 10(c).

3.4. Path optimization

So far, the generated path for a connected region is always continuous that means the area can be deposited once without any retraction motions and idling time. However, we need to notice that the obtained path still have some deficiencies that are not conducive to the deposition quality. For example, if a connected area is deposited with a continuous extruder path generated from the direction parallel-based method, the boundaries are formed by a combination of a large number of line segments, so the deposition quality along the boundary is obviously undesirable leading to poor surface quality and dimensional accuracy. In order to solve this problem, a hybrid path planning approach, similar to that in [16], is used to guarantee the high quality deposition of boundaries. Specifically, several offset contours are generated from the input polygons and the innermost offset contours are used for the generation of non-retraction path. These offset contours are used to generate a continuous path using the strategy that is developed for the generation of sub-paths with the contour parallel-based method. This contour parallel-based sub-path is subsequently connected to the non-retraction path to form the final extruder path. The non-retraction path is generated regarding the innermost offset contours as the input polygons. It should be noted that the connecting points on the contour parallel-based sub-path is supposed to have a minimum distance that is the same with the path space $\boldsymbol{w}$ to the non-retraction path to enable itself to be connected otherwise the start connecting points would be chosen again. It is obvious that the obtained final extruder path is still continuous.

The above issue does not exist in the extruder paths generated with contour parallel-based method. But, as the sharp corners in the extruder paths would deteriorate the deposition quality seriously [17], sharp corners should be eliminated in the generation of sub-paths as well as the connection between sub-paths. At the same time, sharp corners might appear in the innermost offset contours when using the contour parallel-based method. Some approaches need to be

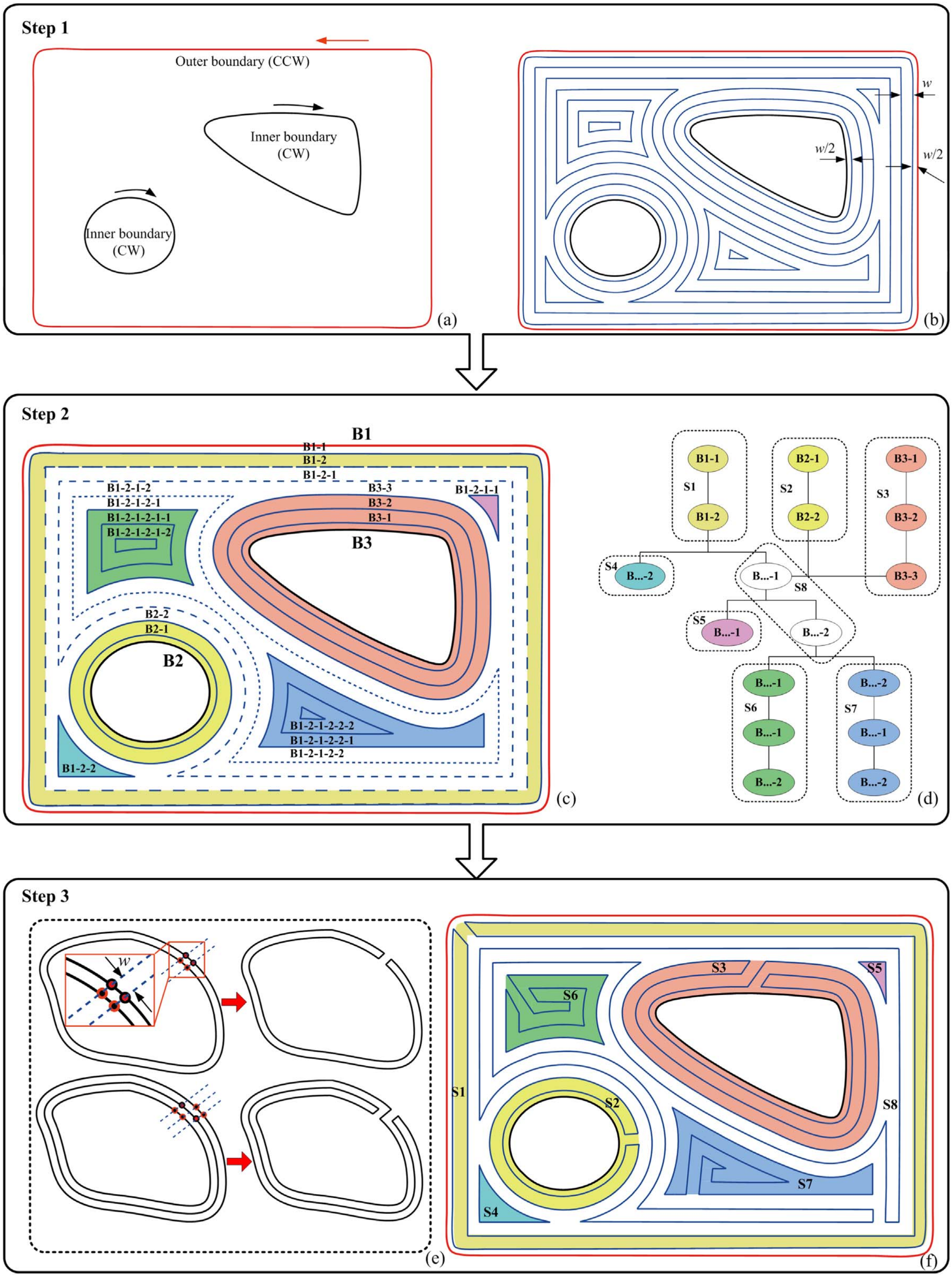


Fig. 7. The illustration of the contour parallel-based sub-path generation process.

developed to alleviate the problems brought by sharp corners. In the connection of offset contours to generate the sub-paths, it is advisable to ensure the connecting path segment is perpendicular to both offset contours to avoid the occurrence of sharp corners. Meanwhile, it is much better to assign the connecting points at the corner of original path elements to reduce the number of corners. These methods are also applicable to the connection between sub-paths. As for the sharp corners in the innermost offset contours, some approximation algorithms can be applied to smooth the path to improve the deposition performance.

Meanwhile, the non-uniform spacing issue existing in the sub-paths would bring in the unevenness of the deposited surface. In the generation of sub-paths with direction parallel-based paradigm, some algorithms for the adaptive adjustment of path elements have been developed to achieve locally uniform space between paths in our previous work [18]. Obviously, this issue would also appear in the

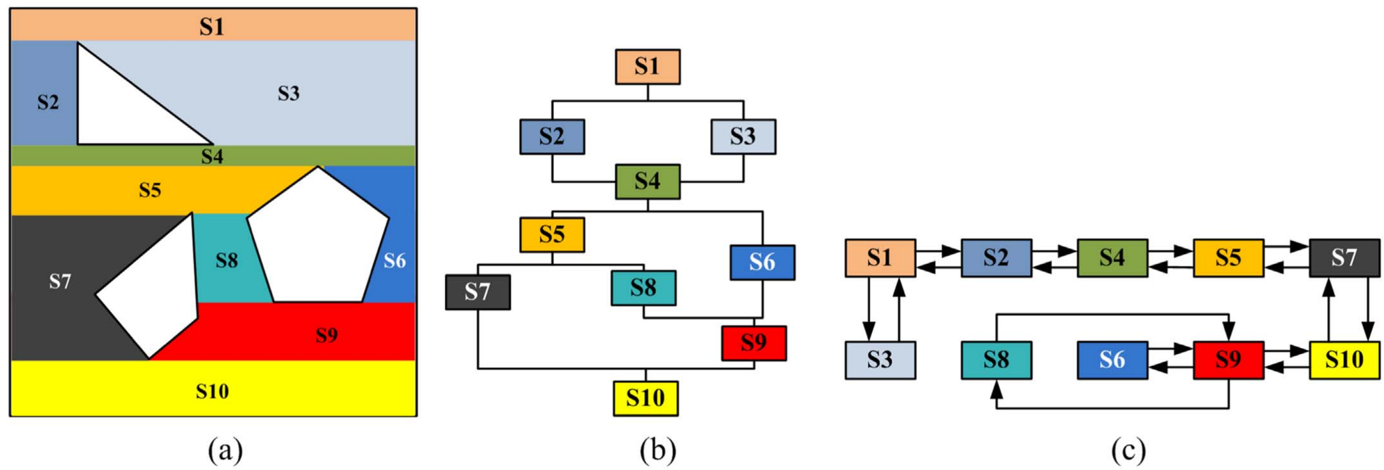


Fig. 8. Construction of (b) adjacent relation graph and (c) linking sequence diagram for direction parallel-based decomposition results.

sub-paths generated with contour parallel-based method. The studies in [47] can be used to solve this problem via iterative Gauss-Newton method.

4. Implementation and discussion

The non-retraction extruder path generation method described in the previous section has been implemented with C++ language and is going to be integrated into the current process planning software for the practical fabrication purpose. In planning the extruder paths for arbitrary 3D models, it should be noted that the deposition of filaments should be arranged in alternate directions for successive layers when the direction-parallel based path pattern is adopted. By doing this, the influence from the voids between filaments and the anisotropy due to the uniform direction of filaments on one layer could be alleviated.

As illustrated in Fig. 11(a)-(c), a bone-shaped part is comprised of 400 slices when the layer thickness is set as 0.2 mm. With a given slice, the outer boundary is formed with contour-parallel path elements while the interior is filled with a connected direction-parallel path loop. Two key parameters for the path planning are the path gap and the inclination. The path gap is mainly determined by the deposited bead width which is affected by the material flow rate and the extruder feed rate. And the path inclination is rotated between layers to strengthen the bonds of the whole object as illustrated in Fig. 11(d).

Firstly, the difference on the part resistance between general path patterns and our proposed path strategy is studied. As the final part strength is mainly dependent on the inter-bead and inter-layer coalescence [14], the bending test is adopted. Four specimens with different types of filling path, as shown in Fig. 12, are deposited using a Lulzbot TAZ3 FDM machine with dimensions 150 mm*15 mm*5 mm. Type I is the general direction-parallel path pattern and type II is the non-retraction direction-parallel filling paths; Type III is the general contour-parallel path pattern while type IV is the non-retraction contour-parallel paths. The path gap for all the path pattern is set as 0.5 mm and the path inclination is 0° and 90° between layers in type I and II. The fabricated specimens are tested under the typical three-point bending loads, as shown in Fig. 12(f). All the specimens are fractured along vertical direction due to the weak joining force between layers.

The test results are shown in Table 1. The maximum compressive loads for each specimen are 37.6, 36.2, 28.7, 28.4 MPa respectively. It is obvious that the flexural strength of the fabricated parts using the proposed filling paths is almost the same with the parts using general path filling methods. So, it can be concluded that the proposed method would not bring any negative effects on the part resistance. At the same time, the build time is also measured and the fabrication efficiency can be improved by using the proposed method obviously from the results by avoiding the travel time for retracting path segments. It can be observed from the close-up views of the deposited part that the direction parallel path patterns would bring voids at corners along the path.

Then, several geometries are processed in order to verify the effectiveness and capabilities of the proposed algorithms and methodologies. The first geometry is a rectangle with a shape of the school badge of Ningbo University inside, as shown in Fig. 13, and the purpose of this test is to demonstrate the application of the direction parallel-based decomposition method to the geometric shape with interior holes, and to demonstrate its advantages by the comparison with general zigzag path pattern. With the input geometry, the first step is to decompose it into several sub-regions based on a pre-defined reference line. After the reference line has been determined as the line along the horizontal direction, the steps in Fig. 5 are applied on the

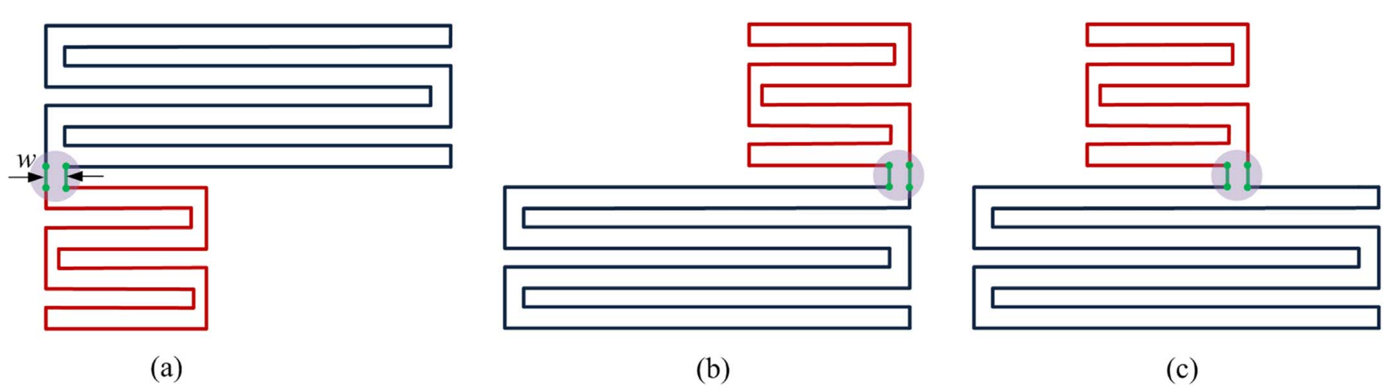


Fig. 9. Linking approach for neighboring sub-paths under three different cases.

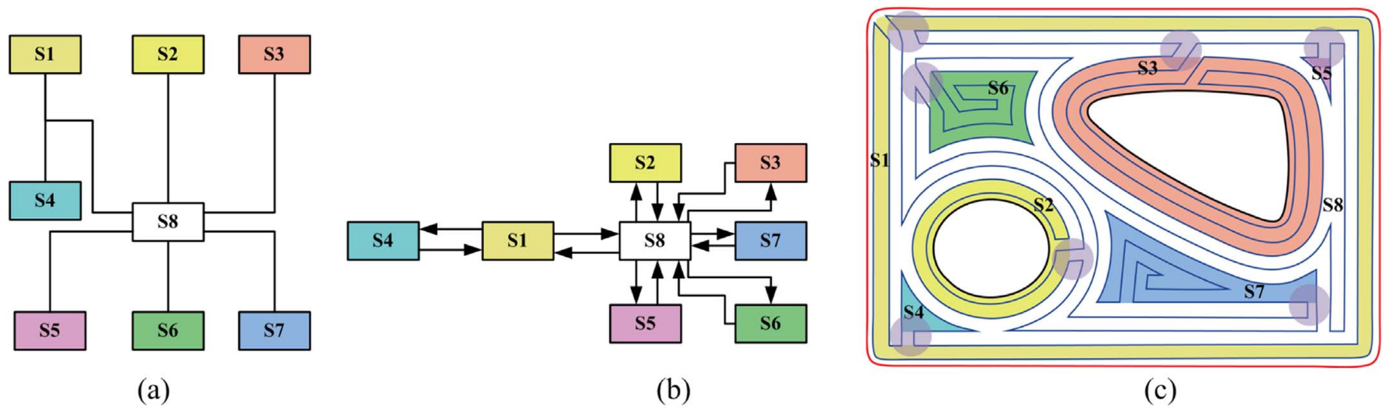


Fig. 10. Construction of (a) adjacent relation graph and (b) linking sequence diagram for contour parallel-based decomposition results, and (c) connection results.

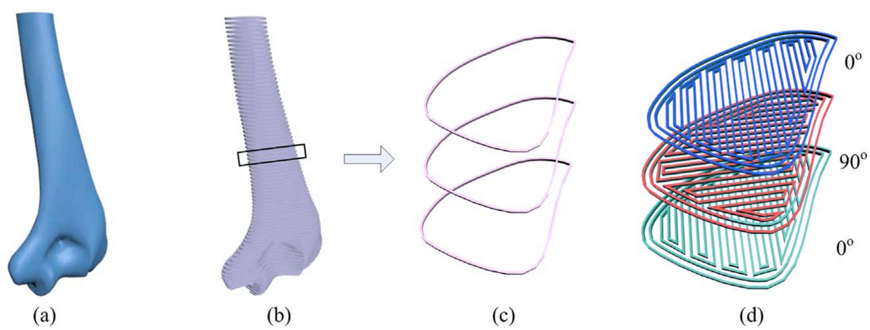


Fig. 11. Implementation on a 3D object.

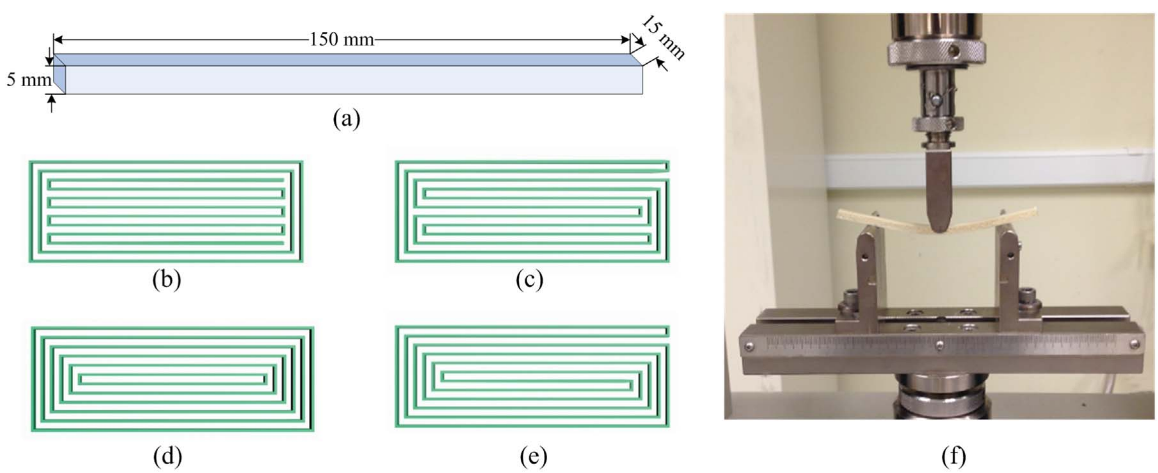
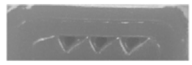
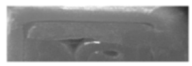
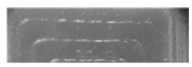


Fig. 12. Tests on the bending strength of parts, (a) dimensions of test part; (b) path type I; (c) path type II; (d) path type III; (e) path type IV; (f) testing setup.

geometry sequentially to obtain the decomposed results as shown in Fig. 13(a). There are totally 6 sub-regions after the decomposition and the sub-path for each sub-region is generated with the "go-and-back" strategy using the direction-parallel path patterns as shown in Fig. 13(b). The last step is to link all the closed sub-paths to form a single continuous path. This step needs to build up the adjacent relation graph at first to construct a linking sequence diagram for all the sub-regions, based on which all the sub-paths would be connected with each other to get the final extruder path without any useless path elements, and thus freeing from retraction motions. The final connected deposition path is as illustrated in Fig. 13(c) and the practical deposition result is shown in Fig. 13(d).

To further analyze the proposed non-retraction path, one of general direction parallel-based path patterns, zigzag path is applied to the same geometry with the same path space $\boldsymbol{w}$. Four sub-paths are generated as shown in Fig. 14 (a), and the total length of the path is 2046.2 mm without considering three useless paths for connecting these sub-paths. To calculate the fabrication time, the frequent acceleration and deceleration process are considered and the acceleration/deceleration algorithm used for the analysis in this paper is the simple trapezoidal feedrate method. The expected feedrate F_0 is set to be 80 mm/s, and the acceleration in the simulation is 200 mm/s^2. The corresponding feedrate profile for the zigzag paths is generated as shown in Fig. 14(b), where the feedrate is always changing during the whole deposition process. A magnified portion of the feederate profile is shown in Fig. 14(b), and we can see that the feedrate varies rapidly when traversing the tiny line segments. Due to the existence of a large number of tiny line segments in the extruder path, the effective value of the fabrication feederate is far smaller than the expected value. This is one of the main reasons for reducing the number of sharp corner in the planned path. According to the feedrate profile, the total fabrication time is 83.98 s for the deposition of the input geometry. When applying

Table 1
Test results on four specimens of different path filling strategy.

Sample type	Build time	Weight (g)	Flexural stress (MPa)	Close-up view
type I	1 h 7 min 49 s	13.905	37.6	
type II	58 min 35 s	13.92	36.2	
type III	1 h 8 min 26 s	13.95	28.7	
type IV	1 h 1 min 7 s	13.97	28.4	

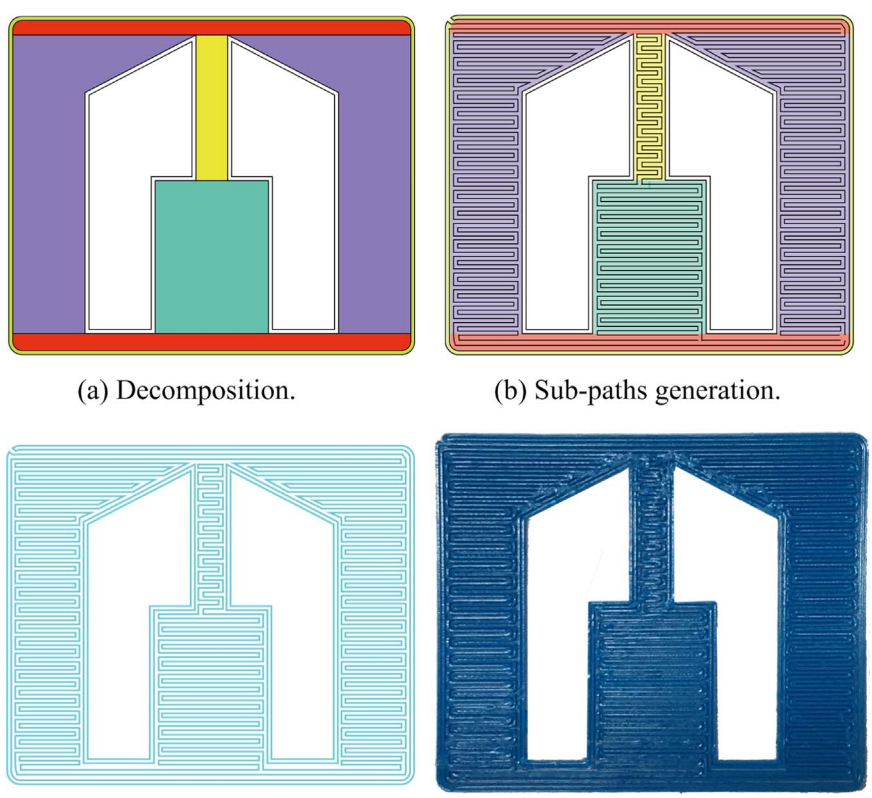
the same parameters on the non-retraction extruder path in Fig. 13(c), the total length of the path is 2047.1 mm, and the fabrication time is 83.51 s, both of them are almost the same with that in zigzag patterns. So, the times for the startup and shutdown of the extruder during the deposition can be reduced to zero without any compromise at the building time.

The goal of the second and the third tests are to demonstrate the application of the contour parallel-based non-retraction extruder path generation method. In this case, the input geometries are the contour of a monkey and the Chinese character of monkey. As illustrated in Fig. 7, three steps are involved in the generation of the sub-paths. The first step is to offset the input geometry repeatedly to obtain a set of offset contours. Then, these offset contours are grouped based on their mutual relationship by building a relationship tree to find their parents and children. Next, sub-paths are generated by means of connecting contours those belong to a same group. So far, the resulted paths are shown in Fig. 15(a). Likewise, a linking sequence diagram can be constructed based on the adjacent relations between sub-paths and they can be connected according to the determined sequence. The last step is to optimize the continuous path mainly from two perspectives: smoothing the sharp corners and adjusting the gap between paths locally. The optimization result is shown in Fig. 15(b) and has quite good geometric properties and the deposition result is shown in Fig. 15(c).

At the same time, a more complicated geometry as shown in Fig. 16 is adopted to further testify the proposed methods. And the generated non-retraction extruder path shows better continuity than general contour-parallel based path patterns, and thus would facilitate the practical deposition. Though there are some voids in the final paths, it is acceptable because these voids usually in the interior of the geometry and they have a very limited influence on the surface finish and the dimensional accuracy. Actually, this issue is bought by the offsetting process, and it is also common in other contour parallel-based tool-path path patterns.

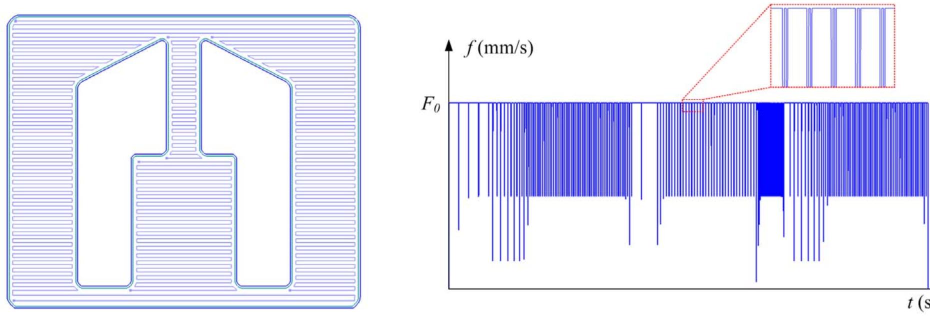
5. Conclusion

Extruder path plays significant roles in the deposition performance and the fabrication efficiency of the extrusion-based AM and the path generation is a critical step in the process planning for AM technology. A novel extruder path generation methodology aiming at improving the efficiency, as well as avoiding the discontinuous deposition is presented in this paper by eliminating the frequent startup and shutdown process



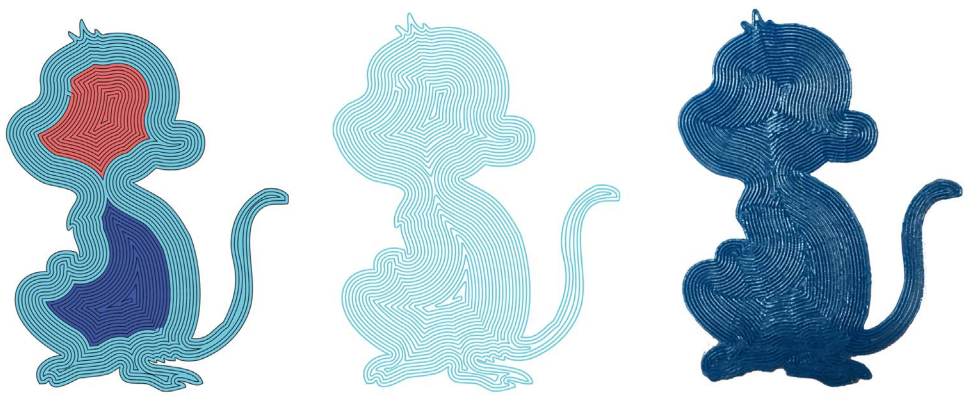
(a) Decomposition. (b) Sub-paths generation. (c) Sub-paths connection. (d) Deposition result.

Fig. 13. Example of non-retraction extruder path generation based on direction parallel-based method.



(a) Extruder path with general zigzag pattern (b) Feedrate profile of the generated path

Fig. 14. Comparison with general zigzag path patterns.



(a) (b) (c)

Fig. 15. Implementation of non-retraction extruder path generation based on contour parallel-based method.

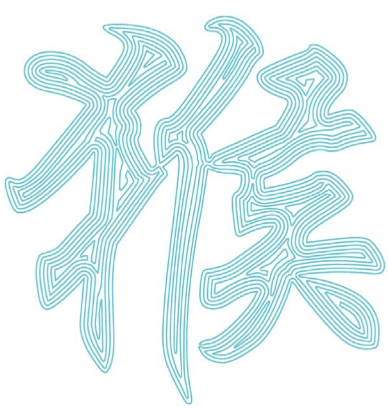


Fig. 16. Implementation on a more complex geometry.

during the deposition work. Based on the investigation and analysis of the retracting motions in the deposition process, a strategy called "go and back" is adopted to turn the open path into a closed path and finally to generate a single continuous path for a connected area. The extruder path generated with this strategy can ensure that the start point and the end point are approximately at the same location. This property enables the path to be connected to its adjacent path easily and conveniently. Two main steps are involved: the first step is the polygon decomposition and the sub-path generation, and then all the sub-paths are connected to form a single continuous path in the second step. Besides, some methodologies are presented to further optimize the generated paths to improve the deposition performance. In order to verify the feasibility of the proposed method, the bending test is conducted on four different specimens with distinct filling paths to compare their flexural stress. The test results show that the implementation of the proposed path planning strategy can shorten the build time while the flexural stress is almost the same with that using general filling paths. Meanwhile, the implementation of the developed methodologies on several typical cases verifies the effectiveness of the proposed algorithms. And the comparisons with conventional path filling patterns are conducted to demonstrate its advantages with respect to fabrication efficiency.

Despite of merits in reducing the retraction motions, there are some limitations for the developed path patterns. For example, the selection of connecting points between contours to form sub-paths is not determined based on any quantitative criteria, and the same case appears in the determination of the sequence for linking all the sub-paths. Besides, although some optimizations have been applied to improve the geometry of the extruder path for better deposition performance, many overfill and underfill issues still appear due to the paths with non-uniform space. So, there are still many important but difficult topics for the research of this new filling path pattern and we will concentrate on these extend works in our ongoing research.

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