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Technical paper

Process planning strategies for solid freeform fabrication of metal parts

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ABSTRACT

Process planning of additive manufacturing of metals is a research interest because of the applications of solid freeform fabrication of metal parts in industry. The strategy is to transform the model of the part into the combinations of 2D layers that will be deposited using different fabrication methods. Process planning for metal deposition in this paper consists of three major modules: spatial decomposition, slicing of the part, and toolpath generation for every slicing layer. Algorithmic improvements are proposed and implemented for these major modules. For spatial decomposition, 3D part decomposition based on modular boundary models and centroidal axis extraction methods are combined to decompose parts more robustly and reliably. For generating slicing layers, a planning process for building non-uniform layers is investigated to greatly increase the variety of the parts that can be manufactured without the need of support structure. For toolpath generation methods, optimization of the generated toolpath is studied especially for complex thin-wall structures to ensure the deposition quality. Experiments were carried out to evaluate the improvements of the major modules of process planning strategies for rapid manufacturing.

1. Introduction

Rapid manufacturing technology has been applied to build functional parts in industry [1–4]. The rapid prototyping process used in this paper is the direct metal deposition (DMD) process, which utilizes a high-powered laser to melt metal powder layer by layer on the substrate to manufacture fully dense metal parts directly. This rapid manufacturing system is located in the Laser Aided Manufacturing Process (LAMP) lab at the Missouri University of Science and Technology (Rolla, MO).

Many process planning strategies and toolpath generation methods for rapid manufacturing are available in the literature [5–12]. There are three major modules of process planning for the rapid manufacturing system in the LAMP lab: spatial decomposition of CAD model of the part, adaptive slicing process of the decomposition results, and toolpath generation for every slicing layer. For every module, different strategies and methods were investigated. As far as decomposition of complex parts is concerned, spatial decomposition [13] and the centroidal axis extraction method [14–16] were advanced to decompose the part into several subcomponents. For every subcomponent, the building direction is consistent. Spatial decomposition is implemented by decomposing the part along the concave boundary silhouette edge of the part model. The disadvantage of spatial decomposition is that this method still cannot avoid the need for a support structure, which means that a support structure is considered to assist in building complex parts. The centroidal axis extraction method decomposes the part model by detecting the change of centroid of presliced layers. For example, Fig. 1 shows the CAD model of a part and the centroidal extraction results of the part model. As the figure shows, the part is decomposed into four components. Decomposition happens where a certain amount of centroidal information change is detected. However, this implementation still has its own limitations. As illustrated in Fig. 2, the centroidal axis of the shape does not indicate the change of the geometry, and the deposition will fail without a support structure. In this paper, the centroidal axis extraction method and decomposition based on modular boundary models will be combined to increase the feasibility of the decomposition process. The former method will be used as a default strategy, and the decomposition method will switch to the latter one if the centroidal positions are the same for the adjacent slicing layers, but the rapid geometric change is detected by comparing the area of the adjacent slicing layers.

After decomposition of the part model is finished, the slicing algorithm will be used to get the 2D slicing layers for every decomposed component. The slicing results will be uniform layers, as shown in Fig. 3(a). However, non-uniform layers as shown in Fig. 3(b) are generated using the adaptive slicing procedure, especially when slicing the parts that have curve features. The process planning strategy for building non-uniform layers will be another research issue covered in this paper. Every non-uniform layer will be considered as another part to build. The goal is to transform

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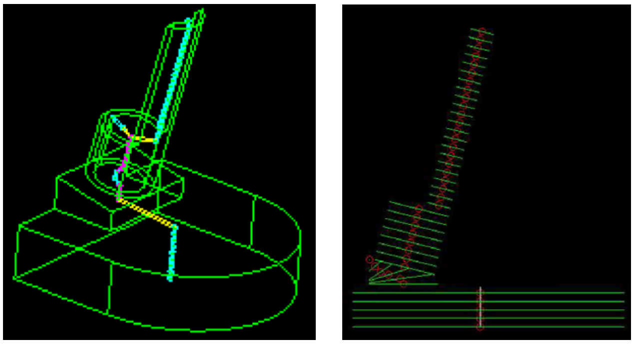


(a) 3D part model. (b) Extracted centroidal information.

Fig. 1. Example of centroidal axis extraction of CAD model.

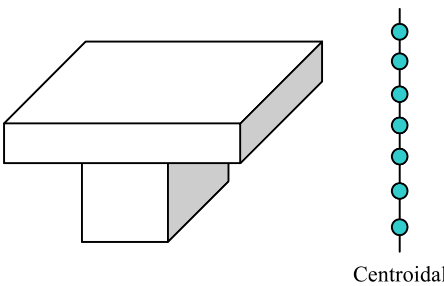
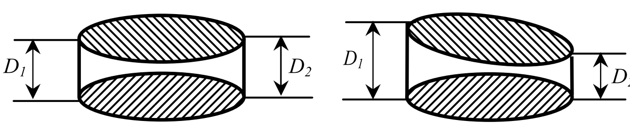


Fig. 2. Centroidal axis fails to detect the geometric change.



(a) Uniform layer $D_1 = D_2$. (b) Non-uniform layer $D_1 \neq D_2$.

Fig. 3. Uniform and non-uniform layers.

the non-uniform layer into a combination of uniform layers. The strategy for process planning of 3D non-uniform layers will be explained in the following sections in detail.

The final module is toolpath generation after the part model is decomposed and sliced into layers. Compared with the previous two modules, the coverage toolpath in rapid prototyping has been studied more extensively as an important component of process planning [5,8,11,12]. Although many researchers studied the optimization of the toolpath planning strategies [17–19], the major toolpath generation patterns in the current research work are still as follows: contour offsetting pattern [20–22] and zigzag pattern [23]. The contour offsetting pattern includes the contour-parallel offsetting pattern and spiral offsetting pattern [24]. The spiral offsetting pattern is the modified contour-parallel offsetting that has better connectivity between every connective offset loop. For the rapid manufacturing industry, the contour-parallel offsetting pattern and spiral offsetting pattern are often adopted due to the nature of additive manufacturing technology. In addition to the above patterns, in the research done by Yao and Gupta [25] multiple cutter path patterns were combined for 2.5D milling to generate the improved cutter path. The objective of this strategy is to find the most efficient toolpath that is the shortest path to cover the area to be machined. And the computational time needed may be a bottleneck. In Ruan et al. [26], combinations of the toolpath generation patterns have been studied in the deposition processes, and a deposition cell was defined. The deposition void was fixed by adjusting the toolpath, that is, adding some straight lines to

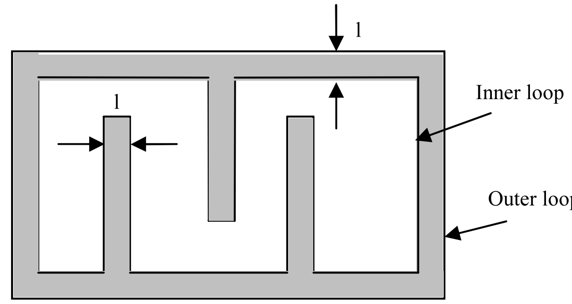


Fig. 4. Thin-wall structures with inner loop.

cover the area where a void may happen. This method can fill the small voids; however, some bigger voids cannot be filled with just several straight lines, and the surface flatness will be impaired as well. So, the method of filling the voids with several lines is not always effective. Another method is to decompose the target area into several loops and to use the different toolpath patterns in different loops. In Ren et al. [27], an adaptive toolpath generation pattern was advanced where coverage and efficiency are both considered as the objectives, with the assumption that coverage has higher priority. The zigzag pattern [28,29] and contour-parallel offsetting pattern will be used as the candidates. The algorithm was developed to predict the possibility of the occurrence of deposition void and switch to the appropriate toolpath pattern automatically when needed.

This paper will focus on one kind of part, a complex thin-wall structure. In CAD modeling, a thin-wall structure is one kind of special body called a shell body. Most toolpath planning is with regard to solid parts. Obviously, toolpath planning for thin-wall structure is different from other solid parts. As shown in Fig. 4, it is a thin-wall structure with an inner loop. The thickness is the major criteria to define a thin-wall structure. Depending on the operational parameters of the different rapid prototyping systems, the definition of the thin-wall structure is certainly different. In this paper, feature recognition of a thin-wall structure is not the research focus. The user will decide whether the loaded part model is a thin-wall structure or not. If a part includes some non-thin-wall features and some thin-wall features, it is also considered a thin-wall structure here. Toolpath planning for complex thin-wall structures will also be demonstrated in the following sections.

The entire algorithm in this paper was programmed using HOOPS as the display engine and ACIS as the 3D modeling kernel, and it has been developed using the Visual C++ programming language. The CAD model in this paper is in.SAT format, which is the surface boundary representation of a solid model.

2. Adaptive spatial decomposition

Adaptive spatial decomposition was developed to enhance the performance of the centroidal axis extraction method, especially when the centroidal information cannot detect the change of the part geometry. For example, Fig. 5(a) is a part model of a turbine blade. Fig. 5(b) shows the centroidal information for every presliced layer. It is clearly shown that the centroidal axis cannot detect the geometry change because of the symmetric blades. The adaptive spatial decomposition strategy will be able to detect the failure of centroidal axis extraction and switch to the decomposition method based on modular boundary models.

Boundary models are assumed to be modular boundary models, which are a class of part representations that describe a solid object as a set of face-abutting components or cells, as shown in Fig. 6. The cell interface is either concave edge or concave loop. If every point on an edge is concave, then this edge is a concave edge.