Robotics and Computer–Integrated Manufacturing 51 (2018) 1–13

Contents lists available at ScienceDirect

Robotics and Computer–Integrated Manufacturing

journal homepage: www.elsevier.com/locate/rcim

Inclined layer printing for fused deposition modeling without assisted supporting structure

Hai-ming Zhao[a,b], Yong He[a,b,*], Jian-zhong Fu[a,b,*], Jing-jiang Qiu[a,b]

[a] State Key Laboratory of Fluid Power and Mechatronic Systems, College of Mechanical Engineering, Zhejiang University, Hangzhou 310027, China
[b] Key Laboratory of 3D Printing Process and Equipment of Zhejiang Province, College of Mechanical Engineering, Zhejiang University, Hangzhou 310027, China

ARTICLE INFO

Keywords:
Additive manufacturing
3D printing
Assisted supporting structures
Inclined layer printing

ABSTRACT

Assisted supporting structures (ASs) are very important and are commonly used for the three-dimensional (3D) printing of overhanging structures to avoid collapse. However, this technique is not always effective, and many challenges remains in printing with ASs, such as low printing efficiency, a complicated process, material-wasting and high cost. Here, we propose a novel and simple printing strategy, inclined layer printing (ILP), which allows printing without ASs. The printed structures are sliced in an incline and overhanging structures are supported by adjacent layers under a suitable slicing angle. We demonstrate that ILP can be easily integrated into the current 3D printing process. To verify this method, we test a new model of filament section, which allows evaluation of the fabrication of the slice's boundary.

1. Introduction

3D Printing (3DP) technology has become the focus of extensive product development in the past 20 years [1]. The process of 3DP is based on layer-by-layer fabrication from an arbitrary geometric model. Driven by customization allowing complicated part production, 3DP is widely applied in electronics [2], energy devices [3], medicines [4], microfluidic analytical devices [5], biotechnology [6], optics [7], structural industry [8], space applications [9] and mold production [10], etc.

Desktop 3D printers are currently based on fused deposition modeling (FDM) which is affordable for uses in daily life, as well as for teaching and scientific research. Due to its low price and wide usage, desktop 3D printers may eventually become as popular as a personal computer (PC) and significantly change our daily life [11].

Like other 3D printing technologies, FDM deposits each layer of melted filament on top of the former material according to the planned tool path. It is a challenge to print the parts successfully, particularly to prevent the collapse of the melted filament, and to facilitate this, ASs are often used. From a geometric aspect, when the slicing sections of two adjacent layers are quite different in printed objects with intricate contour, or with overhanging, floating and ball-shaped surfaces, ASs are needed to help the newly added material retain the designed shape. These challenging regions are called overhanging structures. Fig. 1(A) shows a model of a cup with a handle A_i and A_{i+1} refers to the two adjacent layers seen by horizontal slicing. Fig. 1(B) shows the corresponding slicing contours of A_i and A_{i+1}, from which we can distinguish severe distortion of the curves at the handle part. Large distortion of the curves will create deposition failure as the filament width is far smaller than the offset of the curves.

Another significant use of ASs is to strengthen the structural stiffness of the printing model. Changes in temperature of the deposited material may lead to thermally volumetric shrinkage and residual stresses [12–14]. Thermal residual deformation can make the horizontal processed surface irregular, which can affect subsequent deposition resulting in warping, delamination, or even part fabrication failure [15], shown as Fig. 2(A). Similarly, even when printing some close to vertical areas, the newly added filament still may experience difficulties in sticking to the processed layer if the fabrication area is too small. This is because the stiffness of micro-regions especially of rod like structures may be very low and thermal deformation can be very significant. The tree model in Fig. 2(B) shows the bias error when vibration occurs in a micro-region, which indicates bad surface continuity and even the appearance of deposition errors seen along narrow branches. Hence, ASs also can play an important role in part fixation, shape preservation, and stiffness improvement.

In the last few years, there has been much investigation on the efficient use of ASs to improve 3D printing. Several studies have aimed at designing suitable and efficient support structure. Jin et al. provided an algorithm of automatic ASs generation based on sliced data to increase generation efficiency [16]. Masood et al. proposed an expert FDM support designer (EFS) system aiming at the optimization of the ASs generation process [17]. Thrimurthulu et al. developed a

* Corresponding authors.
E-mail addresses: yongqin@zju.edu.cn (Y. He), fjz@zju.edu.cn (J.-z. Fu).

https://doi.org/10.1016/j.rcim.2017.11.011
Received 4 May 2016; Received in revised form 6 November 2017; Accepted 6 November 2017
0736-5845/

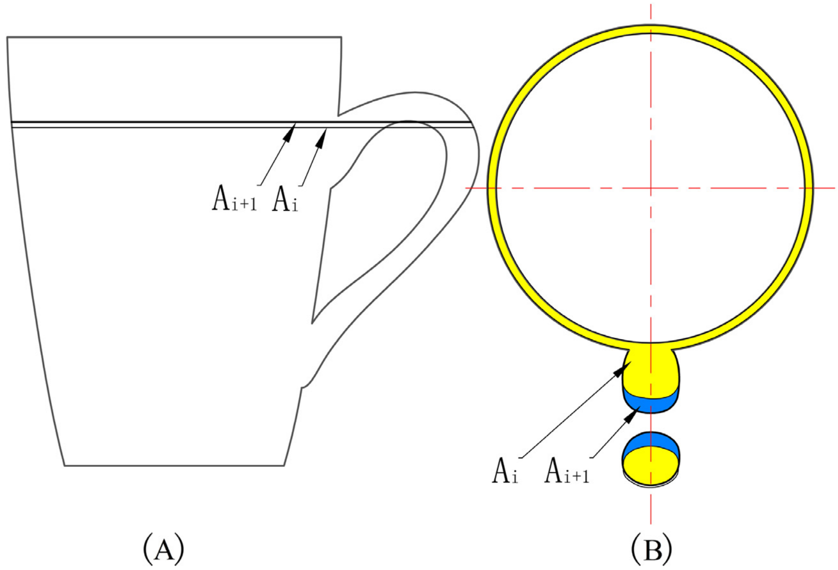

Fig. 1. Dramatic variety between two adjacent sections at the top handle of a cup sample. (A) Front view of the cup model; (B) sectional view of two adjacent slicing layer.

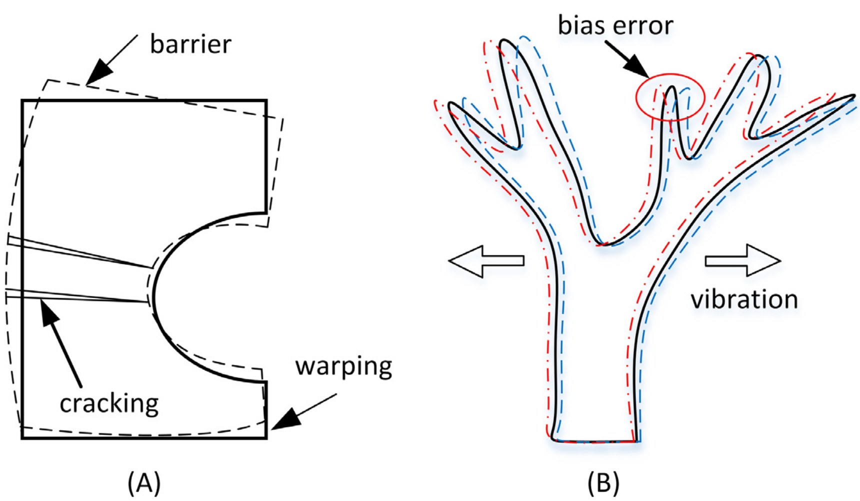

Fig. 2. Examples of inferior printing quality in FDM without ASs. (A) Practical thermal deformation; (B) Influence of part stiffness.

coded genetic algorithm to obtain optimum part deposition orientation [18,19]. Their study provided a new approach to minimize the necessary amount of support. Luc *et al.* introduced a method of adaptive direct slicing of a complex solid model applied to rapid prototyping [20]. This method can save support material by reducing the volume of dangerous sections using an adaptive slicing process. Additionally, new soluble support materials like acrylate copolymer developed by Stratasys Inc. America, provide another approach to improve surface quality and reduce the workload of removing support structures. As a new approach, topology optimization can minimize the ASs and support the overhanging structures by rebuilding the model.

ASs can cause poor surface accuracy, waste of filament, and post processing difficulty. To remove ASs easily after fabrication and save the filament, ASs are often designed as sparse fence or dendroid structures. This may cause irregular contact interface whether by applying water-soluble material or manual stripping. Fig. 3 shows an overhanging hollowed-out model after removing the ASs. It is easy to see that the quality of the surface at the interface is poor compared to the upward surface of the same printed sample.

The usage of ASs can also lead to filament waste and the time of printing can be slowed due to ASs. The extent of this problem varies with printing parameters including the overhang angle (θ_o), the largest slant angle that can be printed without ASs. Calculation of this angle is used to control the surface quality and also the amount of ASs required. To maintain fine surface quality, ASs are required for areas with slant angles of $\theta > \theta_o$. Thus, the numbers of ASs will become very large when constructing models with large areas of overhanging structures.

Are ASs essential for 3D printing, can another strategy be used? Here, we propose and test ILP as a method for generating an unbraced tool path for 3DP. The ILP method can improve printing efficiency, eliminate the time needed to remove ASs and save printing material. Additionally, on the premise of adaptive slicing and slicing angle (θ_s) optimization, the implementation of ILP method will promote the quality of the overhanging surface compared with the supported surface fabricated with ASs.

Here, the concept and principle of ILP is introduced in the section of *ILP Theory*. In the part of ILP theory, a new filament width model is proposed using theory analysis and experimental observation to illustrate the fabricated surface profile. This provides a geometrical theory foundation for the analysis of force situation and surface roughness in ILP method. The implementation of ILP technology is introduced by bringing an objective function into the optimization process of ILP parameters and a practical solid model is tested using an inclined slicing strategy. Finally, we test the efficacy of the ILP method with some models printed by FDM printers.