ARTICLE IN PRESS
COMAID:1671

Computer Aided Geometric Design ••• (••••) •••–•••

Contents lists available at ScienceDirect

Computer Aided Geometric Design

www.elsevier.com/locate/cagd

Orientation field guided line abstraction for 3D printing [☆]

Zhonggui Chen [a,d], Wen Chen [b,c], Jianzhi Guo [b,c], Juan Cao [b,c,d,*], Yongjie Jessica Zhang [d]

[a] *Department of Computer Science, Xiamen University, Xiamen 361000, China*
[b] *School of Mathematical Sciences, Xiamen University, Xiamen 361000, China*
[c] *Fujian Provincial Key Laboratory of Mathematical Modeling and High-Performance Scientific Computation, Xiamen University, Xiamen 361005, China*
[d] *Department of Mechanical Engineering, Carnegie Mellon University, Pittsburgh, PA 15213, USA*

A R T I C L E   I N F O

Article history:
Available online xxxx

Keywords:
Line drawing
3D printing

A B S T R A C T

This paper focuses on printing a 2D color image by using a desktop fused deposition modeling (FDM) 3D printer. A fully automatic framework is presented to convert a 2D image into a non-photorealistic line drawing which is suitable for 3D printing. Firstly, an image is partitioned into a moderate number of regions, and contours of these regions are extracted to deliver the high level abstraction of the image. The contour lines are further refined by taking into consideration the restrictions of 3D printing. Next, an orientation field based on the contours and feature lines at a finer level is computed to guide the placement of streamlines. The distances between streamlines are carefully controlled such that the density respects the pixel intensity values. Finally, the resulting streamlines are converted into printing paths and printed by using filaments with specified colors. Experimental results show the feasibility and efficacy of our method on portraying a given image by using a few of 3D printable non-intersecting lines while preserving features and tone variation in the image.

1. Introduction

3D printing is a form of additive manufacturing, where a three dimensional digital model is turned into a solid object by laying down successive layers of material. 3D printing has a myriad applications in diverse industries, and studies of 3D printing focus on various aspects for different application backgrounds. In the computer graphics community, how to convert a given 3D object to meet different fabrication requirements or how to achieve high-quality and cost-effective fabrication has been the focus of many recent attempts. Instead of addressing the issue of how to print a 3D model, in this paper we focus on printing 2D color images with a 3D printer.

Among existing 3D printing technologies, fused deposition modeling (FDM) is the most simple-to-use and environment-friendly one, and FDM based printers designed for home use are also very economical and affordable. It has become the most widely used 3D printing technology nowadays. Hence, we restrict ourselves to low-end FDM printers in this paper. FDM technology based printers build objects layer by layer from the very bottom up. In each layer, the print head moves

☆ Part of this work was done while Zhonggui Chen and Juan Cao were visiting the Department of Mechanical Engineering, Carnegie Mellon University.

* Corresponding author at: School of Mathematical Sciences, Xiamen University, Xiamen 361000, China.
E-mail address: Juancao@xmu.edu.cn (J. Cao).

https://doi.org/10.1016/j.cagd.2018.03.014
0167-8396/

Please cite this article in press as: Chen, Z., et al. Orientation field guided line abstraction for 3D printing. Comput. Aided Geom. Des. (2018), https://doi.org/10.1016/j.cagd.2018.03.014

along a prescribed path, meanwhile, the thermoplastic filament is heated and extruded throughout a nozzle onto the base or the previous layer. Inspired by this line drawing manner, here we aim at printing a 2D color images using a 3D printer by converting 2D images into a set of 3D printable lines. Essentially, our goal is to render images in a non-photorealistic line drawing style which can be directly printed by a 3D printer.

There has been a lot of efforts in computer graphics on generating non-photorealistic images with line drawing style and impressive results have been achieved (Liu et al., 2016). However, those results usually violate the requirements of direct 3D printing indeed. As a matter of fact, a wide variety of line drawing methods adopt feature edge extraction techniques to capture and convey shape features of the real scene. Represented by a sequence of pixels, the resulting zigzag lines may be very short, intensively locate at some regions and intersect with each other. While in 3D printing, fairly smooth and long lines are desired to avoid discretization artifacts in the final printing results. In particular, sharp turns/corners/endpoints lead to deceleration of the print head and leaking of filament from the nozzle. Intersections cause the extruder to hit and drag across the already printed parts. Closely located line segments either prevent the filament extruding from the nozzle or end up with filament bunching up at corresponding regions. In traditional line drawing methods, lines can be rendered with different colors to better convey the original scene. On the contrary, printing in multiple colors is non-trivial in FDM based 3D printing as most FDM 3D printers work with a single color. Some research focus on generating continuous line illustration, i.e., portraying the scene with a single continuous line (Wong and Takahashi, 2011; Wong and Takahashi, 2013). However, it is difficult to trace out the feature lines and convey the tone variation of the 2D images by using a unicursal curve in general. In a recent literature (Chen et al., 2017), semi-continuous line illustration was generated for 3D printing. Relying on manual segmentation results, the line drawing results are able to preserve the contours of the image while features inside each sub-region are ignored.

In this paper, we focus on printing color images using FDM based 3D printers in line drawing style. Several existing techniques are adapted to our framework to achieve this goal. The specific contributions of this paper are as follows:

(1) We develop a fully automatic non-photorealistic line drawing algorithm for converting a 2D image into a 3D printable line illustration. After specifying the physical printing size, line width and colors, our method automatically generates visually pleasant 3D printing results.
(2) We construct printable contours of the input image, which portray the most important features of the image, even with the strict limitations of printing size and resolution of the 3D printers.
(3) We generate intersection-free and reasonably spaced streamlines, which are suitable for direct 3D printing. In addition, streamline orientations are well controlled to better convey features at the finer level. Their distribution also approximates tone variations of the input image precisely.
(4) Our method is capable of obtaining multi-color outputs using 3D printers with a single extruder, without resorting to costly color 3D printers.

The remainder of this paper is organized as follows. Related work relevant to our research is presented in Section 2. Details of our line drawing abstraction algorithm are provided in Section 3. Results of our algorithm are shown in Section 4, while section 5 presents the concluding remarks and possible extension of this work.

2. Related work

Line drawing is a two-dimensional visual art style featuring of portraying scenes only with lines. Non-photorealistic rendering (NPR) in line drawing style frequently appears in animations, architecture illustrations, and advertisements. There exist numerous investigations on generating a line drawing from an image in the field of computer graphics. As the contours or feature lines convey the most important shape information of an image, most technologies for line drawing are based on the edge detection method, and the generated lines may vary in width, density and color as necessary to portray the features and the overall shading of the scene. For detailed discussions on existing line drawing methods, we refer the readers to a recent survey paper (Liu et al., 2016). In addition, some researches address the problem of continuous line illustration, i.e., portraying a scene with a single line. Due to its restricted nature, the complexity of the problem increases dramatically (Bosch and Herman, 2004; Wong and Takahashi, 2011; Wong and Takahashi, 2013), and the proposed methods are either time-consuming or rely on user interactions. Image processing techniques for generating mazes from images (Xu and Kaplan, 2007; Wan et al., 2010) share some similarities with line drawing methods which trace contours and approximate the tone of the source image. However, all of these techniques, ignore the concerns specific to 3D printing (e.g., line width and spacing). Hence, their results are not applicable for direct printing in general.

With the fast development of modern fabrication technologies, direct drawing of lines in 3D space by using a 3D extruder becomes possible. Fabricating 3D shapes using multiple wires has led to growing interests in the 3D printing community. While wireframe fabrication remains challenging, as various geometric and physical constraints should be considered during the entire drawing process, e.g., the already-fabricated parts should always keep stable and not be collided by the moving extruder. To speed-up the prototyping process, a regular wireframe is fabricated directly in 3D space using a standard FDM 3D printer, instead of printing the original solid layer-by-layer (Mueller et al., 2014). Various 5DOF or 6DOF 3D fabrication systems were also designed to print geometrically complex wireframe shapes (Peng et al., 2016; Hack and Lauer, 2014). Huang et al. proposed to generate a feasible fabrication sequence of struts for creating general frame shapes using a 6DOF

Please cite this article in press as: Chen, Z., et al. Orientation field guided line abstraction for 3D printing. Comput. Aided Geom. Des. (2018), https://doi.org/10.1016/j.cagd.2018.03.014