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Line drawing for 3D printing

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This paper focuses on the problem of generating a line drawing from a given image for fused deposition modeling. The abstracted line drawing, comprising of lines with a single color and thickness, would preserve both tone and edges of the input image. We first partition the image into sub-regions manually. The boundaries of the sub-regions are extracted as the feature lines of the image. Next, a proper number of points are randomly placed on the image plane with a density proportional to the darkness of the image. We use Lloyd's method to push the sampling points away from each other and the feature lines. The points within each sub-region are then connected by solving a travelling salesman problem (TSP). Finally, we further optimize the fairness and the spacing of the lines by minimizing a tailored objective function. A variety of experimental results are presented to show the effectiveness of our method for generating line drawings for 3D printing.

1. Introduction

3D printing, also known as additive manufacturing technologies, departure from the traditional way of manufacturing things. It synthesizes a 3D object in a layer-upon-layer fashion from a digital geometric model under the control of computer. The advent of 3D printing technology has prompted extensive studies for 3D printing in many fields including computer graphics. However, most works in computer graphics community mainly focus on the problem of how to print a given 3D digital model appropriately. In contrast, we consider the problem of producing a non-photorealistic 2D drawing which is visually similar to a given image.

There are diverse 3D printing technologies, and some of them are very popular nowadays. For example, fused deposition modeling (FDM) is wildly spread in a variety of industries. With the help of FDM, objects are built layer by layer from the bottom up by extruding thermoplastic. The printer's extruder is moved following a route calculated in advance during printing each layer. As FDM is deemed to be simple-to-use, it has been adapted in the desktop 3D printing machines designed for home use. We observe that a FDM printer prints object layer by layer, and each layer is printed in a line drawing manner, i.e., the nozzle moves along the paths while extrudes the melted filament material. Inspired by it, we focus on using a desktop 3D print to produce a non-photorealistic image according to a given image in a line drawing manner. Therefore, it is desired to represent the source image into a set of lines, which mimic the original images well and can be adopted as 3D printing paths.

Let us first discuss what specific properties such a line set should ideally possess. First, lines should vary smoothly. Sharp turns/corners, small dots and short spans cause de-acceleration of the print head, while the flow rate of filament from the heads of nozzle cannot be precisely controlled to match the head speed on low-end FDM printers. Hence, unsmooth lines introduce printing artifacts around discontinuous points and sharp turns/corners, bringing along with it the increasing of whole printing time and lowering of printing quality. Second, the total length of the lines should be as small as possible, which will lower the material cost and printing time. Third, the lines are not allowed to self-intersect or be arranged too intensively. As printing paths of 3D printer, the lines have a certain width in practice, there should be appropriate spaces between adjacent lines to avoid artifacts such as stacking or overlapping of the filaments. Forth, line distributions should reflect the tone variations. It is because that a low-end desktop 3D printer only has one or two extruders in general, i.e., scarcely any alternate colors can be chosen from to restore the original image colors and print continuous tones in the printing process. Using multi colors to convey the tone variation requires incessant replacement of filaments and switching between print heads, increasing the total printing time significantly. Besides, the build platform onto which the thermoplastic is extruded has limited size and the width of line is fixed after the printing process starts. In other words, a limited number of lines can be drawing on a build platform. Hence,

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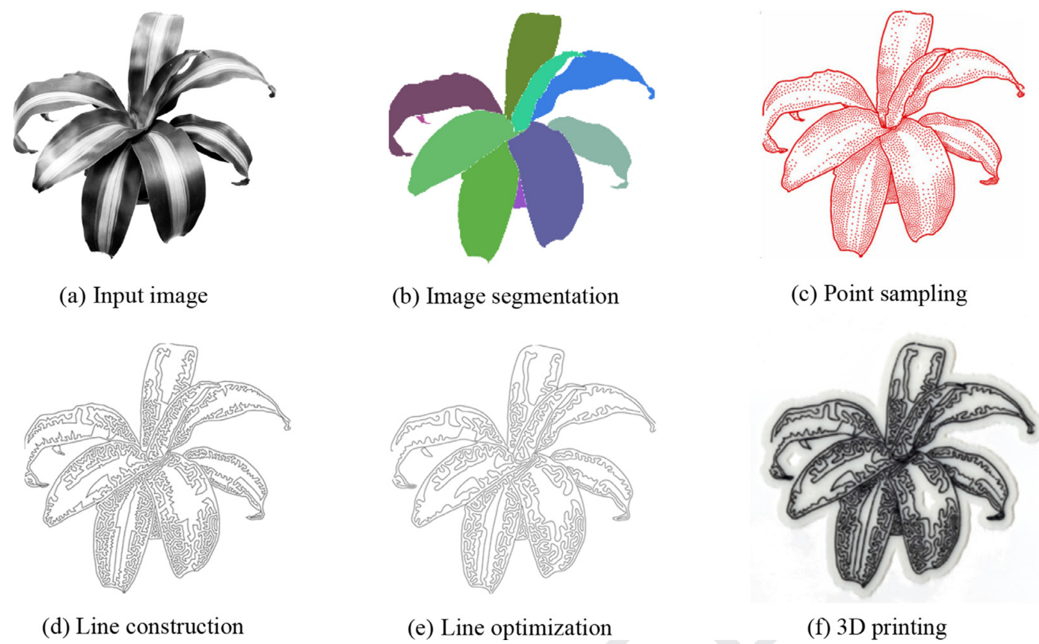

Fig. 1. Overall process.

finally, the lines should preserve the features of images to better mimic the original image.

Although there are various works attempting on generating NPR image in line drawing style [1–4], none of them provides a result satisfying all the requirements discussed previously, hence is not suitable for 3D printing purpose. In this paper, we tailor a line drawing style image generation method for FDM printers to print an NPR images in a line drawing manner. First, the given image is decomposed into several sub-regions manually. The boundaries of each sub-region are extracted as the feature lines of the image. Then, a proper number of points are randomly placed on the image plane with a density proportional to the darkness of the image. A further optimization is applied such that the sampling points drift away from each other and the feature lines. The points within each sub-region are then connected to a single line by solving a TSP. Finally, we smooth the line and average the space between it by minimizing a tailored objective function. The resultant line set makes up a line drawing stylized image, which well preserves the features and tone variation of the original image, and can directly be taken as the path of 3D printing.

2. Related work

In the field of computer graphics, recent research works mainly focus on optimizing or adjusting a given 3D geometric model to fit for the purpose of 3D printing, such as hollowing or strengthening to attain a good balance between quality and cost [5,6], segmenting and assembling to print a model beyond the limited print volume [7,8], minimizing the support to decrease material consumption and scratches on the surface [9]. Cho et al. [10] proposed a dithering algorithm to convert continuous tones into discrete version of machine instructions. However it is not applicable to low-end FDM printers. Reiner et al. [11] produced the continuous tone imagery by applying small geometric offsets between printed layers with different colors. It requires a FDM printer with two color heads. In this paper, we focus on converting a given image into a line drawing for fabrication.

Line drawing is a simple yet effective tool for visual communication, and has received great interests from the community of non-photorealistic rendering (NPR). Most of the existing approaches use edge detectors to extract visually significant lines from the given images [1,12–15]. From the perspective of FDM fabrication, however, those methods have the following limitations. First, the extracted lines can become of different widths and colors, and contain a great many crossed and broken edges. Second, edge detectors typically rely on the computation of image gradients, so that only color differences between adjacent pixels are taken into account, but the variations of tone in different regions are ignored. In recent years, there are also a lot of work tackling the problem of line drawing of 3D objects, which mainly focus on the extraction of silhouettes and feature curves of 3D shapes [16–19].

Stippling is another NRP technique which can simulate varying tone of images by only using small dots. The dots are usually of a single color. The density of the points gives the impression of shading. Lloyd's method has been widely used for generating uniform distributions of stipples in space [20]. It is a simple iterative method, which alternates the generation of the Voronoi diagram and relocation of the stipples. To better adapt the density of stipples to the darkness of images, capacity constraints can be assigned to Voronoi cells associated with each stipple [21]. Analogy to stippling, we can use the density of the lines to convey the shading of the image.

Continuous line drawing (CLD) is a style of drawing which portrays a picture with a single non-intersecting line. The first work on CLD is resorted to a solver of the traveling salesman problem (TSP) on a set of stippled points [22]. On the one hand, the initial point distribution, which determines the CLD and its quality, is crucial for the TSP-based methods. On the other hand, Lloyd's method and its variants are capable of producing very good point distributions. Hence, a combination of Lloyd's method and TSP-based methods usually generates satisfactory results for CLD applications [2]. However, both of the two methods mentioned above often need a large number of points to portray the tone variation of an image, which aggravates the computation complexity of TSP. Moreover, existing TSP-based methods only focus on the tone variation of an image. The connected lines obtained by the TSP solver do not follow the object contours in the image in general. In this work, we accelerate the computation by partitioning the image into sub-regions, and solving the TSP in each sub-region by an efficient heuristic solver. The object contours are preserved in the final

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