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Hatching for 3D prints: Line-based halftoning for dual extrusion fused deposition modeling

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ABSTRACT

This work presents a halftoning technique to manufacture 3D objects with the appearance of continuous grayscale imagery for Fused Deposition Modeling (FDM) printers. While droplet-based dithering is a common halftoning technique, this is not applicable to FDM printing, since FDM builds up objects by extruding material in semi-continuous paths. The line-based halftoning principle called 'hatching' is applied to the line patterns naturally occurring in FDM prints, which are built up in a layer-by-layer fashion. The proposed halftoning technique is not limited by the challenges existing techniques face; existing FDM coloring techniques greatly influence the surface geometry and deteriorate with surface slopes deviating from vertical or greatly influence the basic parameters of the printing process and thereby the structural properties of the resulting product. Furthermore, the proposed technique has little effect on printing time. Experiments on a dual-nozzle FDM printer show promising results. Future work is required to calibrate the perceived tone.

1. Introduction

The ability to apply color to 3D printed parts is relevant for both prototyping and manufacturing. Possible applications include reproduction of color-scanned 3D objects and fabrication of products with logos and labeling. Color can also be used as a design feature or to visualize geometric information such as the results of finite element analyses. See Fig. 1.

At present, 3D printing in color is available for a variety of Additive Manufacturing (AM) systems that are predominantly based on ink-jet technology. Techniques for printing color using only Fused Deposition Modeling (FDM) are sparse and suffer from a low resolution or have radical impact on the printing process.

This paper presents a novel technique for fabricating 3D grayscale objects using the FDM 3D printing method. It uses a principle which is based on modulating the visible width of printed lines of two alternating colors to produce the appearance of continuous tone gradients. Creating the perception of continuous tones by generating small patterns of discrete colors is termed *halftoning*.

Implementing color variation with high frequency details using FDM is a challenge. FDM builds up objects by extruding material in semi-continuous paths, which makes it impossible to apply droplet-based halftoning principles that are commonplace in existing color 3D printers.

A promising technique to fabricate continuous tone objects using FDM has been presented by Reiner et al. However, since that technique inherently produces textures at a relatively low sample rate, it does not allow the fabrication of high frequency details. Furthermore, the technique does not allow fabrication of textures on horizontal surfaces and degrades for diagonal surfaces with a slope approaching horizontal.

Addressing these issues, we propose a novel halftoning technique for dual-extrusion FDM systems. The proposed halftoning technique is based on hatching, an established 2D halftoning principle based on lines rather than dots. The implementation of the technique described in this paper is open source and can be found at github.com/Ultimaker/CuraEngine [2].

This paper is an extension of the techniques proposed by conference paper by Kuipers et al. [3]. The technique proposed there changes the geometry of alternating black and white layers to modulate the perceived grayscale tone when viewed either from directly above or when viewed straight from the side.

Rather than presenting different hatching techniques for two viewing angles, this paper presents a unified hatching technique

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Fig. 1. 3D prints obtained by applying hatching on a 14 cm 3D portrait, a 15 cm artistic figurine, a full size soda can with textual information, and the result of a stress analysis performed on a 16 cm connecting rod of a piston engine.

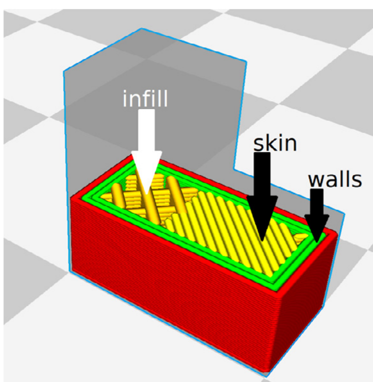

Fig. 2. The lower part of an FDM process plan for an L-shaped 3D model. Several types of print path are indicated.

for viewing surfaces from any angle and in particular a viewing angle locally perpendicular to the surface. The phenomenon that an overhanging line occludes the previous layer, also known as sagging, is exploited for an edge case of that general hatching technique. This paper provides a model of the sagging behavior which is used to derive the proportion of visible white to black filament from any viewing angle. Experimental data of sagging is collected and analysed in order to grasp the limitations of our model.

2. Background

2.1. Process planning for FDM

The following section will briefly explain the basics of process planning for FDM, a.k.a. *slicing*. Some elementary concepts and processes are explained required for understanding the presented hatching technique. The terminology employed and the techniques described apply to the open source slicing software called Cura [2].

FDM generally builds up 3D prints in a layer-by-layer fashion. One of the first stages in slicing is generating the outlines of each layer. The outlines are the boundaries of the regions which are to be filled with material. Line segments are generated by intersecting each triangle of the input mesh with horizontal planes at heights corresponding to each layer. All line segments of a layer are then stitched into polygons which form the outlines of that layer.

Because starting and stopping extrusion of filament causes blemishes, the outlines of a layer are achieved by following the contours of the layer: the walls. Several consecutive walls are printed next to each other. The outer walls are generated by applying an inward offset of half the line width to the outlines. Successive walls are then generated by applying offsets to previous walls. These walls define printed lines which follow the contours of the object. See Fig. 2.

The remaining area within the innermost wall is split into infill and skin. By applying boolean operations on the leftover region with the outlines of layers above and below we calculate the areas which are close to the top and bottom of the model boundary surface: the skin. By applying a difference operation we can then determine the infill areas from the skin areas and the region left over from the walls. The skins are several layers thick and they are densely filled with a pattern of parallel lines.

2.2. Commercial color 3D printers

The first commercial full color 3D printing systems date back to 1993 [4]. These systems use ink-jet technology to apply colored binder onto white powder [5]. Consecutive layers of bound powder form the final 3D model. Instead of jetting a binder onto a substrate, Mcor developed a process in which conventional ink is jetted onto sheets of paper, which are then cut and stacked [6]. Stratasys uses ink-jet technology to print the building material itself. Their recent system incorporates six heads, each able to print a colored material [7]. More recently, HP Inc. introduced a printing technology in which liquid agents are jetted onto powder in order to alter the powder's fusing behavior. According to the company, these agents may also include color in the future [8].

2.3. 3D Halftoning

Because printers work with a limited number of base colors, specific strategies need to be applied to make full color prints. In 2D printing, this is usually done through different halftoning techniques.

2D ink-jet technologies apply a halftoning principle called dithering. In dithering, the distance between printed colored dots is varied to create perceived variations of colors. While halftoning for 2D printing industry is well developed, halftoning for 3D printers is still an active field of research. The first mention of halftoning in 3D printing is not focused on color reproduction but on material density variation for stereolithography [9]. Techniques for 3D color dithering have been presented for binder jetting printers [10]. Vidim et al. presented a programmable pipeline for multi-material