Image Analysis of Surface Elements Reproduction Quality in 3D Ink-jet Printing

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Abstract

Three-dimensional ink-jet printing described here is powder-based rapid prototyping (RP) technique. It is based on conventional ink jet printing technology, with basic build materials being powders and binders (inks). Designed or captured 3D object is virtually sliced in layers and later printed by joining consecutive layers (cross-sections), which are solidified by reaction between basic materials. The process is capable of printing in "full" color as it uses colored binders as well. Due to this, text and other graphic elements can be reproduced on surfaces of 3D objects. Image analysis is a computer-aided technique often used, among other areas, in printing technology, for monitoring and evaluation of substrate-ink interactions and print quality. In the described work, image analysis technique is used for evaluation of reproduction quality and material interaction in 3D ink jet printing by analyzing the surface reproduction of some basic geometric and text elements. A test target, consisting of a number of print elements, is placed on surface of the constructed 3D object. The 3D test plates are then placed and printed in different positions in xyz space, as well as printed with different combination of printing preferences. The image analysis is done on optical microscope captures of 3D prints surfaces which are assessed using custom-made routines in ImageJ software.

Introduction

3D ink-jet printing is an additive RP process, using the powder material and liquid binder as basic materials [1]. The process functions on the basis of the conventional ink-jet printing and it can produce objects in full color, using C, M, Y, K colored binders and clear binder. The basic process principle and color capabilities are the reason why it is a topic of interest for the graphic technology based research. In graphic technology, the need for effective print quality assessment of ink-jet printing has continued as printer technology has developed, and particular attention has been paid to automatic methods based on image analysis. These methods use microscope in conjunction with a digital camera to capture the print target image or are scanner-based [2]. Line quality, dot quality, color reproduction and various surface coverage characteristics are just a few of the many elements that can be characterized in detail by such systems [3]. Dot quality can be influenced by the printer mechanism, the characteristics of the ink and the properties of the substrate. The dot quality test provides information about the spatial and morphological variations of the dots [4].

The scope of the work is to obtain basic information about quality of the surface reproduction in relation to different printing preferences and object position in 3D ink-jet printing by using image analysis.

Basics of 3D ink-jet Printing

The 3D ink-jet printing process functions by building parts in number of layers of defined thickness. The layers have been sliced by computer algorithms from the CAD model of the designed 3D object. For each layer or cross-section of the 3D model, the powder particles are distributed over the printing surface by the roller and selectively joined by jetted binder material. After a layer of powder and binder have been applied, the build bed support piston is lowered, powder bed support piston is raised and the next layer of powder is applied, followed by the binder material. This process is repeated until the object is finished. Figure 1 shows the scheme of powder being distributed by roller in the arrow 1 direction, while the binder is applied from the printheads in the return motion, arrow 2 direction. The printing starts in the striped arrow direction.

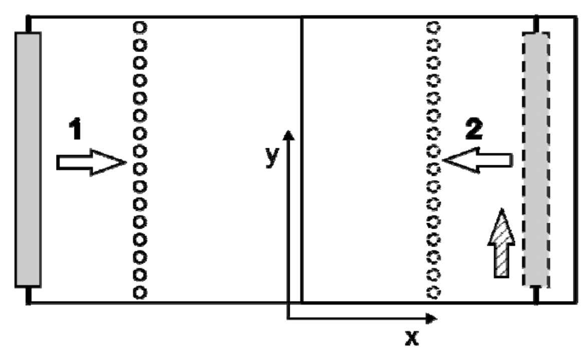

Figure 1. *Top view (x-y) scheme of 3D printing process*

There are several relevant characteristics that are known to affect the 3D print accuracy and definition, such as selected layer thickness, amount of saturation of the binder (powder/binder ratio), bleed control, relative position in the build bed etc. Of most interest here are the shell saturation level, which determines the amount of binder to be applied and is expressed as percentage, relative to the default 100%; bleed control, which compensates for the seepage of binder into the powder layer [5]; x-y orientation, especially relevant for the 3D prints surface facing downwards as this causes potential additional seepage of the binder into the surrounding non-printed powder. These printing preferences have been varied in order to observe their potential impact on the quality of surface reproduction.

Experimental

Test Plates Preparation and Printing

A file was prepared as a test target to be analyzed by image analysis procedure (Figure 2). The test target was prepared in Adobe Illustrator software and saved as a tiff file. It was later positioned and placed as a texture on the 3 cm by 3 cm x 0.3 cm plate in ZEdit software. The test target consisted of various geometrical elements and letters; circles of two different diameters (5 mm and 10 mm), vertical, horizontal and angled lines with the stroke of 2 pt and capital Times New Roman letter E in two different sizes (12 pt and 24 pt). The test target was constructed in magenta color only and it was prepared in such a way to ensure that only the magenta binder will be actually applied during printing, thus making sure that there will be no deposition of two or three binders for obtaining the specified color.

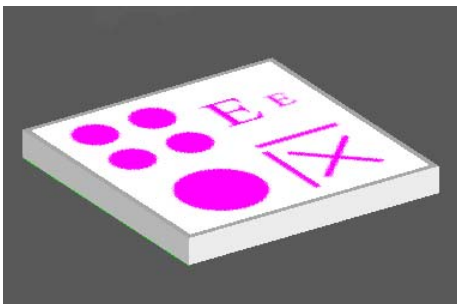

Figure 2. *Prepared test target file was applied as a texture on a test plate, visualization of the test plate in ZPrint software*

The test target plates were placed in specified positions and/or printed with the specified printing preferences. Tables 1 and 2 present the specified printing preferences set up. First group of samples were set up in such a way that the printing preferences were the same and samples were placed in different positions within the xyz space in the build bed. This group of samples was prepared in order to monitor the changes in quality of surface reproduction depending on the relative position in the build bed. The samples were printed with the layer thickness set to 0.1 mm, 100% shell saturation and bleed control off.

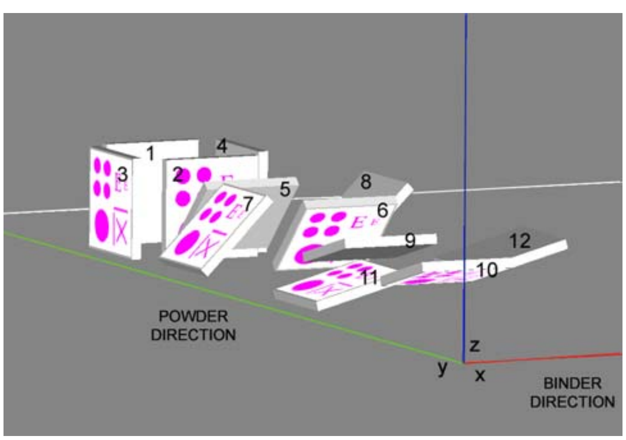

Figure 3. *Graphical representation of the set up with different positions in the build bed, numbers correspond to the labels in Table 1*

Table 1: Printing set up, same printing preferences, different xyz positions

Label	Position
1	xz, binder direction, last
2	xz, binder direction, first
3	yz, powder direction, first
4	yz, powder direction, last
5	xz, binder direction, tilted 45°, facing up
6	xz, binder direction, tilted 45°, facing down
7	yz, powder direction, tilted 45°, facing up
8	yz, powder direction, tilted 45°, facing down
9	xz, binder direction,tilted 75°, facing up
10	xz, binder direction, tilted 75°, facing down
11	yz, powder direction, tilted 75°, facing up
12	yz, powder direction, tilted 75°, facing down

Second group of samples was printed with different printing preferences. It was prepared in order to monitor the quality of surface reproduction depending on the printing preferences, namely the facing direction (up or down), layer thickness, shell saturation and bleed control.

Table 2: Printing set up, different printing preferences

Label	Position	Layer thickness	Saturation	Bleed
A_D	Down	0.1 mm	100%	ON
A_U	Up	0.1 mm	100%	ON
B_D	Down	0.1 mm	100%	OFF
B_U	Up	0.1 mm	100%	OFF
C_D	Down	0.1 mm	150%	OFF
C_U	Up	0.1 mm	150%	OFF
D_D	Down	0.1 mm	75%	OFF
D_U	Up	0.1 mm	75%	OFF

The printing was done on the ZCorporation Spectrum Z510 printer. It is a color printer, with resolution of 600 x 450 pixels, build size 10 x 14 x 8 inches, build speed of 2-4 layers per minute, user selectable layer thickness between 0.0035-0.008 inches (0.0875-0.203 mm). Its printing head system comprises of four printheads (C, M, Y color ink binders and clear binder) with 1216 jets total. Materials used were high performance composite zp131 powder and zb60 binders (cyan, magenta, yellow, clear). The zp131 powder is plaster based powder, with additional components added in smaller percentages. Zb60 binders are based on standard water-based ink-jet fluids, comprising mainly of water, colorants and other additives.

The printed samples were removed from the printing bed and cleaned from the remained powder. Due to the limited space, only several elements of the test form have been discussed in this paper. From the samples printed with different printing preferences (labels A to D), one of the circle with the 5 mm diameter has been analyzed and from the samples printed in different positions in the build bed (labels 1 to 12), 12 pt “E” character has been analyzed.

Image Analysis

After printing and post-processing, the samples were captured using Leica EZ4D stereomicroscope equipped with integrated 3-megapixel CMOS sensor digital camera. The capturing was done using 12.5x and 20x magnification rates. Image size was 2048 x 1536 pixels.

Software ImageJ [6] was used for image processing and analysis. ImageJ is free and open source software, working in Java environment. It is versatile and can be upgraded and fit for specific uses by development of customized macros and plug-ins. Thus, selected plug-ins and custom made macro routines were used in the presented work as well. Images were uploaded to ImageJ, processed and analyzed by using Analyze Particles routine. The measurements parameters of analyzed elements which are discussed here are total area, perimeter and circularity. Higher circularity denotes an element that is closer to an ideal circle (C=1). Circularity was calculated using the formula:

$$C = 4\Pi * area/perimeter^2 \quad (1)$$

In order that images can be analyzed, they need to be thresholded, e.g. regions of interest (ROI) need to be segmented from the background. Therefore, the images were converted from RGB to 8-bit and then binarized by applying a threshold which separated the print elements (in this case value 0) from the background (in this case value 1). Using Auto Threshold [7] method Try all, the images were thresholded using various built-in threshold methods and Otsu [8] thresholding technique was selected as the most appropriate method for automated analysis. The Otsu's algorithm is one of the most well-known techniques for threshold selection methods [9]. Prior to segmentation, Enhance Contrast (1% saturated pixels) and Subtract Background (rolling ball radius 10px) functions were used to process the images. Majority of samples were adequately thresholded using the described routine, although there were some that needed further manual selection of threshold values.

Figure 4 shows the close up of the image of the outline which is the border of the element that was obtained by using the described routine for processing and thresholding of the original microscope images, captured at 12.5x magnification. The image of the outline is superimposed on the original image in order to see the fitting of the outline of the binary image.

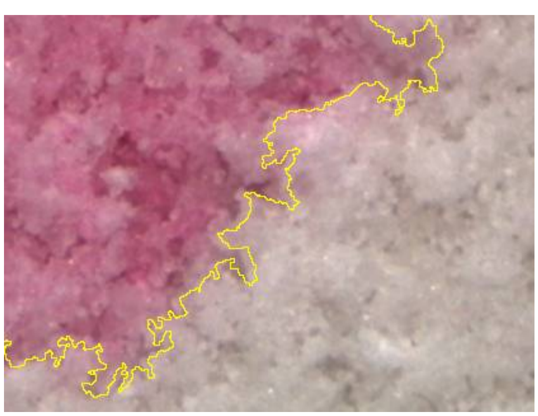

Figure 4. *Close up image of the border (outline) obtained by applying threshold superimposed on the original microscope image*

(a) (b) (c) (d)

Figure 5. *Character "E", 12pt; original microscope image (a), thresholded, binary image (b), mask of analyzed element (c), outline of analyzed element superimposed on the original microscope image (d)*

Figure 5 shows the processing and image analysis routine of a print element, in this case 12pt "E" character, from the original image captured by microscope, 20x magnification, to the mask of the character showing the area which was analyzed by image analysis. As it can be seen, the image analysis routine was set to disregard the particles which are not the part of the analyzed element.

Results and Discussion

Results of image analysis for the 5 mm circle from the samples printed with different printing preferences are presented in Table 3.

Table 3: Results from the image analysis of circle with diameter of 5 mm, samples printed with different printing preferences

Label	Area (mm^2)	Perimeter (mm)	Circ.
A_D	17.70	36.39	0.16
A_U	17.81	36.08	0.17
B_D	18.46	49.04	0.10
B_U	18.70	40.01	0.15
C_D	19.74	48.70	0.11
C_U	18.82	32.80	0.22
D_D	17.52	42.74	0.12
D_U	17.43	34.02	0.19

An ideal circle with the diameter of 5 mm has an area of 19.63 mm^2 and perimeter of 15.70 mm. The example of ideal circle superimposed on the 3D printed element can be seen in the left side of Figure 6. The right side of Figure 6 shows the outline obtained by the image analysis routine of the analyzed element.

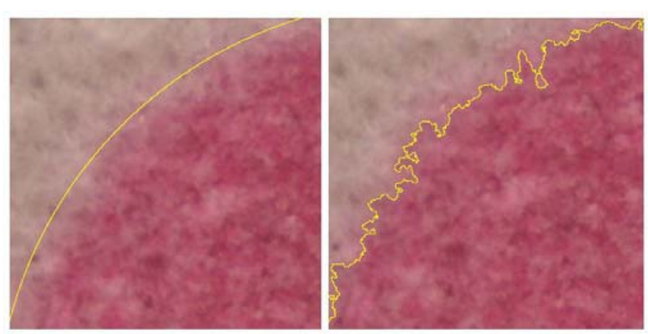

Figure 6. *Image showing close up of the outline of an "ideal" circle with the diameter of 5 mm (left) and the outline of the thresholded element (right) superimposed on the original microscope image*

When comparing A and B samples, which have been printed with the bleed control on and off, the effect of bleed compensation is visible in monitored characteristics; the A samples have smaller area, as expected, but also show smaller perimeter and higher circularity, meaning they are less distorted and resemble more to the ideal circle. The example of the bleed control effect on the quality of the reproduction of the print element is shown in Figure 7. The C samples have the highest area, which is directly related to the highest amount of binder that was applied during printing. In the same time, when compared to B samples, their perimeter is generally smaller and their circularity higher, meaning that the spreading was more uniform. The D samples compared to B samples show the effect of printing with smaller amount of binder. The resulting are of D samples is smaller and the circularity is higher.

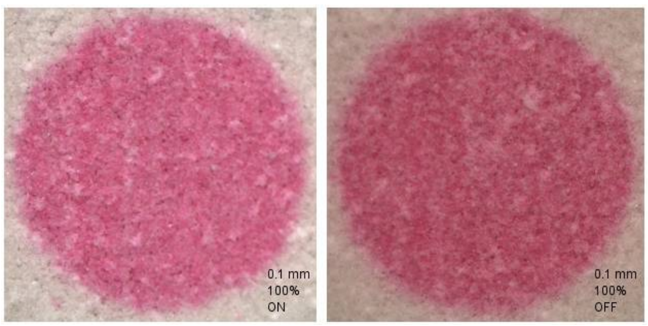

Figure 7. *Image showing the effect of bleed control on or off on the reproduction quality of element; bleed on (left), bleed off (right)*

Figure 8 shows the 12 pt “E” character reproduction on samples printed in different relative position in xyz space. It can be seen that the character morphological characteristics are dependant on the position of the surface, as seen for example on samples 1 and 2, which have been placed in the same x-z position, with the sample marked 2 placed first relative to the application of binder and sample marked 1 on the end of the binder application.

Figure 8. *Masks of binarized and analyzed 12pt character “E” from the samples printed in different relative positions in the print bed*

Conclusions

The use of image analysis for the evaluation of reproduction of surface elements of 3D ink-jet prints was shown. ImageJ software and custom image analysis routines were used on images captured by light microscope equipped with digital camera. The effect of different printing preferences and placing of printed surfaces in different positions in the build bed on the morphological characteristics of the test elements, as analyzed by the described routines, has been discussed. It can be concluded that image analysis is a valuable tool which can be used for objective analysis of both, the reproduction of characters and graphical elements on 3D printed surface and for monitoring of the binder-powder interactions in the printing system. The described work is further broadened to the use of scanner system and development of additional image processing and analysis routines as well, showing high potential of use.

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