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Reproduction in Three-Dimensional Ink Jet Printing

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Abstract. *Three-dimensional printing is a powder-based solid freeform fabrication technique. It is based on conventional ink jet printing technology, basic materials being powders and binders (inks). As the process uses colored binders, text and graphic elements can be reproduced on the objects. The reproduction of three-dimensional prints surface elements was evaluated, also using image analysis, which was studied as a tool for reproduction evaluation. A test target, consisting of selected geometric and text elements, was placed on the surface of designed three-dimensional plate. The test plates were placed in different relative xyz positions, as well as printed with different preferences. The evaluation was done on light microscope captures, while scanned images of three-dimensional prints surfaces were used and observed as well. Changes in three-dimensional printed surface elements reproduction due to the objects' positioning and printing preferences, and binder-powder interactions were discussed. Specific image analysis procedures were researched as a tool for objective reproduction evaluation. © 2010 Society for Imaging Science and Technology.*
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INTRODUCTION

Three-dimensional (3D) printing is an additive rapid prototyping (RP) or solid freeform fabrication (SFF) 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 a clear binder. The basic process principle, ink jet printing, and its color capabilities are the reason why it is also a topic of interest for graphic technology based research. The image processing methods have been investigated as methods for practical measurements, providing data about, for example, particles and shape identification, and size distribution.[2] 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 methods based on image analysis. These methods use the microscope in conjunction with a digital camera to capture the print target image, or are scanner-based.[3] Line quality, text quality, dot quality, color reproduction, ink dot size and various surface coverage characteristics are just a few of the many elements that can be characterized in detail by such systems.[4–6] 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.[7]

The scope of the work presented here is to obtain basic information about reproduction of the surface elements in relation to different printing preferences and object position in three-dimensional ink jet printing, and to study the application of image analysis as a technique for objective evaluation.

BASICS OF THREE-DIMENSIONAL INK JET PRINTING

The three-dimensional 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 three-dimensional object. For each layer or cross-section of the three-dimensional model, the powder particles are distributed over the printing surface by a roller system or distributed from a feeder and later 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 a roller system, in the arrow 1 direction, while the binder is applied from the printheads in the return motion, in the arrow 2 direction. The printing starts in the striped arrow direction.

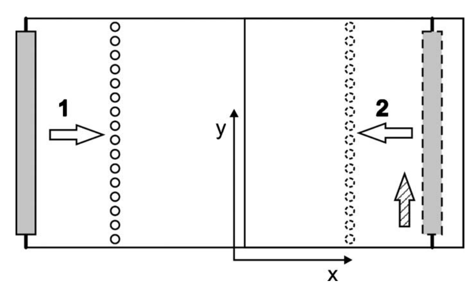

Figure 1. Top view (x-y) scheme of three-dimensional printing process, powder is distributed by the roller in the arrow 1 direction, while the binder is applied from the printheads in the return motion, arrow 2 direction. The printing starts in the striped arrow direction.

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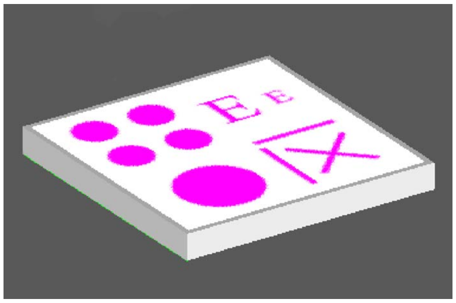


Figure 2. Prepared test target file was applied as a texture on a test plate, visualization of the test plate in ZPRINT software.

There are several relevant characteristics that are known to affect the three-dimensional printing accuracy and definition. Some of those are: 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, surface orientation and position in the build bed. The absorption of binder in the surrounding and non-printed areas leads to potential accuracy and definition loss. The amount of binder seepage and specific surface orientation are relevant for the underside surfaces as it causes poorer surface finish by potential additional bleeding of the binder into the surrounding nonprinted powder.[8] These printing preferences have been varied in order to observe their potential impact on the quality of surface reproduction.

EXPERIMENTAL

A test target file was created and prepared in order to monitor the reproduction in three-dimensional ink jet printing (Figure 2). The test target was prepared in ADOBE ILLUSTRATOR software and saved as a TIFF type file. It was then imported, positioned and placed as a texture on the 3 cm by 3 cm $\times$ 0.3 cm plate in ZCorporation proprietary ZEdit software. The test target consisted of various geometrical elements and letters; circles of two different diameters (5 and 10 mm), vertical, horizontal and angled lines with the stroke width 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, in a way to ensure that deposition of two or three binders for obtaining the specified color will not be required.

The test target plates were then placed in specified positions and/or printed with the specified printing preferences. Tables I and II present the specified printing preferences set up. First group of samples was 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, Figure 3. This group of samples was prepared in order to show the possible changes in the surface reproduction depending on the relative position in the build bed. All the samples from the first group were printed with the layer thickness set to 0.1 mm, 100% shell saturation and bleed control off.

Second group of samples was printed with different printing preferences. It was prepared in order to monitor the surface reproduction depending on the printing preferences,

Table I. 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, inclined at 45°, facing up
6	xz, binder direction, inclined at 45°, facing down
7	yz, powder direction, inclined at 45°, facing up
8	yz, powder direction, inclined at 45°, facing down
9	xz, binder direction, inclined at 75°, facing up
10	xz, binder direction, inclined at 75°, facing down
11	yz, powder direction, inclined at 75°, facing up
12	yz, powder direction, inclined at 75°, facing down

Table II. Printing set up, different printing preferences.

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

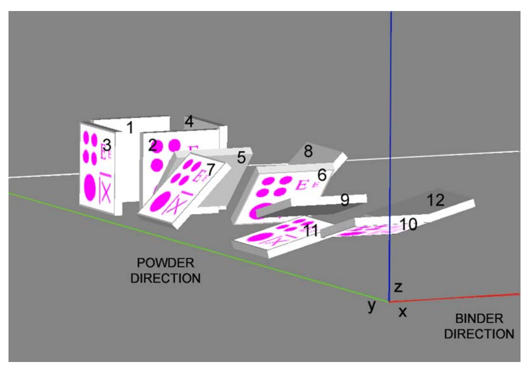


Figure 3. Graphical representation of the second group of samples set up, different positions in the build bed, numbers correspond to the labels in Table I.

namely, the facing direction (up or down), layer thickness, shell saturation and bleed control.

The printing was done on the ZCorporation Spectrum Z510 printer, using ZCorporation sourced materials. The Spectrum Z510 is a color printer, with resolution of 600×450 pixels, build size $10 \times 14 \times 8$ in, build speed of 2–4 layers per minute, user selectable layer thickness between 0.0035–0.004 in (0.0875–0.100 mm). Its printing head system comprises of four printheads (one for the each of the C, M, Y color ink binders and one for the clear binder) with 1216 jets in total. Materials used were high performance composite zp131 powder and zb60 binders (cyan, magenta, yellow, clear). The zp131 powder is a 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.

After the printing was finished, the samples were removed from the printing bed and cleaned of the remaining loose powder. The elements which are analyzed, shown and discussed in this article are a circle of 5 mm diameter and the character "E." Circle was selected as a sample element on which the image analysis procedures and the reproduction in three-dimensional printing were researched. As image analysis as a technique has yet not been extensively or at all used on three-dimensional prints, the sample element was analyzed and used as a starting point in researching the specific application. The reproduction of the character "E" was shown for samples that were placed in different xyz positions on the print bed, to show if the nature of the three-dimensional printing process leads to potentially visually noticeable differences in reproduction.

After printing and postprocessing, the samples were captured using a Leica EZ4D stereomicroscope equipped with an integrated 3 megapixel CMOS sensor digital camera. The photography was done at $12.5 \times$ magnification rate. Image size was 2048×1536 pixels. The magnification rate used was chosen based on the element size to be captured in order to obtain the highest level of detail. The microscope images were used for detailed observations of the reproduction of elements, and, for practical reasons, insofar as the procedures studied would be of potential use in industry, scanned images were used for observations as well. The samples were therefore scanned, in reflection mode, on an HP ScanJet G4010 flat-bed scanner, at resolution of 1200 dpi. All the captured samples were saved as TIFF type files.

RESULTS AND DISCUSSION

Image Analysis

The IMAGEJ software[9] was used for image processing and analysis. IMAGEJ is free and open source software, working in the Java environment. It was selected as the tool for performing image analysis primarily since it can be upgraded and fit to specific uses by the use and development of customized macros and plug-ins. IMAGEJ has a built-in function for particle analysis, with a user defined set of measurements analyzed and provided in the output results, such as number of particles, area and total area, perimeter, percentage of coverage, best fitting ellipse axes, circularity, and roundness.[2] Images were uploaded to IMAGEJ, preprocessed and later analyzed by using the built-in Analyze Particles function. The measurement parameters of the analyzed circle elements which were calculated are total area, perimeter, circularity, feret diameter, major and minor axes. Feret diameter denotes the longest distance between any two points along the selection boundary, also known as caliper length. Major and minor axes denote the primary and secondary axes of the best fitting ellipse. Circularity is one of the measurement parameters in ImageJ that can be used to describe how different is the element from the ideal circle ($C=1$). Circularity is directly dependent on the relationship between the area and the perimeter of the element, and was calculated using the following formula:

$$C = 4\Pi(\text{area}/\text{perimeter}^2). \tag{1}$$

In order that images can be analyzed by the IMAGEJ Analyze Particles function, the regions of interest (ROI) need to be segmented from the background. The segmentation divides the image into specific and separate regions. There are a number of segmentation methods, one of which is based on the histogram thresholding.[10] The segmentation is done based on intensity differences of the ROI and background, and defined threshold values separate the pixels with intensity below the lower and above the higher threshold values from the pixels with intensity above the lower and below the higher threshold value. Once threshold is applied, the image is transformed into a binary image.[11]

In the research presented here, the images were thresholded using the Threshold Color plug-in[12] which deals with color images, as separate threshold values for each channel (in the Threshold Color the channels are either R,G,B; H,S,V; CIE L,a,b; and Y,U,V) can be selected and passed/stopped. The images are segmented by selecting the threshold values for selected channels or for all channels at which the ROI elements are separated from the background. They can then be binarized if necessary, using the Make Binary function. Other than using specific threshold values for each channel in the image, grayscale thresholding could be used as well, with or without image preprocessing, and with automated or manual selection of the threshold values.

Figure 4 shows the RGB profile of the selected part (line selection) of a sample image. The RGB profile shows the differences in values of R, G, and B channels for the background and the element. This facilitates the selection of threshold values for color thresholding since it shows if and in which channels there is a distinctive difference between values of the ROI and the background pixels. In this research, color thresholding was done by blocking specific values belonging to the background pixels in G channel, as it most clearly differentiated the ROI and the background pixels. The thresholding could be done by blocking the specific values of the background pixels in the B channel as well, although the separation of the G channel values was adequate. Figure 5 shows the same differences in a form of a

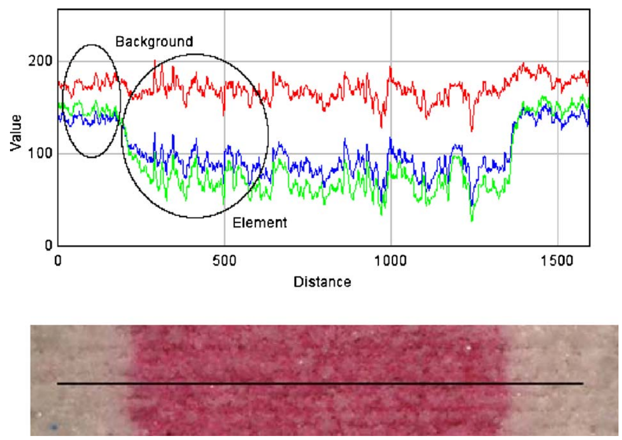


Figure 4. RGB profile of a sample microscope image of a 5 mm circle and its background, showing the difference in values of channels for the element and the background; the bottom image shows the line of the RGB profile.

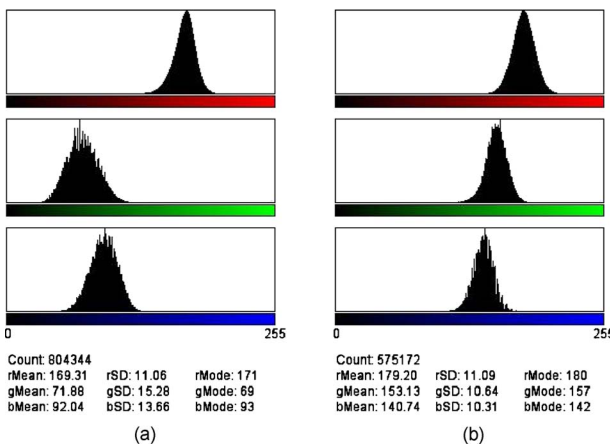


Figure 5. RGB histograms of element (a) and background (b) of the sample image of a 5 mm circle, showing differences in channels; R channel histogram top, G channel histogram middle, B channel histogram bottom.

RGB histogram, showing separate histograms for each of the channel, presented from the sample image rectangular selections of the area of the element and the background. The RGB profile was made by using the real-time RGB profiler plug-in.[13] The RGB histograms were made using the Color Histogram plug-in.[14]

Figure 6 shows the close up of the image of the outline which is the border of the element that was obtained using the color thresholding procedure for processing and thresholding the original microscope images, captured at 12.5× magnification. The image of the outline is overlaid on the original image in order to see the fitting of the outline of the binary image obtained by the procedure described.

Figure 7 shows the processing and image analysis procedure on a sample image, from the original image captured by the microscope, 12.5× magnification, to the mask of the character, showing the area analyzed by image analysis. As can be seen, the image analysis procedure was set to disregard the particles which are not the part of the analyzed

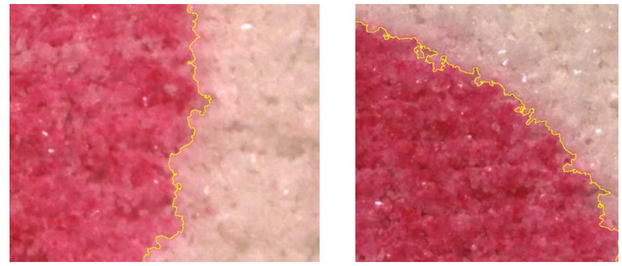
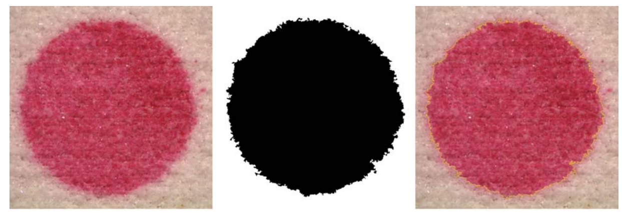


Figure 6. Close up of the samples images, border (outline) obtained by applying threshold overlaid on the original microscope image.



(a) (b) (c)

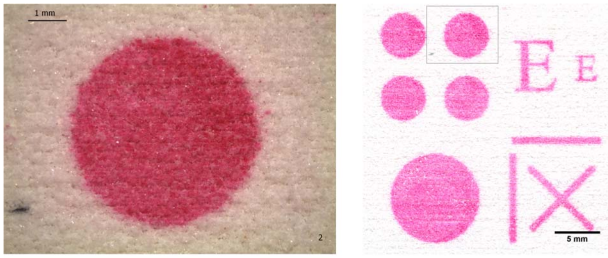
Figure 7. Image analysis procedure, illustration; original microscope image (a), mask of analyzed element (b), outline of analyzed element overlaid on the original microscope image (c).

element but were included in the thresholded image based on their intensity level falling in the selected specific threshold range.

The objective evaluation by image analysis depends on obtaining reliable quantitative data from the images.[15] The issues in application of image analysis for print reproduction in 3D printing mostly arise from the structures of 3D print surfaces. When compared to evaluation of ink jet prints on substrates such as paper, the surface of 3D prints is much rougher and more uneven,[16] due to the "substrate" material being in the shape of powder. This causes problems in segmentation of the images, especially the ones captured from microscope, as selection of an appropriate threshold value at which the pixels belonging to the ROI are clearly separated from the background is, in some cases, difficult. The structures in surfaces caused from unbound powder, visible layers, cracks, etc., that are in the proximity of printed areas can cause difficulties during segmentation, both by grayscale or color histogram thresholding. The histogram thresholding does not take into account the spatial details and can be difficult to perform on images without distinctive histogram peaks and valleys.[5] The selection of different threshold values that are next to each other for the same image can cause differences in the results of obtained thresholded images of, e.g., perimeter, and therefore circularity, values, and makes development of automated segmentation procedures possibly challenging.

ANALYSIS OF REPRODUCTION

Figure 8 shows the sample element from the first group of samples printed in different positions in the xyz space. The microscope capture is shown on the left and the same area is marked on the scanned image on the right.



(a) (b)

Figure 8. Images showing the sample element, 5 mm circle, captured by microscope (a) and the same area marked on the scanned image of the test plate surface (b)

Figure 9 shows the 12 pt "E" character reproduction on the samples printed in different relative position in xyz space. The differences in reproduction of characters depending on the position of the surface can be visually observed. Note the differences in, for example, characters reproduction on samples 1 and 2, which have been placed in the same x-z position, but with a different position relative to the application of the binder; sample 2 was placed first relative to the application of binder, and the sample marked 1 was at the end of the binder application. Further, the differences in character reproduction between samples placed in the same position relative to the direction of powder and binder application (samples 1, 5 and 9; 2, 6 and 10; 3, 7 and 11; 4, 8 and 12) but inclined at different angles, 0°, 45°, 75° respectively, can also be observed.

Table III shows the results of image analysis of sample element characteristics, 5 mm circle for samples printed in different relative xyz positions in the print bed. The apparent differences in reproduction of surfaces of the first group of samples can be due to the nature of the three-dimensional printing process. As the powder is distributed from one direction and binder in a perpendicular direction, the surfaces that are placed in different positions relative to the direction of powder and binder application are possibly influenced by these process characteristics. The angle of inclination of the surface also contributes to the surface reproduction. Potentially pronounced striping effect is often visible on inclined surfaces in all the manufacturing techniques that use layers as the basic process element.[1] The visibility of the "stripes" is influenced by characteristics of materials and surfaces, and layer thickness. In the three-dimensional printing process, "stripes" are sometimes visible on the vertical surfaces as well, especially on the large colored areas, and are caused, among other things, by the just printed layer being pushed slightly by the printing of following layer, contributing to the rougher surface. In addition to the reproduction of elements, this also affects color reproduction.[17] The results of sample elements of first group of samples are comparable to the samples marked B from the second group, as the same printing preferences were used, and potential differences resulting from different positions in xyz space can be observed. Results of image analysis of sample element characteristics for samples printed with different printing preferences, for a 5 mm circle are presented in Table IV.

The A sample elements, Table IV, are generally reproduced with smallest distortions. When comparing results of image analysis of A and B samples elements, Table IV, which have been printed with the bleed control on and off respectively, the effect of bleed compensation is visible in monitored characteristics: A samples have smaller total area, which was expected, but also show smaller perimeter and higher circularity. This shows the efficiency and effect on the reproduction of the print element of bleed control in the three-dimensional printing process. Bleed compensation is set up in such a way that it takes into account the expected spreading of the print areas into the surrounding unprinted areas and offsets the print areas from the designed size inward.[8]

The elements from the C samples (printed with higher shell saturation or amount of binder applied), have the highest total area, which is directly related to the highest amount of binder that was applied during printing. Results show that other characteristics, perimeter, circularity, and Feret diameter, have relatively similar values for B and C samples elements. This is an important parameter for the three-dimensional printing process as it shows that the elements are somewhat similarly reproduced, apart from element total area that is directly related to the amount of binder applied. The B sample elements compared to the D sample, printed with lower shell saturation, elements show the effect of printing with a smaller amount of binder. The resulting total area of D sample elements is smaller, and the circularity is relatively higher.

The reproduction of surfaces facing downward and upward can be seen if comparing the samples marked _D and _U, Table IV. The differences are due to the printing process, as the objects are created from the lowest layer first and built upward. That means the bottom downward object planes are being built first and are observed to show potentially rougher surfaces, more bleeding to the unprinted powder,[8] especially with higher shell saturation, more saturated and darker colors, which show differences in relation to the surface orientation,[18] etc. Figure 10 shows the differences in reproduction among samples printed with higher amount of binder in scanned images. The areas of the E character in 24 pt and 12 pt on the surface that was facing downward is 17.58 mm^2 and 5.77 mm^2 and on the surface facing upward 13.7 mm^2 and 4.21 mm^2, respectively.

CONCLUSIONS

The reproduction in three-dimensional ink jet printing was evaluated in this work. The effect of different printing preferences and placement of printed surfaces in different positions on the build bed on reproduction has been presented, and morphological characteristics of the test elements, as analyzed by the described routines, have been discussed. The evaluation was done on light microscope images and shown on scanned images of three-dimensional print surfaces. Image analysis, using IMAGEJ software with built-in functions and plug-ins, was studied as a tool for objective evaluation of the surface elements. The research of image analysis as a

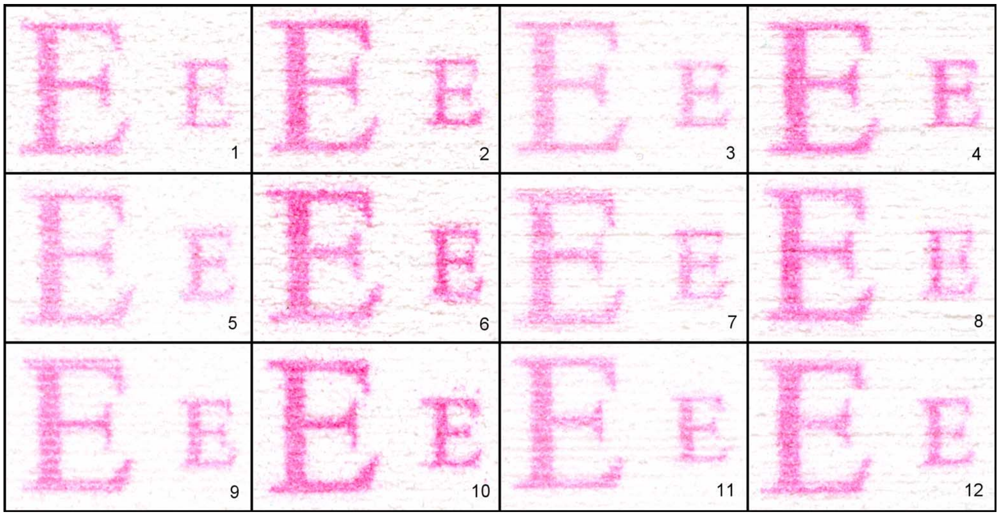


Figure 9. Reproduction of character "E," from the first group of samples, printed in different relative xyz positions in the print bed, scanned images, sample number marked in the bottom right corner

Table III. Results of image analysis, sample element characteristics, circle with diameter of 5 mm, samples printed in different relative xyz positions in the print bed.

Label	Total area (mm^2)	Perimeter (mm)	Circularity	Feret (mm)	Major (mm)	Minor (mm)
1	18.20	34.53	0.19	5.15	4.85	4.77
2	18.12	33.50	0.20	5.07	4.82	4.79
3	18.76	36.08	0.18	5.44	4.94	4.83
4	17.99	26.61	0.32	5.18	4.82	4.75
5	18.98	44.41	0.12	5.40	4.94	4.89
6	19.31	34.80	0.20	5.28	5.05	4.87
7	19.04	39.62	0.15	5.26	5.01	4.84
8	19.63	39.78	0.16	5.30	5.12	4.88
9	18.14	33.76	0.20	5.10	4.84	4.77
10	17.87	29.09	0.27	5.03	4.78	4.76
11	19.03	35.54	0.19	5.26	4.94	4.90
12	19.03	31.27	0.24	5.14	4.95	4.90

Table IV. Results of image analysis, sample element characteristics, circle with diameter of 5 mm, samples printed with different printing preferences.

Label	Total area (mm^2)	Perimeter (mm)	Circularity	Feret (mm)	Major (mm)	Minor (mm)
A_D	18.12	29.82	0.26	5.08	4.89	4.72
A_U	18.41	32.56	0.22	5.13	4.87	4.81
B_D	19.24	47.60	0.11	5.72	5.08	4.83
B_U	19.25	37.82	0.17	5.24	4.97	4.93
C_D	21.21	48.32	0.11	5.60	5.21	5.18
C_U	20.19	35.54	0.20	5.50	5.10	5.04
D_D	18.39	41.03	0.14	5.23	4.85	4.83
D_U	17.83	32.98	0.21	5.11	4.81	4.72

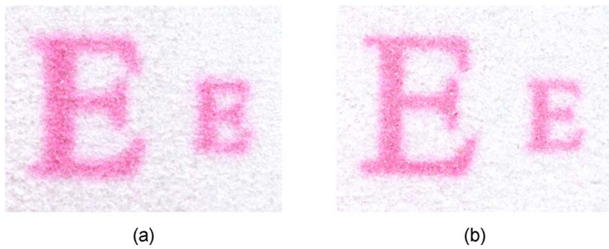


Figure 10. Reproduction of characters "E," 24 pt and 12p, downward and upward facing surfaces; C_D sample (a), C_U sample (b), scanned images, 1200 dpi

technique for objective reproduction analysis showed it can be a valuable tool, acknowledging the specific issues that arise from application to the evaluation of reproduction in three-dimensional ink jet printing.

The effects of different printing preferences and relative orientation of the object in the xyz space on the reproduction on the surface elements were observed. The presented results give perspective to the interaction of materials and define the factors that influence the reproduction in the specific area of three-dimensional ink jet printing. They are of importance insofar as they show how the principles of three-dimensional printing, with process specific parameters such as orientation of the objects and surfaces, bleed control and saturation levels, influence, and to what extent, the surface element reproduction and appearance of 3D prints.

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