Color Measurements of Three-dimensional Ink-jet Prints

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Abstract

Reproduction of colors in three-dimensional ink-jet printing (3DP), dependant on the materials used, was studied. A lot of different types of rapid prototyping techniques exist; some of them are based on the standard ink-jet printing. 3D printing is classified as additive, powder-based rapid prototyping technique. The binder is ink-jetted onto the successive layers of powder. The chemical interaction of the binder and the powder results in solidification of material and thus the three dimensional prints are produced. In recent years, the opportunity of color 3D prints has been made possible. In a 3D color printer, the colorants make part of the binder solution. The system uses four printheads – CMY and clear binder and reproduces color on the basis of 2D desktop ink-jet printer. Considering 3D prints have much more rough surface compared to conventional ink-jet prints, the instrument-related aspects of color measurements were discussed. Spherical geometry spectrophotometer was used. As 3D prints are almost always post-processed by applying a selected infiltrant as a finishing agent, the color change of finished versus non-infiltrated prints has been studied. Infiltrants used as finishing agents were epoxy resin based and cyanoacrylate.

Introduction

3D printing is a rapid prototyping method which functions on the basis of the conventional ink-jet printing. It is currently the only RP method which is capable of producing objects in full color. Although being a RP process, its basic principle of objects production and color capabilities are the reason why it is a topic of interest for the graphic technology based research. 3D printing itself has been a topic of interest in a number of articles in the last few years, mainly in rapid prototyping and advanced engineering journals. Topics researched include, among other, general overview of technology and future outlooks, achievable accuracy, mechanical properties, bioprinting, benchmarking to competing rapid prototyping technologies. However, there are only a limited number of scientific articles dealing with the 3D printing color capabilities [1, 2], which raises the need to assess this topic in greater detail.

The scope of the work is to obtain basic information about reproduction of color in three-dimensional ink-jet printing as well as to research the methodology of 3D color measurements and analysis.

Basics of 3D Color Ink-jet Printing

3D printing is a type of rapid prototyping (RP) process. It is an additive RP process, using the powder material which is fused by ink jetting the binder [3]. 3DP™ process has been developed by the Massachusetts Institute of Technology (MIT) and licensed to various companies in diverse fields of use [4, 5].

The process technology itself is based on ink-jet printing; it employs a similar method of jetting the binder material in a form of controlled droplets which join the powder particles together. 3D printing process functions by building parts in layers, which have been sliced by computer algorithms from the CAD model of the desired object. For the each layer production, the powder particles are evenly distributed over the printing surface and selectively joined by employing a binder material. The support piston is then lowered and the next layer of powder is applied, followed by the binder material. This process is repeated until the desired 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.

When the printing process finishes, the object is raised out of the unbound powder, de-powdered and usually finished with the appropriate agent.

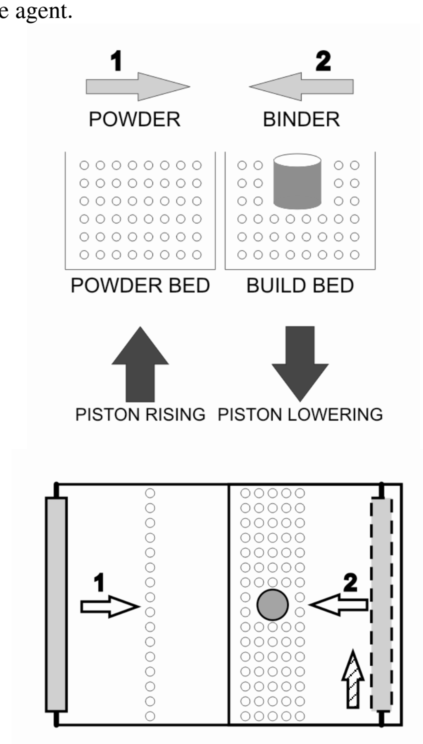

***Figure 1.** Scheme of 3D printing process, side view (upper figure) and top view (bottom figure)*

In a 3D color printer, the colorants are a part of the binder solution and the color is produced from the cyan, magenta and yellow binder. Currently, there is no black ink binder in the 3D color printing.

Methodology

Test Targets File Preparation

Two kinds of color test targets were constructed and printed (Figure 2), marked ECI 2002 3D and CMY+.

ECI 2002 3D target was used for characterization of color capabilities of 3D printing process. Group 1 portion of ECI 2002 Visual Layout test target [6] was used. Group 1 belongs to the profiling part of the ECI 2002 V test target and it consists of 729 patches. The patches are constructed of varying percentages of cyan, magenta and yellow colors. Due to the material surface characteristics and measuring equipment specifications, single patch of at least 1 cm in length and 1 cm in width was needed. Therefore, Group 1 patches were separated into nine equal squares and prepared as nine single tiff images. Images were fitted onto 10 cm by 10 cm plates (0.5 cm of white space on every end of the plate), measuring 3 mm in height, in ZEdit software.

For observing the reproduction of basic colors, user defined target, CMY+ target, was created in Adobe Illustrator software and saved as a tiff image. Following patches from the test target were used in this work, their labels marked in parenthesis: 100% coverage of cyan, magenta and yellow colors in 1 cm by 1 cm patches (C, M, Y); 100% coverage of red, green and blue colors in 2 cm by 2 cm patches (R, G, B); “black” patch consisting of 100% of cyan, magenta and yellow, 2 cm by 2 cm (CMY); and “white” patch, clear binder, 2 cm by 2 cm (W).

Printing and Finishing

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). Material options are high performance composite, elastomeric and direct casting materials. Its printing head system comprises of four printheads (C, M, Y color ink binders and clear binder) with 1216 jets total. Z510 printer uses HP thermal ink-jet printheads, with the continuous supply binder containers. 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 (humectants, buffer solution). Layer thickness was 0.004 inch (0.100 mm) for all the printed samples.

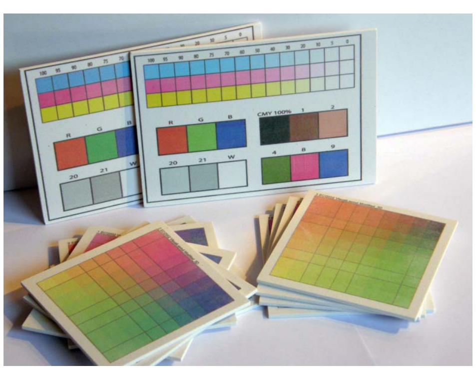

Figure2. *3D prints used for measurements, non-infiltrated sample presented*

The printed samples were removed from the printing bed and cleaned from the remained powder. The samples were divided into three subgroups in accordance to the finishing process that followed, first group was left un-treated, second group was finished with Z-Bond 101 infiltrant and third group with Z-Max Epoxy infiltrant. Z-Bond 101 infiltrant is cyanoacrylate based infiltrant. It is ultra low viscosity finishing agent, which bonds in seconds. Z-Max infiltrant is epoxy resin based infiltrant, comprising of two components, the resin and the hardener, which have to be mixed together prior to use. It is medium viscosity finishing agent [7]. Infiltration methods used were: pouring for Z-Bond infiltrant and continuous brushing for Z-Max infiltrant.

Color Measurements

Color measurements were made with the X-Rite (Gretag Macbeth) Coloreye XTH sphere spectrophotometer. Some comparing measurements were made with the X-Rite 528 spectrodensitometer. Microsoft Excel software was used for the calculations and representation of data. Gretag Macbeth ProfileMaker 5.0 tools MeasureTool, ProfileMaker and ProfileEditor as well as open source software ICCView 2.0 [8] were used for the assessment of colorimetric data.

XTH sphere spectrophotometer has the following characteristics: pulsed xenon as the light source and diffuse 8°, Ø 38 mm integrating sphere as the optical configuration. The following measurement characteristics were set and used in the colorimetric assessment: D65 illuminant, 10° observer, SPI, SAV (aperture Ø 5 mm illuminated, Ø 2 mm measured).

Results of the measurements were recorder in the form of the CIE L*a*b* and CIE L*C*h values were later computed. Differences in L*, C* and H* between the non-infiltrated versus infiltrated samples, as well as between the differently infiltrated samples were calculated. The color difference formulas used were dE CIE2000 and dE CMC 2:1. Gamuts of the 3D prints, dependant of the finishing agent used, were assessed as well.

Results and Discussion

Color Measurements Methodology

Due to the surface of the 3D prints being far rougher [9] than the ink-jet prints on paper substrates, it was presumed that the instrument based on most commonly used measurement geometry in graphic technology, the 45/0° or 0/45°, will not always produce repeatable and credible results. Thus, some preliminary measurements were done with the X-Rite 528 spectrodensitometer, which uses 45/0° geometry. Same trial patches were measured with the X-Rite XTH sphere spectrophotometer. Sphere spectrophotometers are commonly used when measuring color on textured surfaces such as textiles and fabrics, canvas, plastics, etc.

The d/8° measuring geometry proved to be more reliable in interpreting the colors than the 45/0° geometry. The use of standard graphic arts spectrophotometer was found to be dubious for this purpose since the measurements result depends on the actual material reflectance characteristics and the topography feature that the incident light hits when measuring the spectral reflectance of the surface. Thus, the measurements with the devices with 45°/0° or 0°/45° measuring geometry can work well on smooth and fairly uniform 3D prints surface (for instance with the filled up and smooth surface areas of the Z-Bond infiltrated samples), but give diverse readings if the surface is uneven in topography, which is often the case with 3D prints. 3D prints not only vary in surface topography between differently infiltrated samples, but in the same sample surface as well. The 3D printer prints color binder on the approximately last ten layers (up to cca. 1 mm), meaning that the color is in sort of under layer and the ink binder is always combined with powder. In addition, the samples are most commonly infiltrated and can have a thin layer of the finishing agent on the top, depending on the infiltrant agent used and its absorbance and hardening behavior.

The surface gloss of the 3D prints depends on the infiltrant used. The cyanoacrylate based agents generally contribute to more glossy surfaces than the epoxy based ones, bearing in mind that the term glossy needs to be relatively taken. As the used spectrophotometer allows simultaneous readings with specular included (SPI) or excluded (SPE) initial measurements were done with the specular component (gloss) included and excluded. The differences were generally very small and not noticeable on all evaluated samples.

3D Prints Color Characteristics

The results of measurements of selected colors of CMY+ test target of non-infiltrated, cyanoacrylate and epoxy based infiltrated samples are presented in Table 1 a) to c) respectively.

Differences between the non-infiltrated versus infiltrated samples are presented in Tables 2a) and 2b).

Differences in L*, C* and H*, as well as color differences dE CIE2000 and dE CMC 2:1, between differently infiltrated samples are presented in Table 2c).

Table 1 a) to c): Measured and calculated 3D color data

1a) non-infiltrated

	L*	a*	b*	C*	h/°
C	72,59	-9,53	-22,64	24,56	247,17
M	65,09	35,30	-6,46	35,89	349,63
Y	86,13	-5,20	57,29	57,53	95,19
R	64,88	26,78	21,18	34,14	38,34
G	73,02	-29,64	23,40	37,76	141,71
B	59,16	2,73	-23,99	24,14	276,49
CMY	59,12	-2,20	-0,45	2,25	191,56
W	92,02	3,18	-3,36	4,63	313,42

1b) cyanoacrylate (Z-Bond)

	L*	a*	b*	C*	h/°
C	57,51	-10,76	-29,88	31,76	250,20
M	49,75	47,58	-4,75	47,82	354,30
Y	77,52	-2,33	72,41	72,45	91,84
R	47,26	40,23	28,38	49,23	35,20
G	56,58	-40,45	29,07	49,81	144,30
B	39,72	4,89	-31,16	31,54	278,92
CMY	38,32	-2,06	-2,01	2,88	224,30
W	85,36	3,66	-0,59	3,71	350,84

1c) epoxy resin based (Z-Max)

	L*	a*	b*	C*	h/°
C	55,54	-10,54	-26,10	28,15	248,01
M	46,07	40,74	-3,15	40,86	355,58
Y	68,70	-0,70	59,38	59,38	90,68
R	44,28	32,15	21,47	38,66	33,74
G	51,32	-37,34	25,15	45,02	146,04
B	37,53	2,58	-25,48	25,61	275,78
CMY	35,84	-3,67	-0,64	3,73	189,89
W	79,37	2,95	-0,24	2,96	355,35

Table 2 a) to c): 3D prints color differences

2a) non-infiltrated to Z-Bond

	ΔL*	ΔC*	ΔH*	ΔE_{00}	ΔE_{CMC}
C	-15,08	7,19	1,47	12,77	7,10
M	-15,34	11,93	3,38	14,71	8,49
Y	-8,61	14,92	3,77	7,35	6,63
R	-17,62	15,09	2,25	17,31	10,23
G	-16,44	12,05	1,96	14,19	8,34
B	-19,44	7,40	1,17	19,60	9,23
CMY	-20,80	0,63	1,43	20,74	9,02
W	-6,66	-0,92	2,66	4,93	4,24

2b) non-infiltrated to Z-Max

	ΔL*	ΔC*	ΔH*	ΔE_{00}	ΔE_{CMC}
C	-17,05	3,58	0,38	14,29	6,84
M	-19,02	4,98	3,97	18,08	8,35
Y	-17,43	1,86	4,60	12,75	6,79
R	-20,60	4,52	2,92	19,82	9,01
G	-21,70	7,26	3,11	18,77	9,08
B	-21,63	1,47	0,31	21,46	9,16
CMY	-23,28	1,48	0,08	22,93	10,00
W	-12,65	-1,67	2,65	8,71	5,85

2c) Z-Bond to Z-Max

	ΔL*	ΔC*	ΔH*	ΔE_{00}	ΔE_{CMC}
C	-1,97	-3,61	1,14	2,35	2,11
M	-3,68	-6,95	0,99	4,34	3,29
Y	-8,82	-13,06	1,34	7,40	5,49
R	-2,98	-10,57	1,12	4,62	4,47
G	-5,26	-4,79	1,44	5,34	3,03
B	-2,19	-5,93	1,56	2,65	3,37
CMY	-2,48	0,85	2,56	4,24	4,11
W	-5,99	-0,75	0,26	4,15	2,34

From the Tables 2a) and 2b) it can be seen that infiltration has a positive effect on chroma values, which are increased more by the cyanoacrylate agent than the epoxy based agent. The lightness values are decreased. For the chromatic colors, the color hue changes in much less amount than the chroma. dE differences are from ~ 4-7 in white and yellow patches to ~ 9-20 (depending on the formula used) in cmy, red and blue patches. They follow the same trend for both infiltrant agents.

Table 2c) presents color differences between the samples infiltrated with two types of agents. Chroma values are again changed more than hue values. The lightness values do not change much. dE differences range from ~ 2 for cyan patch to ~ 5-7 (depending on the dE formula used) for yellow patch.

Display of 3D prints gamut

The gamut of the 3D prints, depending on the infiltrant used, is presented in Figures 3 and 4.

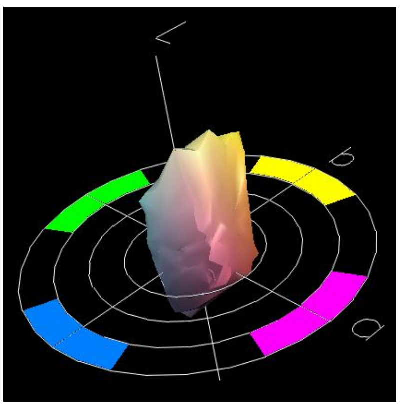

Figure 3. *Gamut representation of 3D prints infiltrated with cyanoacrylate agent (Z-Bond)*

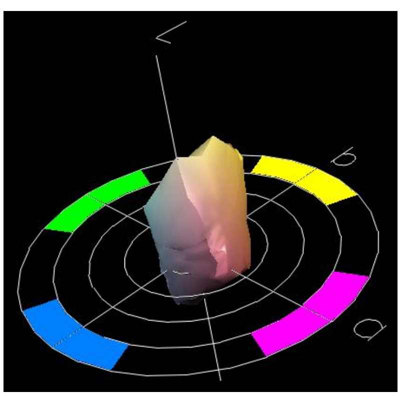

Figure 4. *Gamut representation of 3D prints infiltrated with epoxy-based agent (Z-Max)*

ECI 2002 3D targets measurement results were used for the characterization of the 3D printing color capabilities and gamut representation as based on the colors from the used test target. The gamut of prints infiltrated with the cyanoacrylate agent is larger than of corresponding prints infiltrated with the epoxy based agent. This result was expected since the cyanoacrylate infiltrated samples had higher chroma and lightness color values than epoxy infiltrated ones. Differences are mostly pronounced in the range from red to yellow-green colors, in the upper part of the gamut. There are areas containing colors that are very similarly reproduced, irrespective of the infiltrant used. They are mainly located in the bottom part of gamut in the range from cyan to darker green-yellows.

Conclusions

The 3D printing color capabilities and methodology were determined and discussed. Due to the color characteristics and surface topography of 3D prints, sphere spectrophotometer (d/8° measuring geometry) was used.

The finishing of 3D prints, influenced by the infiltrant agent used, was found to decrease the lightness values and increase the chroma values. The hue angle does not significantly change. Infiltration with the cyanoacrylate agent, compared to the epoxy agent, contributes to the higher chroma values, while lightness and hue values do not differ much. Consequently, the gamut of cyanoacrylate finished 3D prints is larger than the epoxy infiltrated, although there are areas of the gamut that are reproduced very similarly.

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