https://doi.org/10.2352/EI.2022.34.15.COLOR-180

An Exploration into Color Reproduction for Inkjet FDM Color 3D Printing

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Abstract

Advancing in inkjet fused deposition modeling (FDM) color 3D printing enables to create dedicated aesthetical appeal. However, the complete fabrication of a target color remains limited due to the unusual mismatch in 3D color management systems. In particular, the 3D aspect that makes the 3D color systems different from standard 2D printing, such as ink and substrate characteristics, viewing conditions, and base materials. Therefore, to the best of our knowledge, there is no suitable established method that supports color reproduction for inkjet FDM color 3D printing. In this paper, we analyze the color profile of an inkjet FDM color 3D printer to obtain a color model that could bridge the gap between a digital design (as an input) and the actual 3D printed results (as an output). We then created the color model by reproducing each color mapped to every possible color pair to determine the closest color between the target and printing colors on the basis of the color difference value, which can be rendered in lieu of the original printing colors. We verify our proposed color model by printing the mapped color and conduct a color measurement to compare it with the target colors. From the experimental results, we showed that our mapped colors can represent those desired by the user with an 80% success rate, which can be matched through controlled conditions.

Introduction

Inkjet fused deposition modeling (FDM) color 3D printing has enabled personal to commercial fabrication of aesthetically appealing products with full color. Advance in printing methods enabled color droplets to be mixed with extruded filaments to create colored 3D-printed products. Such technologies have been used in various applications from mock-up designs to medical applications [3, 4]. While color difference can affect the feel and attitude of a product, full-color 3D printing has yet to determine a color management standard similar to that of a 2D printing framework. For example, Wu et al. [8] proposed benchmarks that would control the quality of 3D printing. Brunton et al. [1] suggested a halftoning workflow that applied an International Color Consortium (ICC) profile conversion by gamut mapping to polymer-based color 3D-printing. While previous work consider the quality control or gamut mapping algorithm into account, its does unsuitable for full-color 3D printing. Furthermore, the digital discretization that enables color transmission in 2D-printing and 3D-printing are also different [9]. In 2D-printing, discrete dots and lines are transferred to a planar pattern. In 3D-printing, discrete layers are combined to create a 3D-entity. Such processes

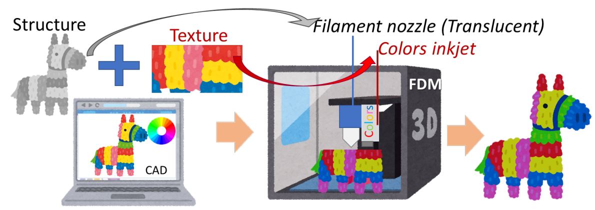

Figure 1. Process of inkjet FDM 3D color printing. The printing software slices the 3D object structure with texture into a layer and then maps the colored parts into color channels. The failure of color mapping is a main cause of mismatching color reproduction.

make the color 3D-printing is more complex, which requires the efficient method to control (Fig.1).

Instead of extruding the color filaments, in which each color is based on the blending of multiple filaments colors [6, 7], inkjet FDM color 3D printing extruding standard filaments and coloring them using the color inkjet in each layer (Fig.2). In addition, printing conditions also affect color mismatched, for example, when printing under translucent plastic materials and different viewing angle (Fig. 8). To achieve the goal to enable a user to obtain aesthetically appealing products with full color, the sufficient color transfer system is necessary [**?**].

This paper explores a method to reproduce color using inkjet FDM 3D color printers. We initially investigate a color profile that could bridge the gap between digital design (e.g., users design) and actual printed results. Then, we manually reproduce the color from profiles by directly mapping the selected color difference to estimate the represented color that could replace the original color close to what the user desires. Finally, we verify our exploration by 3D-printing the mapped color through the color measurements to be compared with the target colors.

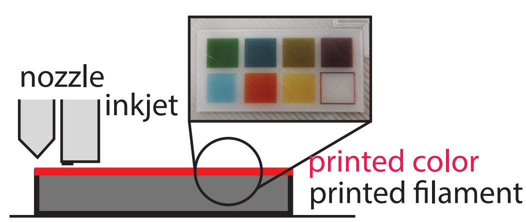

Figure 2. Printing mechanism of FDM color 3D printers. In the attached layer, ink is dropped to create color artifacts over the printed filament.

Figure 3. *125 color chart used in the Experiment 1. (a) The original designed color chart vary RGB values, (b) 16-bit color code(html)(#RRGGBB), (c) 3D printed object with 4 mm thick (Output).*

Color Reproduction in FDM Color 3D Printers

When reproducing color using inkjet FDM 3D color printers, the user first creates or selects the texture they want. This selection is then applied to a 3D object using a computer-aided design (CAD) software. The printing software slices the 3D object with texture into layers and map the colored parts into color channels, e.g., sRGB color space (Fig.1). However, it is unclear whether the color space needs to be used to create textures that can reproducing the same color as the user's desired input. Thus, this leads color gamut mismatching between the input (design) and output (3D object).

Silapasuphakornwong et al. [5] presented a practical file conversion framework (i.e., CMYK-sRGB), suitable for color reproduction in inkjet FDM color 3D printing system, which is different from the conventional workflow (i.e., sRGB-sRGB). In this work, we investigate the factors that caused the color mismatch including the color difference value in 3D color space, its distribution and pattern of color difference between input (design) and output (3D object). To do so, we utilize the color mapping technique by comparing the color difference before and after printed as an input, and then calibrate such color information before generate the color profile that link the source to match the target color.

Our technique to generate the color profile is to map every possible color pair to find the closest color using the color difference value. To do so, we render in lieu of original printing colors and investigate the normal distributions of each color.

Experiments and Results

In this section, we described our experiments; (1) color distribution, (2) color management, and (3) color verification. As for the reminder, our work aim to find the color difference between the systems, which depending to the devices (input—design from the software and display), to the system which devices are independent (output—human perception). Then, we create the profile by matching the closest colors between input and output by any color models.

We hypothesize that color profile is the least color difference value between the pair of color input and output. Such color profile would mapped every possible color pair. Hence, we explore and verify the colors reproduction of the printer and comparing the difference from the input colors, in purpose to find the possibility of create the mapping method. It is to link the 2 systems between depending to the devices (input—display), to the system which device independent (output—human perception). Finally, we can create the profile by matching the closest colors between input and output by any color models.

Note that, we designed the input texture and mapped the object with texture using a standard software (Adobe Photoshop and 3D Builder). Then, we used the XYZ Davinci Color 3D Mini to print and investigate the color reproduction of the inkjet FDM color 3D printer. Finally, we observed the printed result using a spectrophotometer (Spectrolino CH-8105) with $L^*a^*b^*$ color space, D65, polarized filter, reflection at 2° observer. We choose $L^*a^*b^*$ color space since it is relative to the human perception.

Experiment 1: Estimation of Color Difference

We create 125 sample colors chart, adjusted the color values in a scale of each red, green, blue color (color palette 16-bit), and vary in 5 steps (5^3 = 125 colors) included 0, 64, 128, 192, and 255. As shown in Fig. 3 the color test chart of image texture design, 16-bit color code (css), and 3D printed objects (with 4*mm* thick), respectively.

We compared the color profile between the original digital file (***o*** symbol) and the printed one (***** symbol) by plotting the color gamut, in three- (L^*, a^*, *and* b^*) and two- (a^*,*and* b^*) dimensions, respectively (Fig.4). We calculated the color differences between each color by the distance between each linked line (Fig.4) from the following equations.

$$\Delta E^*_{OI} = \sqrt{(L^*_O - L^*_I)^2 + (a^*_O - a^*_I)^2 + (b^*_O - b^*_I)^2} \quad (1)$$

where the ΔE^*_{OI} is the color differences values from the original input points (I) to the output points (O). L^* is the Lightness, a^* is the (+)red and (-) green color value, and b^* is the (+)yellow and (-)blue color value.

Since the distribution of the line directions are unpredictable, we cannot obtain the simple model that represents all the color difference between original and printed results. Therefore, we perform the simple match by matching each color pick up from the color chart to create the basic color profile.

Experiment 2: Simple Match

We conducted the simple match experiment to identify the closed color value that should be used as the suitable input color profile for inkjet FDM color 3D printing. We calculate the $\Delta E^*_{OI} L*a*b*$ from every pair of color (125 colors = 15,625

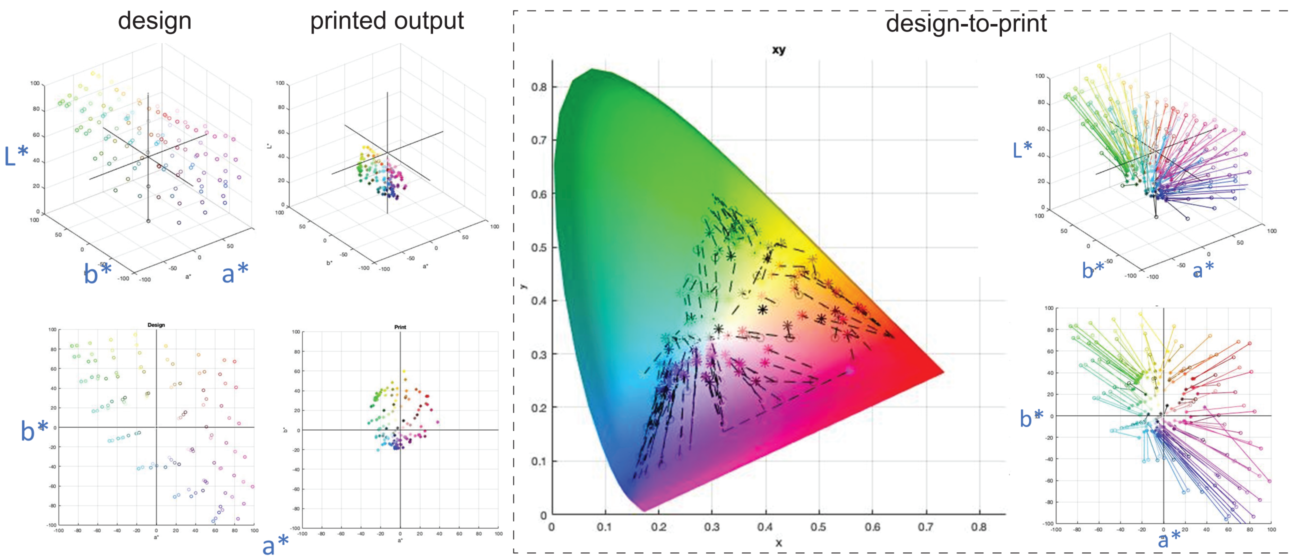

Figure 4. *Gamut of color differences. 125 colors of the tested chart, between input (design 0) and output (3D-printed *). The lines draw to connect the design to real-print, presented as 2D (a*,b*) and 3D (L*a*b*).*

pairs) between input and 1st printed object. We found the least ΔE (minimum different value), in order to print this color (2nd printed object) and, again, compare to the original input designed color. The experimental flow of this experiment is illustrated in Fig. 5.

Table 1 shows the results of color difference (ΔE) corresponding to the human color mismatch cognition of normal person [2].

Table 1: Standard color different (ΔE), corresponding human color mismatch cognition of normal person

ΔE	**Cognition**
$\Delta E \leq 1$	Imperceptible by human eyes
$1 < \Delta E \leq 2$	Perceptible by close observation
$2 < \Delta E \leq 10$	Perceptible at a glance.
$10 < \Delta E \leq 50$	Clear different in colors is noticed
$\Delta E > 50$	Exactly 2 different colors

From the results in Table 2, we choose the paired-color of matching that $\Delta E^*_{OI} L*a*b* \leq 10$ to reprint and checking the feasibility of color reproduction. In total, we have proceed eight colors as shown in Fig. 6. However, two colors (at the right-

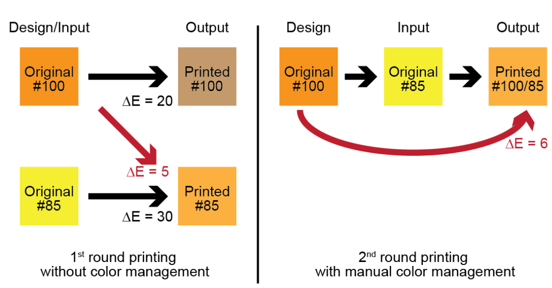

Figure 5. *Experimental procedure of the experiment 2.*

column of the printed sample) are removed from the considering in next experiment because these are the limitation on the color reproduction. Notice that, both colors are *Gray*, not black and white, in input. This point is interesting for future study also that we should have the color compensate calculating or not in the color rendering model.

Table 2 presents the RGB, L*a*b*, and ΔE^*_{OI} values, and compares all six input colors (original color) with the fewer output colors (printed). First row (*original color*) shows the RGB, and L*a*b* values of original color (O), which is the same color for the input (O_o) and output(O_p). Second row shows the color that has the least ΔE^*_{OI} (E), in the RGB and L*a*b* values, which is also the same color for the input (E_o)and output (E_p). Third row shows the second print's (S) L*a*b* (S_p), including the color number (from the 125 colors), the Δ E calculated from the original color input (O_o) and the least ΔE output color (E_p). Forth and Fifth row, shows the L*a*b* values of the printed objects color in images *HoneyComb* (HC_p) and *Abstract* (Ab_p), respectively. The ΔE of both rows were calculated by comparing them with the color of the input (O_o).

Our results show the six pairs of mapped colors from our proposed method. The ΔE at the "2nd print" value. These were calculated by comparing O_o & S_p with the value ≤ 10. All values were improved compared with the ΔE of the original output printed color (ΔE of O_o & O_p). However, after we asked the observer to see the real printed of a 3D object (S) with the naked eye, the observers felt *accepted* only 4 out of 6 mapped colors (66.67%),to be similar. The mismatched printed colors were numbers 5 and 6 as showed in Fig. 6.

Experiment 3: color reproduction verification after mapping colors

We conducted an experiment to verify the visibility of image content whether or not it acceptable in the human perceptual case. Our experiment take into account the ΔE to find whether the color representation to the original input is effectively. We created two

Table 2: Results of Experiment 2 and 3

color (chart)		original design (input)						dE	printed (output)		
		R	G	B	L*	a*	b*		L*	a*	b*
#A47(6)	original color	0	64	0	22.54	-32.02	30.12	18.35	23.20	-16.66	20.10
#B40(12)	less dE	0	128	64	46.72	-45.50	26.36	7.92	26.75	-29.69	23.83
	2nd print							13.83	22.95	-21.91	20.69
mapped color #1	image 1 (HC)							14.13	28.87	-26.18	18.91
	image 2 (AB)							19.51	29.26	-20.62	15.78
#A46(7)	original color	0	64	64	23.72	-17.86	-5.25	8.36	20.09	-14.41	1.04
#B39(38)	less dE	64	128	128	49.60	-20.42	-6.33	1.95	25.66	-17.87	-5.84
	2nd print							7.49	23.96	-10.39	-4.83
mapped color #2	image 1 (HC)							4.03	26.38	-15.49	-7.22
	image 2 (AB)							7.37	26.27	-16.31	1.51
#A48(31)	original color	64	64	0	26.03	-8.01	34.72	9.71	22.64	-6.56	25.74
#B38(62)	less dE	128	128	64	52.28	-9.63	34.45	3.53	29.36	-8.94	35.48
	2nd print							8.09	26.85	-0.93	30.88
mapped color #3	image 1 (HC)							6.42	29.48	-7.17	29.37
	image 2 (AB)							16.19	28.21	-8.62	18.69
#B39(38)	original color	64	128	128	49.60	-20.42	-6.33	24.08	25.66	-17.87	-5.84
#A11(75)	less dE	128	255	255	93.16	-35.23	-10.87	9.99	42.67	-13.32	-7.47
	2nd print							11.89	42.40	-11.63	-9.85
mapped color #4	image 1 (HC)							9.55	43.19	-13.53	-7.95
	image 2 (AB)							14.33	37.85	-16.01	0.96
#B25(56)	original color	128	64	0	34.51	23.97	44.82	23.99	24.91	5.40	33.05
#B27(81)	less dE	192	64	0	45.46	49.21	56.68	9.25	30.75	16.19	41.51
	2nd print							9.95	28.20	23.52	37.14
mapped color #5	image 1 (HC)							23.21	26.16	6.95	31.43
	image 2 (AB)							27.19	28.99	5.99	25.17
#B38(62)	original color	128	128	64	52.28	-9.63	34.45	22.96	29.36	-8.94	35.48
#A20(122)	less dE	255	255	64	97.29	-20.34	84.11	9.63	45.33	-4.59	30.08
	2nd print							10.76	44.95	-1.77	34.02
mapped color #6	image 1 (HC)							12.14	45.26	-4.09	26.22
	image 2 (AB)							21.45	36.41	-10.9	20.08

general images called *HoneyComb* (*HC*) and *Abstract* (*AB*). Fig. 7 presented the input (i.e., digital design) and output (i.e., printed result) from both content-images objects. These two sample objects composing of the matched colors were arranged in different through the content of images. In the HC-texture, each color is individually separated, but for the AB-texture, all color is mixed.

We ran a small psychological experiment with two observers to measure their visual perception of the printed images uder two conditions; 1) blending colors together (*AB*), and 2) separating each color clearly (*HC*). We asked whether the color of the printed image is similar to the input image using Two-alternative forced choice (2AFC) method. Though the experimental results, in the HC image, where each color is separated clearly, our mapped colors can represent those desired by the user at an 80% success rate of the mapped colors (5 out of 6 = 83.33%), which can be matched under controlled conditions (only color number 6 was not matched). For AB image the observers felt that all colors were harmonious. They did not feel that any color was mismatched from seeing the entire image and not including each color reference on the right of the image.

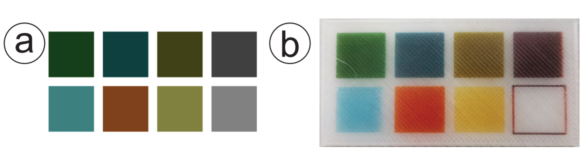

Figure 6. *Results of experiment 2; (a) original input design, and (b) the photos took from the real 3D fabricated object.*

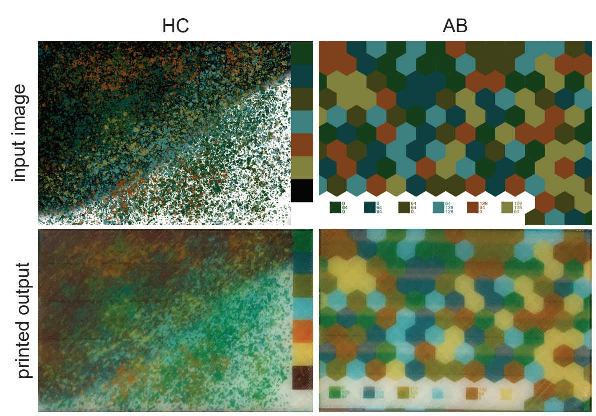

Figure 7. *Results of experiment 3: (top) input images, and (bottom) 3D printed output from our proposed method.*

Discussion

From the results, we believe that the color model of an inkjet FDM color 3D printing is not in normally distributed. The direction and distribution of each color is irregular. This indicates that the color each have an individual rendering pattern for a mapping and matching profile. Thus, it is difficult to estimate the mapping pattern or generate the formal color model. Therefore, we created a new color profile by manually reproducing each color and mapping every possible color pair to determine the closest color on the basis of the least color difference value. This method can be rendered in lieu of the original printing colors.

From an experiment, we noticed the perceived color different of the mapped color number 5 from the Experiment 2 and 3. In the *HC* image the observers perceived a similar color to the input color. However, in the reprinted sample of Experiment 2 and in the reference colors in the AB image, the observers perceived the different colors clearly. Although the original color input was the same and the ΔE of both colors was close, but there were the conflicts in the perception results. This means that the content of the image has influence on the acceptable of the color perception.

Interestingly, in experiment 2, we confirmed that the reference black and white in FDM color 3D printing is shifted to the gray color instead of the pure black and white colors. Our consideration is that the color of a translucent filament (Fig. 8) should affect the absorption and reflection of the color from the ink. Moreover, we believe that the ink characteristic, the system for link and transfer texture data into the multi-layer structure for printing (RIP system), and content of the image texture, affects to the color perception.

Our work starts with the manually mapping color as we would like to know the direction and distribution of the color model before integrating for the whole gamut. We have reprocess in the larger scale for improve more colors in the future.

Conclusion

We proposed the method to reproduce the color of 3D object in an inkjet FDM color 3D printing. We investigated the color profile that bridge the gap between digital design and actual printed results by comparing the selected color difference between each represented color that could replace original printed color that closed to user desired. Finally, we verify our exploration by 3D printing the mapped color and conduct the color measurement compared with target colors. We founded that the mapped color can represent to the user desired better than the original printed color with around 80%.

Acknowledgments

A part of this study was under a memorandum of understanding (MOU) of the collaborative research project between Chulalongkorn University and Kanagawa Institute of Technology in 2020-2021. We give thanks to Asst. Prof. Suchitra Sueeprasan, Department of Imaging and Printing Technology, Chulalongkorn University of Thailand for her useful advice on color measurement methods. We also give thanks to two exchanged students from her lab, Sirapat Thitasirimanirada and Punnada Wisetsing, for preparing the input data using in Experiment 1.

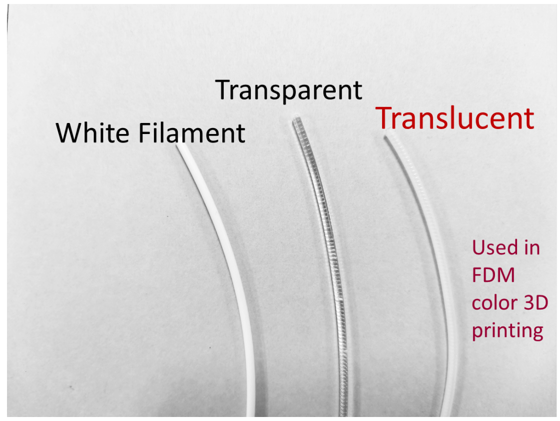

Figure 8. *Translucent filament is a cause that the perceived color is drop from the input.*

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