Color Uniformity Improvement for an Inkjet Color 3D Printing System

Pei-Li SUN, Yu-Ping SIE; Graduate Institute of Color and Illumination Technology, National Taiwan University of Science and Technology; Taipei, TAIWAN

Abstract

A hybrid 3D color dithering method is proposed to improve image quality of a 3D color inkjet printing system. The method extends the conventional two-dimensional ordered dithering into 4 layers with 3-axis optimization. It results in smoother color mixing in multiple viewing directions by stacking and distributing the color ink-drop evenly in each of 4×4×4 voxels in a 3D print. 3D color error diffusion also applies to texture-rich areas to enhance its sharpness. A method to measure and compensate the color differences of a 3D print in different surface directions also is proposed to improve the consistency of color across different faces of the print.

Introduction

The development of 3D printing technology has accelerated over the past few years. However, only few commercial products are capable of generating full-color 3D prints with acceptable quality. Z-Corporation develops powder-bed with color inkjet 3D printing technology over last 2 two decades. However, it needs complex post-processes to enhance the color quality and toughness of a 3D print. To speed the printing process and to reduce the use of powder, photopolymer color inkjet systems are under development. 3D error diffusion method was recommended for the color inkjet system to enhance its image quality. Lou and Stucki [1] reviewed the technologies of clustered monochrome 3D dithering and adapted error diffusion which quantizes 3D model into frame elements. Brunton Arikan and Urban [2] a serious of algorithm to deal with voxelization, color management and error diffusion based halftoning for the surface of a 3D print. However, the error diffusion method would generate unpleasant worm patterns in uniform color areas. To improve the uniformity, the present study proposes a hybrid 3D dithering method to reduce the annoying patterns and to preserve the sharpness of image pattern at the same time. On the other hand, we tested a commercial color printer and found the colors are not consistent across different printing orientations. Therefore, we developed a multi-directional test target to evaluate the color variations previously. And now we have developed a vector-based method to compensate the color differences.

The purpose of this study is to develop several methods to improve the consistency of color across different printing directions and to improve the uniformity of dithering patterns in 3D color halftoning. To this end, we need:

- A color dithering algorithm to determine tonal values for each voxel of the input 3D model.
- A 3D test target for evaluating color variations across different orientations.
- An algorithm for estimating surface normal of any local area on a 3D model.
- A method for color compensation based on the above estimation.

The methods will be introduced in the following sections.

Optimization of dispersed 3D threshold matrix for 3D ordered dithering

Method

To apply ordered dithering for 3D printing to generate halftoned voxels, a special design threshold matrix is needed. Although conventional dispersed threshold matrix works well in one direction of the 3D surfaces, it is hard to avoid obvious dots and stripe patterns occurred particular tones on the other sides of the 3D print. The classic method of dispersed-dot dithering is Bayer matrix, which was designed to reduce low frequency components of Fourier transform. [3] The 4-by-4 version of Bayer matrix is as Table 1, which works well in 2D printing. However, if we apply it to x-y axis for 3D printing, only Face z (i.e., the normal of surface towards z axis) will show uniform dotted patterns. It will generates significant strip-like patterns on Face x and y which can be seen in Figure 1. To avoid visible patterns in 3D halftoning, we designed a process which is similar to simulated annealing (SA) technique [4] to optimize the dispersed 3D threshold matrix.

To optimize the threshold matrix, we designed a process to search the better matrix from original one and to evaluate the uniformity of 3D grayscale patches. To generate a new matrix, there is a function to shift one of the layer in particular face in several steps. We set some parameters to evaluate the uniformity resulted from the new threshold matrix. We simulated 3 viewing directions x, y and z-axes of a 3D cube orthogonally, and the projected image of each viewing direction were calculated by assuming equal transparency for each layers.

Table 1: The 4-by-4 version of Bayer matrix

0	8	2	10
12	4	14	6
3	11	1	9
15	7	13	5

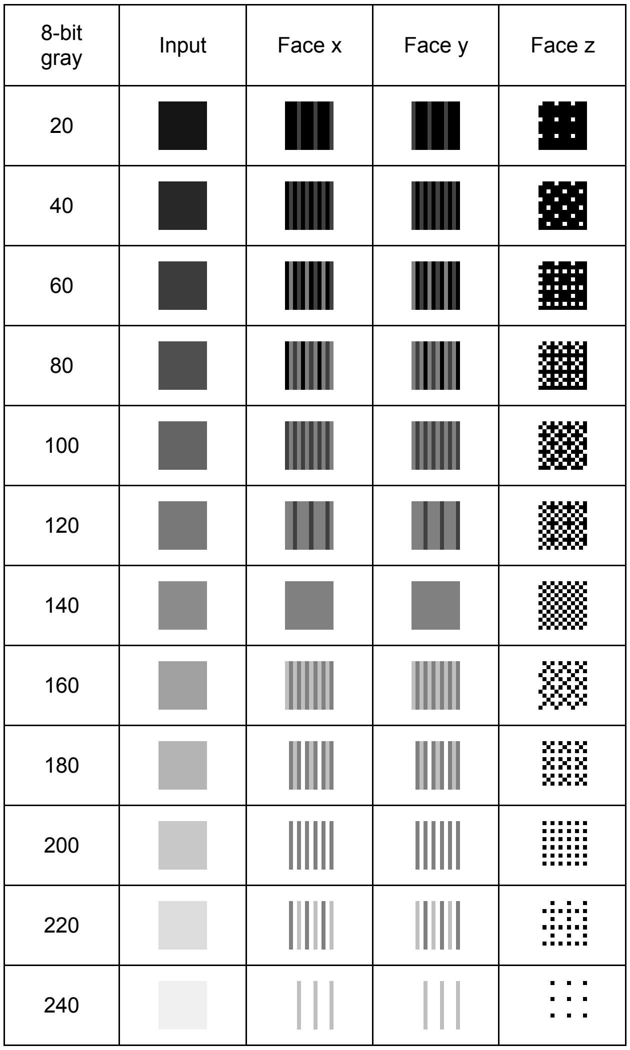

Figure 1. X,Y, Z direction views of halftoned gray-level patterns generated by the thresholding matrix shown in Table 1.

The first metric to judge the uniformity of projected image of halftoned voxels is standard deviation, which describes how the uniformity of projected image is generally. Lower standard deviation indicates the uniformity of the halftoned voxels are good. In addition, human vision is also sensitive to high contrast spots, horizontal and vertical stripes, so there are other metrics to detect the visual artifacts. In this case, we use Gaussian filter to simulate spatial vision. For human response of dots and stripes, Laplacian filter and Sobel filters including vertical, horizontal, 45 degrees and -45 degrees gradient were used, which give the metrics about where or not the dots and stripes are visible. The reason of establishing the rules for these metrics (indices) is to derive the optimized matrix for the best visual uniformity.

Results

For preparing the optimization, the former purposed 3D dispersed threshold matrix [5] which was designed based on Bayer threshold matrix with black/white cancellation was used as original input threshold matrix. The matrix is shown in Table 2 and three-directional halftoned patterns are simulated as Figure 2. Compared to Figure 1, the improvement is quite significant.

In the optimization, the program processes 3-step layer-shifting and search 3 times. At first, the total indices of the uniformity metrics includes standard deviation of projected image and the absolute mean of Laplacian and Sobel filtered images, when the uniformity indices of new 3D threshold matrix are better than the former one, the new matrix will replace the old one and use its index values as the new reference score. The optimal 3D threshold matrix was shifted for 9 steps from the original 3D threshold matrix.

Table 2: Bayer-based 3D dithering threshold matrix

Layer 1				Layer 2				Layer 3				Layer 4			
0	48	6	54	40	24	46	30	3	51	5	53	43	27	45	29
32	16	38	22	8	56	14	62	35	19	37	21	11	59	13	61
4	52	2	50	44	28	42	26	7	55	1	49	47	31	41	25
36	20	34	18	12	60	10	58	39	23	33	17	15	63	9	57

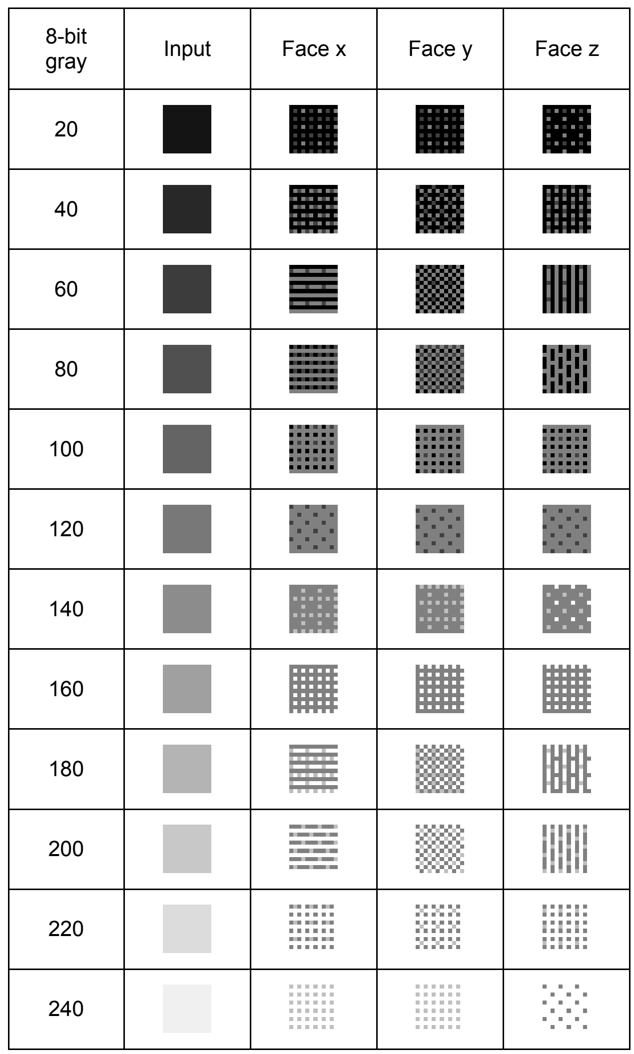

Figure 2. X,Y, Z direction views of halftoned gray-level patterns generated by the thresholding matrix shown in Table 2.

To evaluate the visual effect of 3D halftoning, we projected halftoned grayscale tone 4×4×4 voxels from 3 viewing directions x, y and z and composite 4 layers into image in each viewing direction. Then we have 3 projected images of face x, y and z. Comparing grayscale patches halftoned by optimized 3D threshold matrix with original 3D threshold matrix, we can find that although the arrangement of the original one looks organized, the optimized one reduced high contrast dots and stripes and looks soft. It proved that the method to optimize 3D threshold matrix can achieve the goal to improve uniformity by simulated annealing algorithm and the metrics to judge uniformity.

Table 3: Optimized 3D dithering threshold matrix

Layer 1				Layer 2				Layer 3				Layer 4			
16	45	54	0	52	19	46	21	12	55	5	49	40	9	29	36
56	6	37	30	28	59	61	11	39	31	22	47	3	34	14	58
8	51	1	53	44	13	25	32	20	41	50	4	48	23	42	17
35	27	18	43	7	38	10	62	60	2	33	26	24	63	57	15

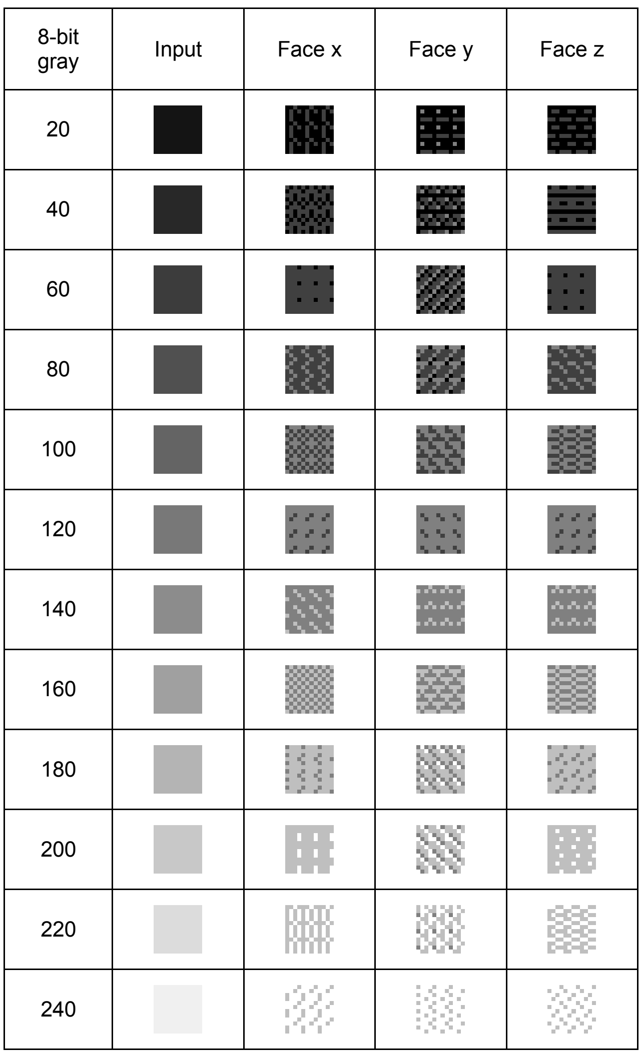

Figure 3. X,Y, Z direction views of halftoned gray-level patterns generated by the optimized 3D thresholding matrix shown in Table 3.

Apply the optimal threshold matrix to a CMYKW color 3D printer

As previously mentioned, the proposed method is going to be used for a (UV-curable) photopolymer color inkjet system. In this system, white tonal is essential. White color cannot be generated by mixing CMY, CMYK or RGB [6]. One solution is to use CMYW as primary colors. However, black won't be dark enough by mixing these four color primaries. If five primary is allowed, CMYKW is recommended as it can maximize the color gamut of the 3D print.

Figure 4 illustrates the framework of applying the optimal thresholding matrix to a CMYKW color 3D printer. The input is a RGB color voxel from a 2D slice of an input 3D model. To correct the color, ICC-based color management can be applied to transfer the voxel colors from standard RGB space to the printer's RGB space. Equation 1 to 4 is used for RGB to CMYKW color conversion. 'W' represents white ink which is essential for photopolymer-based color 3D printing. The conversion will ensure that a gray input-voxel will be output only by black and white inks. Next step is color quantization. It has done by first calculating color ratio of the five primaries of the input color, and then normalized the ratio to 64 in KMCYW order for the thresholding. The reason of using KMCYW order is that the matrix was optimized for grayscale patterns initially. As human vision is more sensitive to luminance channel compared to chromatic channels, the CMYKW signal must be sorted based on their lightness order. For example, if (C,M,Y,K,W)=(0, 6, 30, 20, 18) represents the number of sub-voxel of each inkjet color for one 4×4×4 cube, lightness ascending order, K20-M6-Y30-W18, must be used for applying the 3D thresholding matrix to assign 1-bit ink signals to the 4×4×4 space.

$$\begin{bmatrix} C' \\ M' \\ Y' \end{bmatrix} = \begin{bmatrix} 1-R \\ 1-G \\ 1-B \end{bmatrix} \tag{1}$$

$$K = \min(C, M, Y) \tag{2}$$

$$W = \min(R, G, B) \tag{3}$$

$$\begin{bmatrix} C \\ M \\ Y \end{bmatrix} = \begin{bmatrix} C'-K \\ Y'-K \\ M'-K \end{bmatrix} \tag{4}$$

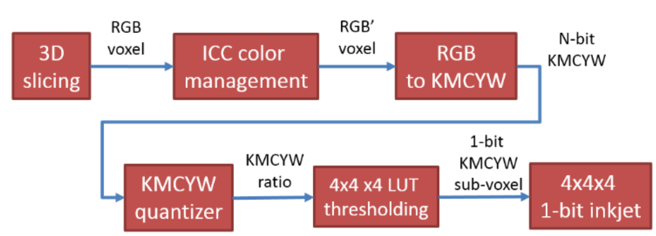

Figure 4. Flowchart of the proposed 3D ordered dithering method.

The ICC color management can be done by using a device-link profile [7] with 3D interpolation. The device-link profile is a combination of two profiles: source and destination profile. The source profile could be a sRGB profile for standard display, or a camera profile for a color 3D scanning system. The destination profile is generated by measuring color patches printed by the 3D printer. Due to Equation 1 to 4 are used, each RGB combination will map to only one set of CMYKW combination. In other word, we can use printer RGB to represent limited set of the CMYKW colors. The following process can be applied to generate the LAB-to-RGB 3D LUT (loop-up-table) for the destination profile for its ICC-B2A data transform.

- Print RGB test target, the color of the 3D printer are composed by CMYKW voxels. The relation between RGB and the CMYKW is referred to Equation 1 to 4.
- Measure the colorimetric values of the printed target.
- A 3D color LUT for printer RGB to LAB conversion (referring to A2B transform) can be generated.
- Invert the 3D color LUT for LAB to printer RGB conversion (referring to B2A transform).
- The device-link profile can be generated by the source profile and the B2A color LUT.

Figure 5, 6 and 7 simulate color halftoned patterns in three rendering directions (x,y,z) using the Table 1, 2 and 3 matrix, respectively. As can be seen, all of them cannot display text clearly. Figure 5 which uses conventionally Bayer's matrix show stripes in Face x and Face y, but not in Face z (i.e., x-y plane). Both Figure 6 and 7 provide uniform dotted patterns across the three directions. Figure 7 which uses the optimal matrix is slightly better than the Figure 6.

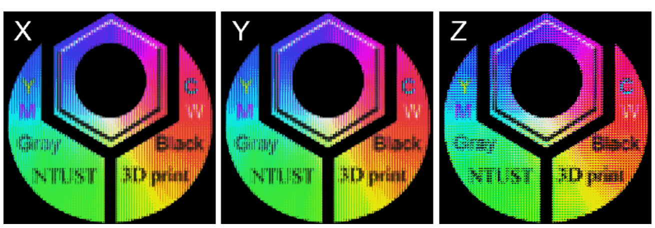

Figure 5. Color 3D ordered dithering using the Table 1 matrix.

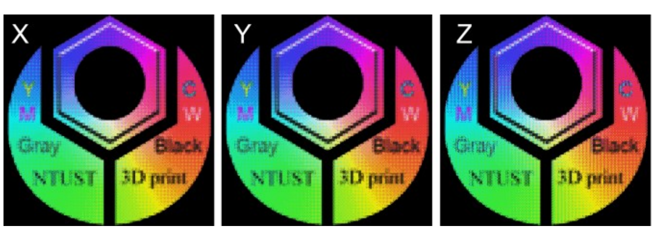

Figure 6. Color 3D ordered dithering using the Table 2 matrix.

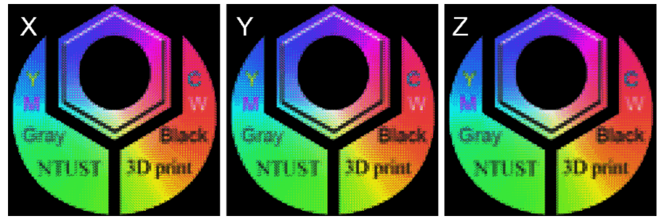

Figure 7. Color 3D ordered dithering using the Table 3 matrix. (optimized)

Error diffusion

The previous method can generate uniform dotted patterns, but the spatial resolution will be reduced significantly. To maintain the resolution, 3D error diffusion method can be considered. Figure 8 illustrates the flowchart of the proposed 3D error diffusion method. The process also applies Equation 1 to 4 for RGB to CMYKW conversion. But it only scales the color ratio to 4. To improve the smoothness, the process also involves 4 layer printing towards the surface of the printed 3D object. The threshold matrix here is [0 1 2 3]. K-M-C-Y-W order all should be applied for better visual effects. The resulted 1-bit KMCYM sub-voxel signals will be used for RGB color estimation. The RGB errors compared to the input will be distributed to surround RGB voxels for compensating the color differences. Figure 9 simulates its image appearance in the three printing directions. As can be seen, the texts are much sharper than the ordered dithering method.

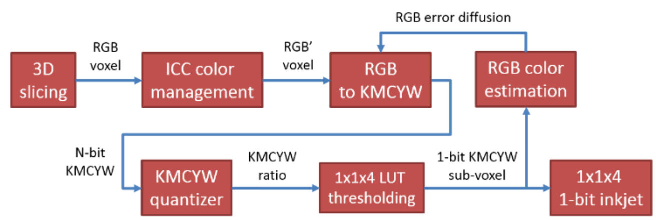

Figure 8. Flowchart of the proposed 3D error diffusion method.

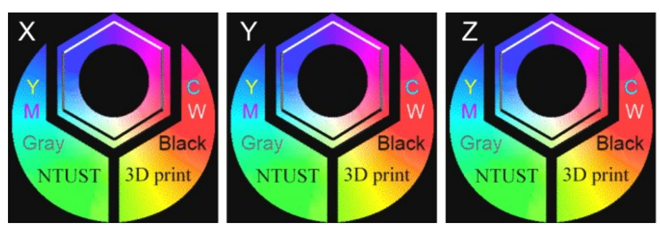

Figure 9. 3D halftoned images using proposed color 3D error diffusion method.

A hybrid approach

The error diffusion method would generate unpleasant worm patterns in uniform color areas. To improve the uniformity, the present study proposes a hybrid 3D dithering method to reduce the annoying patterns and to preserve the sharpness of image pattern at the same time. Figure 10 shows the flowchart of the decision of choosing either ordered dithering or error diffusing for each 4x4x4 input voxels. The variations can be estimated by averaging the standard deviation of the 4x4x4 cube for each of the RGB channel.

Alternatively, a high-pass filter can be used to extract non-flat image content (e.g., text or lines) in the cube. Figure 11 shows a simulation of the hybrid-halftoned images in three printing directions. As can be seen, the images have uniform dotted patterns in their uniform areas and have very sharp edges in the non-uniform areas such as texts and lines.

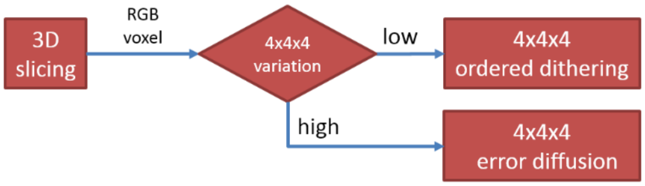

Figure 10. Flowchart of the decision of choosing either ordered dithering or error diffusing for each 4x4x4 input voxels.

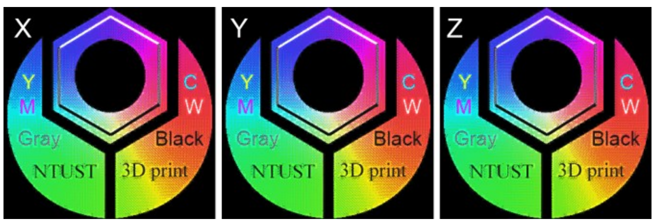

Figure 11. 3D halftoned images generated by the proposed hybrid method.

A multi-directional color target

Design

A Multi-directional Color Target was designed to estimate color performance of surfaces in 26 directions (Figure 12). The target is combined with 13 pieces in different surface directions, like a puzzle, and each piece has two sides with several color patches on it. The biggest piece, which is printed on top and bottom, has 225 color patches for general color management. The 225 colors contents 6-level RGB and 9-level grayscale. The other pieces have 4 or 14 color patches and can represent the color differences in various surface normals. 4 pieces of 4-color patches are consist of CMYK colors, and rotated to evaluate the color performance on 8 corner directions. 8 pieces of 14-color patches are consist of CMYKRGB colors and half lightened CMYKRGB colors, and rotated to evaluate the color performance on 16 different directions, including front, back, right, left, and other 45 degrees oblique angle directions. Each color patch has 9×9 mm, and the corner of every patches has 4.5 mm. The target can be measured by X-Rite i1 Publish after combined 26 pieces in a correct position. In our model, the target is designed as a puzzle. Each piece has a unique shape to avoid mistakes in assembling [8].

Results

3D Systems Projet 460 Plus Color 3D printer. The printer support RGB 3-channel color input and have CMY inkjet heads to print full-color 3D model. All of the glue-jet and the material of model which is gypsum-like powder are made by 3D Systems. The color inkjet heads are provided by HP. After we measured the spectral reflectance of every color patches of the target using i1iO automatically, we pack the color patches into 26 groups, which represent different surface direction.

To analyze color difference on different surface normal, we regard the color patches on top (+z direction) surface as the standard color and compare the color differences with the other color patches. The mean and maximum color difference across different orientations is up to 6.71 and 22 ΔE_{00} [9] respectively, which is noticible by human eyes (referring to Figure 14). Color differences on different surface normal are mostly depended on the differences of lightness, and happened in black color which is mixed with all of the cyan, magenta and yellow inks (Figure 15). It also may cause by many sources, such as moving direction of inkjet, diffuse velocity of ink, and force of gravity. Considering the effect on different surface normal, color reproduction of 3D printing model can be improved.

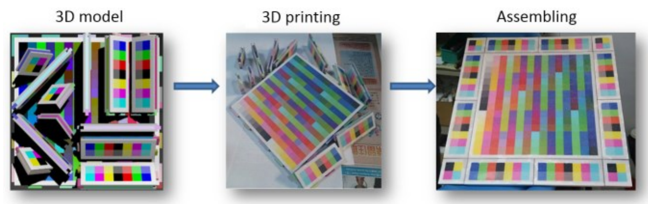

Figure 12. Left: the arrangement of each pieces in modeling software Autodesk 3DsMax. Each piece is arranged to face particular direction. Middle: printed sample after post-curing process. Right: the printed sample after puzzle-like assembling.

Figure 13. Measure the puzzle-like test target using an X-rite i1 spectrophotometer in either manual way (left) or automatic way (right). Note that the inverse side also contains the same number of color patches.

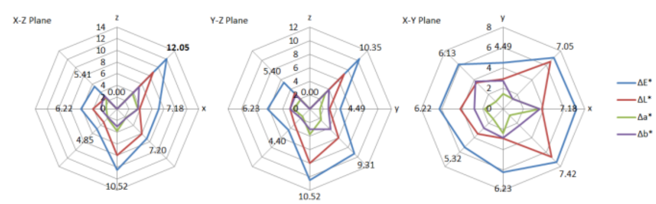

Figure 14: Average color differences on each surface normal and average differences on L, a* and b*.*

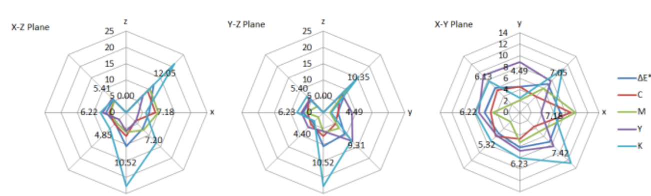

Figure 15. Average color differences on each surface normal and color differences on CMYK colors.

Color compensation

Since we have the information of color variations of a 3D print across different printing direction, it is possible to compensation the color differences for improving the color consistency of the print. To compensate the color, it is necessary to know the surface normal of each triangle mesh. If the 3D data are stored as point clouds, their surface normals can be judged directly. One solution is to evaluate the surface normals from the 3D sliced voxelized data.

Estimating surface normal

To apply color correction for color difference of surface normal, the information of surface normal is important. However, computation cost of estimating surface normals of each voxels of a 3D model is high. We propose a rapid surface normal estimation method which is used in the sliced voxels. We made a 1D filter with weighting value in Equation 5. In this array, the center position will map to the processed layer, and the others are former and next layers. Apply the filters to layers forward x, y and z directions, we can get the information about how the neighbor voxels exist in former and next layer. With 3 sets of filtered value along x, y and z directions, we can estimate partial x, y and z vectors of each voxel. Though properly normalizing, the surface normal can be estimated. Figure 16 shows the result of rapid surface normal estimation on ball voxels in opposite color space (red-green, yellow-blue and black-white represent x, y and z axis of surface normal).

$$h = \begin{bmatrix} -1 & -3 & -5 & 0 & 5 & 3 & 1 \end{bmatrix}^T \quad (5)$$

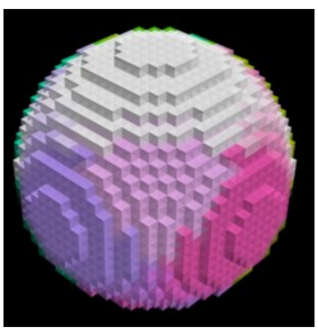

Figure 16. An example of the proposed rapid surface normal estimation. The normal vectors are represented by lightness (z-axis) and opponent colors (x- and y-axis).

Conclusions

A hybrid 3D color dithering method is proposed to improve image quality of a 3D color inkjet printing system. The method extends the conventional two-dimensional ordered dithering into 4 layers with 3-axis optimization. It results in smoother color mixing in multiple viewing directions by stacking and distributing the color ink-drop evenly in each of 4×4×4 voxels in a 3D print. 3D color error diffusion also applies to texture-rich areas to enhance its sharpness. A method to measure and compensate the color differences of a 3D print in different surface directions also is proposed to improve the consistency of color across different faces of the print.

The UV-curing photopolymer inks are highly translucent [10]. To predict the color in different thickness, the characterization model for the translucent colors [11] should be studied next.

References

[1] Q. Lou and P. Stucki, "Fundamentals of 3D Halftoning," Electronic Publishing, Artistic Imaging, and Digital Typography, pp 224-239, RIDT'98 St. Malo, France, March 30 – April 3, 1998 Proceedings

[2] A. Brunton, C.A. Arikan and P. Urban, " Pushing the Limits of 3D Color Printing:Error Diffusion with Translucent Materials," technical report of Fraunhofer Institute for Computer Graphics Research IGD

[3] M.l Kriss, " Handbook of Digital Imaging Vol 2: Image Display and Reproduction," pp 952, WILEY

[4] Kirkpatrick, S.; Gelatt Jr, C. D.; Vecchi, M. P. (1983). "Optimization by Simulated Annealing". Science 220 (4598): 671–680

[5] Yu-Ping Sie, Pei-Li Sun (2015, June). Developing Multi-Layer Halftoning Algorithm of Color 3D Printing, Photonics Festival in Taiwan, Taipei, Taiwan

[6] Pei-Li Sun, Yuping Sie (2015, Feb) Color Dithering Methods for LEGO-like 3D Printing, Electronic Imaging 2015, SanFrancisco, USA.

[7] ICC, Specification ICC.1:2010. Image technology colour management — Architecture, profile format, and data structure, International Color Consortium.

[8] Yu-Ping Sie, Pei-Li Sun and Yun-Cian Su (2015, May). Developing Test Targets for Color Management in Full Color Three-dimensional Printing, AIC 2015, Tokyo, Japan.

[9] CIE Central Bureau, Vienna 2012. Colorimetry – Part6: CIEDE2000 colour-difference formula, CIE DS 014-6/E:2012

[10] Arikan, Can Ates; Brunton, Alan; Tanksale, Tejas Madan; Urban, Philipp, Color-Managed 3D-Printing with highly Translucent Printing Materials, Proc. of SPIE, 93980S.

[11] D.R. Wyble and R.S. Berns, " A critical review of spectral models applied to binary color printing," Color Research & Application, Volume 25, Issue 1, pages 4–19, February 2000

Acknowledgements

This work was partially supported by Ministry of Science and Technology (MOST104-2218-E-011-003).

Author Biography

Pei-Li Sun was awarded his Ph.D. at the Colour & Imaging Institute of the University of Derby in England, 2002. He is currently an assistant professor at Graduate Institute of Color and Illumination Technology in National Taiwan University of Science and Technology. His current research interests are image quality enhancement, appearance measurement and color vision. He is a member of SID, IS&T and CIE.

Yu-Ping Sie is currently a graduate student at National Taiwan University of Science and Technology.