Effect of Aqueous Adhesives on Color Performance of Paper-based 3D Printing

Zhaohui Yu, Guangxue Chen*, Chen Chen, Liuxi He

State Key Laboratory of Pulp and Paper Engineering, South China University of Technology, Guangzhou, Guangdong, 510640, China

***Abstract* — The paper aims to study the effect of aqueous adhesives on color performance of paper-based 3D printing. Sixty-four color cubes of 3D Color Puzzle were printed in Matrix 300A, whose *L*a*b** color values on six faces were measured before and after all the faces of the 64 cubes were coated with aqueous adhesives. Before the coating operation, the color differences between the upper and the lower surfaces on the 64 cubes were all below 2.84 *NBS*, and the color differences between two of four side faces were all below 2.88 *NBS*. However, the color differences between the front and the side were large, with a maximum of up to 32.53 *NBS*; After the coating operation, the average color difference between the upper and the lower surfaces of the 64 color cubes was 1.60 *NBS*, and the maximum was 4.92 *NBS*, the average color difference between two of four side faces was 1.97 *NBS*, and the maximum was 4.61 *NBS*. However, the color differences between the front and the side were greatly reduced, with an average value of 4.02 *NBS*, and a maximum value of 6.03 *NBS*. Moreover, the average color difference between the front on 64 color cubes before and after the coating operation was 2.59 *NBS*, with a maximum of 3.57 *NBS*. Relative to the effect on the side, aqueous adhesives had a minimal effect on the front. The coating operation could reduce the gap of the color difference between the front and the side, thereby ensuring a more realistic 3D color reproduction and color accuracy control.**

Keywords - Paper-based; 3D Printing; Color Cube; Aqueous Adhesives; Color Difference

I. INTRODUCTION

Introduced in the late 1980s, when Charles Hull patented a technique called stereolithography and developed the first practical 3D printer called the stereolithgraphy apparatus [1], 3D printing technology produces physical 3D objects through rapid layer-by-layer fabrication. Many materials can be used as the raw material for 3D printing, such as plastic, metal, ceramic, and even edible objects [2]. 3D printing technology began to take shape in the 1990s and entered its early stages at the time. With the development of modern science and the extensive introduction of 3D printing technology, an increasing number of companies and businesses have expressed interest in 3D printing and have begun to enter the market in recent years. As a result, a variety of 3D printers for consumers [3] have been released.

Four dominant 3D printing technologies exist, namely, stereolithgraphy, selective laser sintering, fused deposition modeling, and powder/binder fusion [4, 5, 6]. These four processes begin with a 3D digital model that is sliced into layers by using software and then printed layer by layer by using a 3D printer. Although the four technologies have been developed to achieve good accuracy, their color performances are unsatisfactory, especially in gradient colors. Given that 3D printers extend from upmarket to the public, an increasing number of users want to produce final objects with accurate colors. Therefore, the ability to control the color properties of 3D printers has become increasingly important. Being able to measure and predict 3D-printed colors is also an important part of the 3D color printing workflow. The paper-based 3D printer of Matrix 300A used in this paper can print full-color objects with the use of paper that can produce color faithfully [7]. With the process of laying down, cutting, and adhering successive pieces of paper to produce objects, this method can produce many complicated objects, including hollow crafts, thereby performing well in reproducing cultural relics and topographic maps.

As in inkjet color printing, accurate color reproduction models for 3D color printers should be developed. Related studies have been conducted in recent years. Maja Stanic et al. attempted to assess the lightfastness of 3D color prints after accelerated exposure to a xenon-arc light source, but little effort had been made in terms of colorimetric characterization of 3D printers partly because of a lack of availability [8]. With the use of the Yule-Nielsen Modified Neugebauer model and Principal Component Analysis on the spectral absorptance of printed samples, Brittany D. Hensley et al. predicted the colors of 3D-printed objects from RGB color values by using the Zcorp Spectrum Z-510 Printer [9]. Carinna Parraman et al. proposed a wax post-processing method, in which the 3D printed artifact was infiltrated with paraffin wax as part of the finishing process, thereby increasing the chroma, hue, and deepening of colors [10]. On the basis of the principle of paper-based 3D printing and the mechanism of color reproduction on paper, the current paper aims to study the effect of aqueous adhesives on color performance of paper-based 3D printing by coating a layer of aqueous adhesives on the surface of 3D color cubes. Paper-based 3D printing process includes the printing of color layers and the construction of color cubes. The colors on the side of the color cube result from physical accumulation, while the colors on the front of the color cube are the printed colors, similar to the colors on a poster. The color characteristic of inkjet printing is mature, and will therefore not be stated[11, 12]. This paper mainly explores how the colors on the side of the color cube can be reproduced accurately to be the same as the colors on the front of the color cube.

II. METHODS FOR ARRANGING AND PRINTING COLOR

A. *Methods for Generating the Color Cube*

The COLORCUBE of 3D Color Puzzle selected in this research is a unique combination of fun, art, and science, and one of its proposed higher functions is the ability to represent the gamut/color capacity of various reproductive technologies [13]. It would be useful that creating COLORCUBE of print, digital camera, or monitor for researchers to improve the technology and for consumers to compare the performance of competing products. In this paper, the test color space mapped by a 4 × 4 × 4 model totals 64 distinct colors, as shown in Fig. (1). The 64 color cubes with a size of 30 mm × 30 mm × 30 mm are designed and produced in 3D Studio Max.

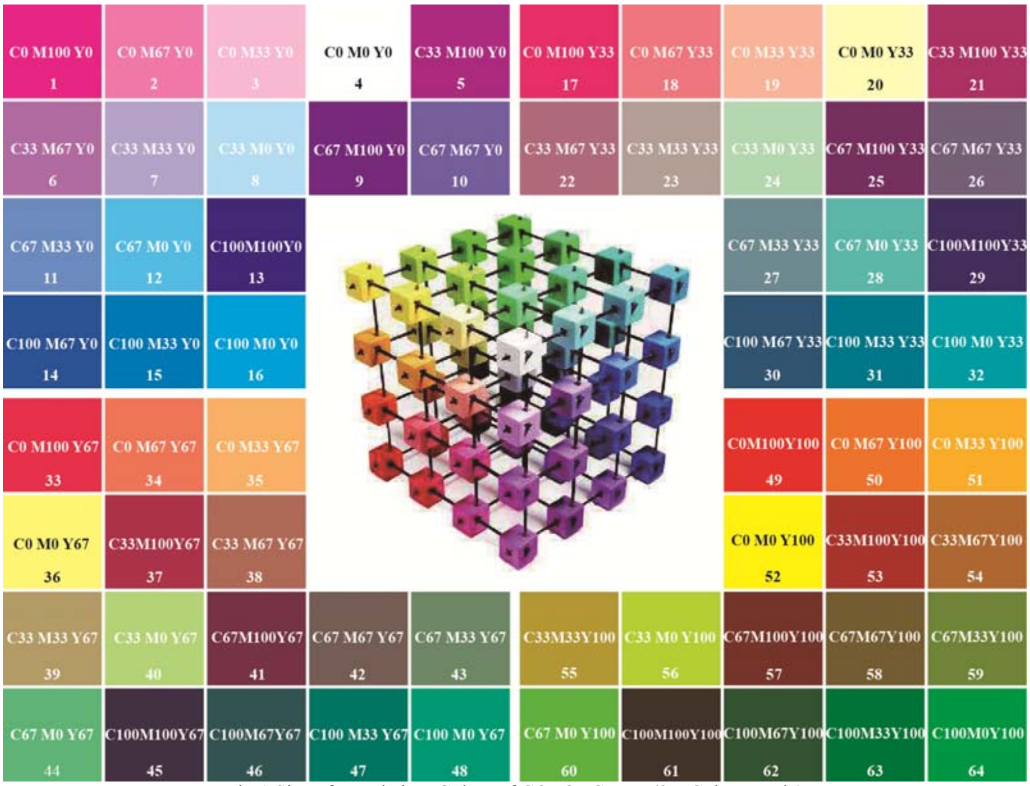

Fig.1 Sixty-four Distinct Colors of COLORCUBE (3D Color Puzzle)

B. *Methods for 3D Printing and Coating Operation*

Coming from MCOR technologies, Matrix 300A is a kind of paper-based 3D printer, whose main consumables are A4 paper and blade. The printer contains two systems: an Epson 310N printer provided the color system, and a matrix printer responsible for 3D building. The A4 paper is CHUANMEI electrostatic copy paper with a basis weight of 80 g/m2, a thickness of 103.2 µm, a whiteness of 94% ISO, and a size of 210 mm × 297 mm.

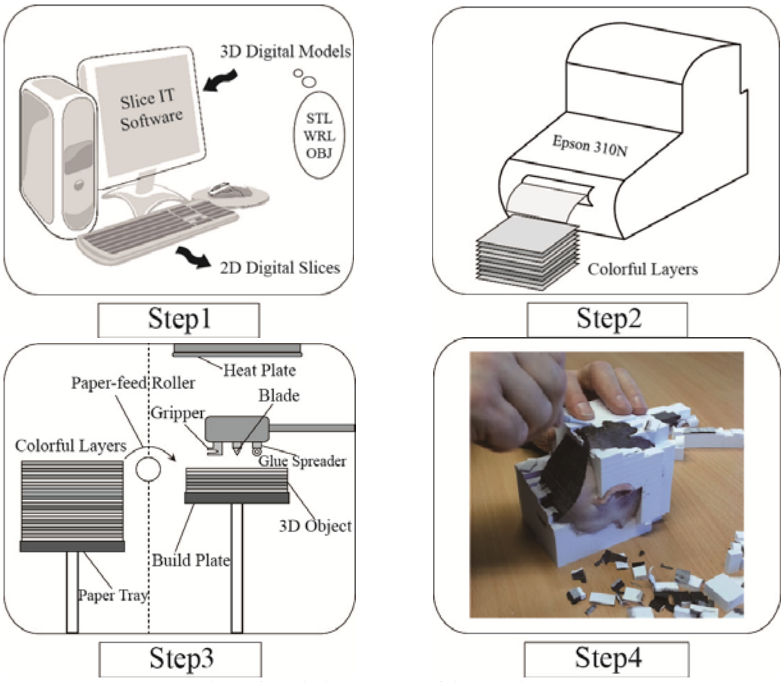

Fig.2 The Printing Process of the Matrix 300A

The printing process begins with a 3D digital model in STL (Stereo Lithography), WRL (VRML2, Virtual Reality Modeling Language) or OBJ format (Wavefront Object Files). The 64 color cubes are sliced into 2D cross sections by using the Slice IT software (Fig. (2), Step1). These 2D sections are printed on double sides of the papers to produce many colorful layers in the "no color management mode" in Epson 310N (Fig. (2), Step2). Each layer edge is printed with bar codes that are used to determine the sequence of the layers. These colorful layers will be sent to the matrix printer to build the 3D object. Before the building, a piece of blank paper is affixed to the build plate, and a glue spreader is then used to uniformly coat aqueous adhesive on the blank paper. Then, the colorful layers will be laid on the paper tray, and the top layer will be pulled onto the built plate by paper-feed roller and gripper. As shown in Fig. (2), Step3, the build plate will rise to press the heat plate at the top of the build space, thereby smoothing the top layer and ensure that it will adhere firmly to the blank paper at a high temperature. When the build plate is lowered, the blade will cut the top layer into the contour of the corresponding 2D cross section, and a glue spreader will uniformly coat aqueous adhesive on the top layer. Afterwards, the next colorful layer will be sent in, and the process will be repeated until all the necessary layers have been sent in to complete the 3D object. When the matrix printer stops working, a large paper cube will be produced, as shown in Fig. (2), Step4. After the excess portion is removed, the 64 color cubes will be obtained and have a similar appearance as the 3D digital model.

The printer colors only the surface of the object, the excess and the interior portions are all blank, thereby ensuring low cost and high efficiency. Each cube has two faces whose colors are the printed colors on the sheet-fed, both faces are called "the front" of the color cube. Four faces have colors that result from physical accumulation of many colorful layers, the four faces are called "the side" of the color cube.

To explore the method of producing accurate colors for 3D printing, the COLORCUBE of the 64 cubes is coated with a PAVDA aqueous adhesive by using a soft brush. The COLORCUBE is then placed in a drying oven to dry for 2 minutes at 50 °C.

C. Procedures for measuring and evaluating printed color differences

Given that each color cube has two kinds of color, we uniformly measured 9 times of $L^*a^*b^*$ color values for each face of the 64 samples with X-Rite 530 optical density meter before the coating operation. The average values are taken as the $L^*a^*b^*$ color values of each face. When the 64 samples were fully dry after the coating, the $L^*a^*b^*$ color values for each face of the 64 samples were measured 9 times, and their averages were obtained as the $L^*a^*b^*$ color values for each face. To scientifically evaluate the color difference, the following indicators were calculated:

(a) No special coating instrument for 3D objects exists. Thus, artificial coating operation of aqueous adhesive was conducted in this research. Obviously, guaranteeing the uniform coating on the surface of samples can be difficult for the artificial operation. Whether the coating uniformity had a great effect on the color values should be verified. Thus, the standard deviation of 9-time values was calculated by the following:

$$S = \sqrt{\frac{1}{N}\sum_{i=1}^{N}\left(X_i - \mu\right)^2} \tag{1}$$

where μ represents the average value of 9-time values for L^*, a^* and b^* values.

(b) Before the coating operation, the color difference between the upper and the lower surfaces was calculated by using Eq. (2) and represented by E_b. With any one of the four side faces selected as the standard face, E_{b1}, E_{b2} and E_{b3} were the color differences between other three side faces and the standard face.

After the coating operation, the color difference between the upper and the lower surfaces was calculated by using Eq. (2) and represented by E_a. With any one of the four side faces selected as the standard face, E_{a1}, E_{a2} and E_{a3} were the color differences between the other three side faces and the standard face.

$$E = \sqrt{\left(\Delta L^*\right)^2 + \left(\Delta a^*\right)^2 + \left(\Delta b^*\right)^2} \tag{2}$$

where ΔL^*, Δa^* and Δb^* are the D-values between two of L^*, a^* and b^* values that were compared.

(c) The average value of the upper and the lower surfaces is taken as the front value, and the average value of the four side faces is taken as the side value of the 64 samples. The color difference between the front and the side before the coating operation was presented by E_1, the color difference between the front and the side after the coating operation was presented by E_2. To evaluate the effect of aqueous adhesive coating on the colors of the 64 samples, the color differences before coating and after coating should be calculated, as represented by E_3.

III. DISCUSSIONS ON PRINTED COLOR DIFFERENCES

A. Scientific Analysis for the Coating Operation of Aqueous Adhesive

The standard deviation of 9 $L^*a^*b^*$ color values on each face of the 64 samples represents the fluctuation of the measured data, and its size can also show the effect of coating uniformity on the $L^*a^*b^*$ color values as the result of the uniform selection of 9 measuring points on each face, thereby helping to prove whether the coating operation is scientific. This experiment used 64 samples, each sample had 6 faces, and each face had 9 sets of $L^*a^*b^*$ color values. The standard deviation of 9 measured data for L^*, a^*, and b^* was calculated, and 2304 standard deviation values could be obtained before and after the coating operation. Before the coating, the average of the 1152 standard deviation values was 0.26 *NBS*, and the maximum value was 0.65 *NBS*. After the coating, the average of the 1152 standard deviation values was 0.40 *NBS*, and the maximum value was 0.69 *NBS*. The result indicated high manufacturing accuracy of paper-based 3D printing and that the coating uniformity of aqueous adhesives had little effect on $L^*a^*b^*$ color values of the samples. Thereby, the results obtained by artificial coating was scientific to some extent mainly because the good permeability, volatilization, and transparency of aqueous adhesive allowed the adhesive to infiltrate through the paper capillary [14], volatilize quickly under high temperature, and have good transparency after drying. The covering abilities of different coating thicknesses were the same.

B. Color Difference before Coating

Fig. (3) shows the color differences of the 64 samples before the coating. Observation indicates that the color differences between the upper and the lower surfaces (E_b) were all below 2.84 *NBS*, and the color differences between two of the four side faces (E_{b1}, E_{b2} and E_{b3}) were all below 2.88 *NBS*. These values were both within the quality requirement range of inkjet printing, therefore, the colors of the upper and the lower surfaces on each sample were thought to be the same, and the colors of the four side faces on each sample were the same [15]. This result was due to the principle of paper-based 3D printing. The upper and the lower surfaces were both paper surfaces, as in actual application. Therefore, their colors were also the common printed color even if double-sided printing was used, while the side faces were accumulated by multiple layers of paper, and their colors were formed by the infiltration of ink and physical accumulation. Therefore, the colors of the upper and the lower faces on each sample were the same, and the colors of the four side faces were the same as well.

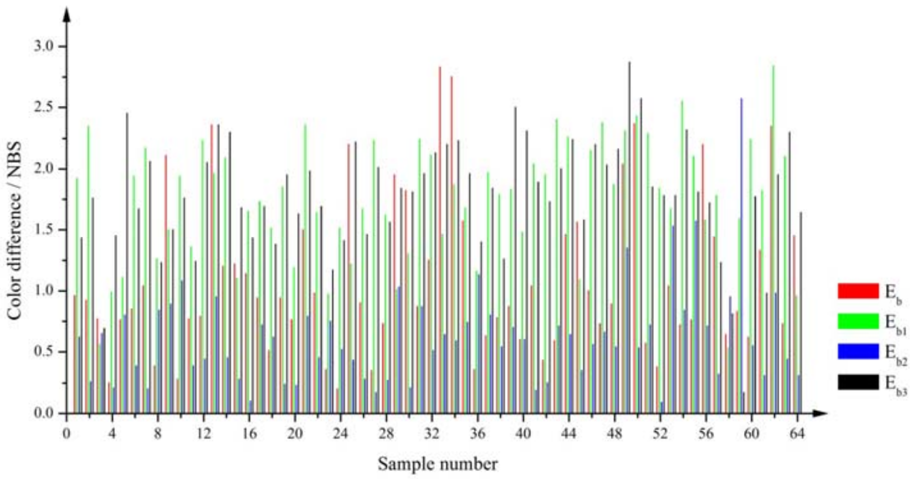

Fig.3 Color Differences before the Coating of Aqueous Adhesives

C. Color Difference after Coating

Fig. (4) shows the color differences of the 64 samples after the coating. The average value of the 64 color differences between the upper and the lower surfaces of the 64 samples (E_a) was 1.60 *NBS*, 90.6 percent of the 64 color differences was below 3 *NBS*, where 6 color differences were above 3 *NBS*, and the maximum value was 4.92 *NBS*. The average value of 192 color differences between two of the four side faces of the 64 samples (E_{a1}, E_{a2} and E_{a3}) was 1.97 *NBS*, 83.9 percent of the 192 color differences was below 3 *NBS*, where there were 31 color differences above 3 *NBS* and the maximum value was 4.61 *NBS*. The color difference after the coating was slightly higher than that before the coating, mainly because the artificial coating weight could not be absolute and the ink infiltration on paper surface was different from that on the side face. However, only a few color differences were above 3 *NBS*, and the color differences were all below 5 *NBS*. In terms of 3D printing, these color differences would have little influence on 3D visual observation. Thus, the result after the coating was consistent with that before the coating, the colors of the upper and the lower faces on each sample were the same, and the colors of the four side faces were the same as well.

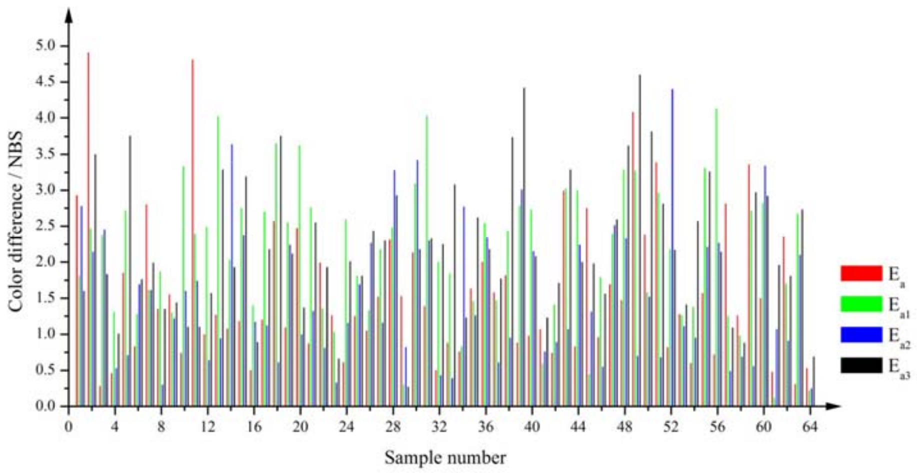

Fig.4 Color Differences after the Coating of Aqueous Adhesives

D. Comparison of Color Difference before and after Coating

Fig. (5) shows the color differences between the front and the side of the 64 samples. Before the coating, majority of the 64 color differences (E_1) were all above 5 *NBS*, and the maximum value was up to 32.53 *NBS*, where 4 values were below 5 *NBS* (sample 4: 3.22 *NBS*, sample 8: 3.18 *NBS*, sample 12: 4.62 *NBS*, sample 23: 4.87 *NBS*). On the basis of this result, the colors on the front and the side could be considered two completely different colors. This phenomenon was mainly caused by three cases: (a) A fundamental difference existed between the paper front and the paper side. The front was formed through a series of papermaking process, such as pressing, coating, and light pressure, while the side was cut by blade. These different methods resulted in two different optical effects on the front and the side. (b) Two different functions between paper and ink would occur. Spreading effect occurred mainly on the front, thereby ensuring that the pigment could spread evenly. However, infiltration occurred mainly on the side, and infiltration uniformity was poor because of the crisscross fiber in the paper [16]. (c) Blank paper was present on the side because ink infiltration could not be absolute despite the double-sided printing. The light that enters people's eyes while looking at the paper is composed of the light reflected from the color ink and the light reflected from the blank paper, which would inevitably lead to the difference between the front and the side.

An observation of E_2 shows that the color differences between the front and the side of the 64 samples reduced greatly. The average value of the 64 color differences was 4.02 *NBS*, where only 5 values were above 5 *NBS* (sample 13: 5.15 *NBS*, sample 24: 6.03 *NBS*, sample 33: 5.33 *NBS*, sample 42: 5.26 *NBS*, sample 51: 5.70 *NBS*) and 7 values were below 3 *NBS* (sample 26: 2.18 *NBS*, sample 29: 2.67 *NBS*, sample 35: 2.18 *NBS*, sample 39: 1.91 *NBS*, sample 54: 2.18 *NBS*, sample 56: 2.97 *NBS*, sample 57: 1.55 *NBS*). The result could lead to a small color difference between the sample front and the sample side as a consequence of the further filtration of ink with the wetting effect of aqueous adhesives, thereby improving the filtration uniformity and reducing the blank portions on the paper side.

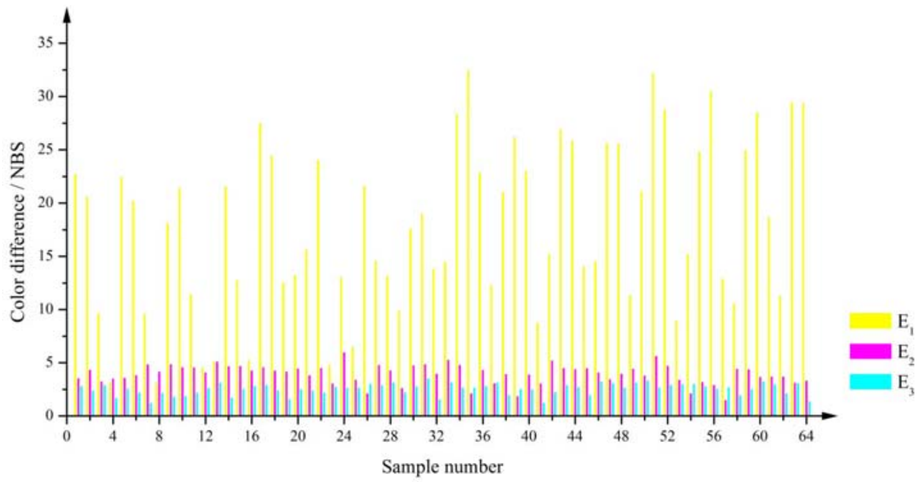

Fig.5 Color Differences between Front and Side of the 64 Samples

E_3 shows that the color difference between the front before and after the coating was small. The average value of the 64 color differences was 2.59 *NBS*, where 15 values were above 3 *NBS* and the maximum value was 3.57 *NBS*. This result indicated that the influence of coating on the sample front was small enough. The colors on the sample front before and after the coating were the same.

Color characterization for printer is greatly necessary to improve the printed color effect, but the paper-based 3D printing process is divided into two steps of inkjet printing and 3D model building. Inkjet printing can achieve WYSIWYG through color characterization [11]. However, some uncontrollable factors arise during the 3D building process, such as paper selection, model design, model location and model angel. Moreover, the color representation of the cube side is a complicated optical and physical process [16, 17], thereby presenting many difficulties in the color characterization of paper-based 3D printer. This paper found that coating aqueous adhesives on the surfaces of color cubes would obviously reduce the color differences between the front and the side, with the front color remaining unchanged. The coating operation improved the color accuracy of the 3D paper model significantly. Therefore, the 3D color model obtained by the paper-based 3D printer could be post-processed by coating aqueous adhesives on the surface to improve color accuracy.

IV. CONCLUSIONS

This paper presented a method of accurately reproducing the colors on the side of a paper cube just to be the same as the colors on the front. PANDA aqueous adhesives coated on the surface of the paper cube could improve the filtration uniformity and the ink filtration on the paper side without harmful gas volatilization. Therefore, the coating method could not change the color on the front, but reduce the color difference between the colors on the front and on the side. Paper-based 3D printing technology lays down, cuts, adheres and stacks up successive pieces of A4 paper to build a 3D model. This approach introduces the 3D printing technology of full color printing with the use of paper's excellent color rendering. This scheme provides a good technical reference to solve the color problem for paper-based 3D printing. However, some difficult problems in paper-based 3D printing need to be overcome, for example, the substrate of A4 paper limits printing accuracy because of the thickness of a piece of A4 paper, and achieving a smooth curved surface is difficult. 3D color printing is still a continuously developing technology. Therefore, we should not only carry out an intensive study of the existing technology, but also maximize its existing advantages to extract more possibilities and further the development of 3D color printing.

CONFLICT OF INTEREST

The authors confirm that the article content has no conflicts of interest.

REFERENCES

[1] H. Charles, “Plastic prototypes from CAD data without tooling”, Modern Casting, vol. 78, pp. 38, 1988.
[2] B. Albouy, Y. Lucas, S. Treuillet, “3D Modeling from uncalibrated Color Images for a Complete Wound Assessment Tool”, Conf Proc IEEE Eng Med Biol Soc, pp. 3323-3326, 2007.
[3] Zolfagharifard, Ellie, “3D printing has helped fuel a new generation of DIY producers”, Engineer, pp. 37-38, 2012.
[4] S. Agrawal, J. P. Antunes, E. Theron, et al., “Physical modeling of catchment area by rapid prototyping using GIS data”, Rapid Prototyping Journal, vol. 12, pp. 78-85, 2006.
[5] C. R. Ruiz, R. Cabredo, L. J. Monteverde, et al., “Combining Shape and Color for Retrieval of 3D Models”, Fifth International Joint Conference on INC, IMS and IDC, pp. 1295-1300, 2009.
[6] T. Kuwata, S. Matsubara, M. Suzuki, “3D color Doppler of monoamniotic twin cord entanglement”, Archives of Gynecology and Obstetrics, vol. 281, pp. 973-974, 2010.
[7] Z. W. Zhu, G. X. Chen, Q. F. Chen, “Influence of Ink-jet paper surface characteristics on color reproduction”, Packaging Engineering, vol. 33, pp. 109-112, 2012.
[8] M. Stanic, B. Lozo, D. G. Svetec, “Colorimetric properties and stability of 3D prints”, Rapid Prototyping Journal, vol. 18, pp. 120-128, 2012.
[9] B. D. Hensley, J. A. Ferwerda, “Colorimetric characterization of a 3D printer with a spectral model”, Color & Imaging Conference, pp. 160-166, 2013.
[10] A. C. Parraman, P. Walters, B. Reid, et al., “Specifying colour and maintaining colour accuracy for 3D printing”, Proceedings of SPIE-The International Society for Optical Engineering, vol. 6805, pp. 68050L- 68050L-8, 2008.
[11] L. L. Chen, G. X. Chen, R. X. Xu, “Research on Color Characterization for Inkjet Printer Based on the Spectral Murray-Davies and YNSN Model”, JOURNAL OF INFORMATION & COMPUTATIONAL SCIENCE, vol. 11, pp. 5621-5630, 2014.
[12] C. C. Jin, H. L. Shen, S. J. Shao, et al., “Color Characterization Method for Colorful Inkjet Printers”, ACTA OPTICA SINICA, vol. 31, pp. 123001-1 - 123001-5, 2011.
[13] Davies, W. Kenneth, Color cube model: EP, US 5634795 A. 1997.
[14] Y. Zhang, R. A. Li, Y. F. Cao, “Pore analysis of Inkjet paper surface based on image technology”, Packaging Engineering, vol. 36, pp. 129-133, 2015.
[15] W. H. Liu, G. S. Hu, Q. Wang, *Graphic Arts Chromatology*, 1st ed., Chemical Industry Press: Beijing, 2004.
[16] Y. Y. Liu, J. H. Qian, “Study of print quality based on ink transfer and penetration”, Packaging Engineering, vol. 33, pp. 117-120, 2012.
[17] L. Y. Hao, J. H. Qian, “Research of bonding effect of ink and paper during contact printing”, Packaging Engineering, vol.33, pp. 92-94, 2012.