A colour image reproduction framework for 3D colour printing

DOI:
10.1117/12.2247467

Document Version
Accepted author manuscript

Citation for published version (APA):
Xiao, K., Sohiab, A., Sun , P., Yates, J., Li, C., & Wuerger, S. (2016). A colour image reproduction framework for 3D colour printing. In *SPIE Proceedings - Advanced laser manufacturing technology* (Vol. 10153). (Advanced Laser Manufacturing Technology). https://doi.org/10.1117/12.2247467

Published in:
SPIE Proceedings - Advanced laser manufacturing technology

A colour image reproduction framework for 3D colour printing

Kaida Xiao*[a,b], Ali Sohiab[c], Pei-li Sun[d], Julian M Yates[c], Changjun Li[a], Sophie Wuerger[b]
[a]University of Science and Technology Liaoning, Anshan, China, 100041;
[b]Department of Psychological Science, University of Liverpool, Liverpool, United Kingdom;
[c]School of Dentistry, University of Manchester, United Kingdom;
[d]National Taiwan University of Science and Technology, Taipei, Taiwan;

ABSTRACT

In this paper, the current technologies in full colour 3D printing technology were introduced. A framework of colour image reproduction process for 3D colour printing is proposed. A special focus was put on colour management for 3D printed objects. Two approaches, colorimetric colour reproduction and spectral based colour reproduction are proposed in order to faithfully reproduce colours in 3D objects. Two key studies, colour reproduction for soft tissue prostheses and colour uniformity correction across different orientations are described subsequently. Results are clear shown that applying proposed colour image reproduction framework, performance of colour reproduction can be significantly enhanced. With post colour corrections, a further improvement in colour process are achieved for 3D printed objects.

Keywords: 3D colour printing, colour image reproduction, colour management, colour uniformity in 3D printing

1. INTRODUCTION

In the last decade, additive manufacturing technique, including 3D printing has developed dramatically. Colour 3D printing has also evolved to produce full spectrum coloured solid objects utilising a range of materials. With the evolution of various 3D imaging techniques, another milestone has been achieved, allowing accurate acquisition and transformation of target object geometric data into 3D digital models. By combining the 3D image capture and printing techniques, there is huge potential to achieve "What You See Is What You Get" processing. More importantly, it has the ability to directly interconnect with advanced manufacturing techniques, allowing customized production with excellent accuracy resulting in savings of both time and costs [1]. Those technologies have been extensively utilised in rapid prototyping, successfully applied in medical sciences, and is gaining popularity in multidisciplinary applications [2, 3].

When 3D objects were designed and produced using 3D printing system, both colour preference and colour fidelity are highly desired and could affect overall quality of product significantly. However, colour reproduction for 3D printing an object is still a huge challenge for colour and imaging science now day. This is not only due to the complicity of 3D printing processing, but also under developed image processing system. To printing 3D objects in full colour spectrum, different technologies have been developed and utilisted in different 3D printing systems. This includes Colour FDM and Polyjey ™ from Stratasys Inc. , 3DP™ from Z Corp Inc. and 3D system Inc., MultiJet Fusion from Hewett Packard Inc.p and SDL processing from Mcor Inc. For 3DP™, MultiJet Fusion and SDL processing, colour inkjet technology is developed to print CMY(K) ink on printing materials with single colour. For colour FDM and PolyJet technology, coloured materials are used and melted together in order to generate full colours. Comparing with conventional colour printing technology, colour control for 3D printing system is much more complicate in general. Without a specific protocol, 3D objects can often be produced with poor reliability, accuracy and quality.

Conventional colour image reproduction techniques have been developed for more than 80 years based on the CIE colorimetry standardized by the International Committee on Illumination [4]. Standard methods to conduct colour measurement, to predict colour appearance under various viewing conditions and to evaluate performance of colour reproduction were defined. The system performs very well in transforming colour images from one digital media to

Advanced Laser Manufacturing Technology, edited by Bingheng Lu, Huaming Wang, Proc. of SPIE
Vol. 10153, 1015318 · © 2016 SPIE · CCC code: 0277-786X/16/$18 · doi: 10.1117/12.2247467

another under various viewing conditions. However, the colour image reproduction was designed for colours in flat images rather than 3D objects. Application of conventional colour image reproduction technique for 3D printing is not as straightforward since image processing between 3D image devices have much more complicated working processes. Furthermore, a full-colour 3D model contains a significant amount of data and a trade off between the complexity of a model and accuracy of the model prediction has to be taken into consideration as well.

Therefore, accurate colour management processes are not only essential, but also needs to run in conjunction with the specific 3D manufacturing processes used. The aim of this study is to develop a colour image reproduction framework for 3D colour printing processing. A five stage-framework is introduced. Two key studies are introduced for different applications and performance of colour reproduction for each key study was evaluated.

2. COLOUR IMAGE REPRODUCTION FRAMEWORK FOR 3D PRINTING

In this paper, a 3D colour image reproduction framework was developed based on the steps shown in Figure 1. The first step involved 3D image acquisition. 3D image data can be obtained using a variety of different techniques. In majority of cases the data is obtained using a 3D scanning device or 3D camera system. 3D image can be created by image 3d CAD design software. Although the image acquisition and 3D reconstruction techniques are different using these methods, the outputs produced are similar in terms of the data produced and they all produce 3D mesh data and colour information for the scanned geometry. Raw 3D scan data often cannot be directly used for 3D printing due to errors in geometry and colour. Geometrical errors mostly consist of bad edges, intersecting triangles, non-manifold geometry, holes, overhangs etc. Therefore, 3D image edit needs to be conducted for the 3D model. In the third step, this mainly involved colour management of the 2D colour image from original RGB to printer RGB for each pixel in order to preserve colour appearance for 3D objects. Once the colour management was finalised, as the fourth step, 3D surface texture mapping was applied to map the newly generated colour image onto the manipulated 3D model. The final step was 3D colour printing to produce the 3D model using the 3D printing system.

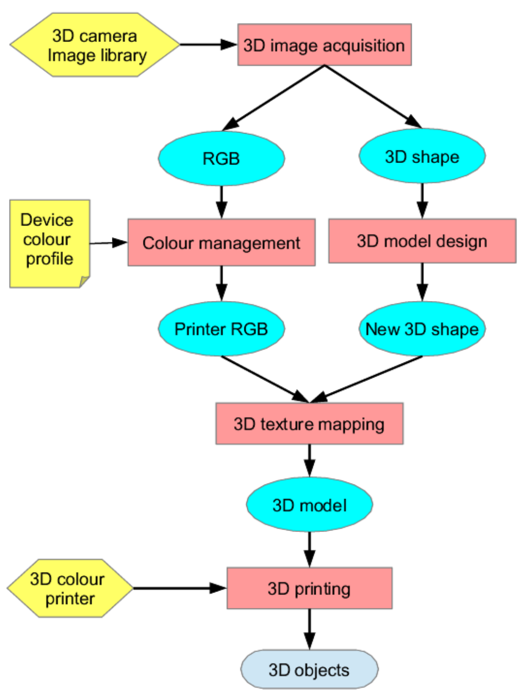

Figure1. Frame work of colour image reproduction for 3D colour printing

3. COLOUR MANAGEMENT

For colour management for 3D printed objects, two approaches can be employed. One is the conventional colour reproduction system based on CIE colorimetry, the other is spectral based colour reproduction system based on spectral reflectance of objects. For the former method, as can be seen that the workflow in Figure 2, includes five components based upon the CIE specification system, i.e. (1) forward characterisation model, (2) forward colour appearance model, (3)gamut mapping, (4) reverse colour appearance model, and (5) reverse characterisation model. To apply this approach, colour appearance of 3D object can be reproduced cross different illumination and different media. However, when a complicate viewing condition is encountered, a spectral based colour reproduction can give a better performance. For this approach, three steps needs to be performed: (1) forward spectral characterisation to transform device RGB to spectral reflectance, (2) spectral gamut mapping to maximally map spectral data from one media to another media, (3) reverse spectral characterisation to transform spectral data to printer RGB (CMYK) for 3D printing.

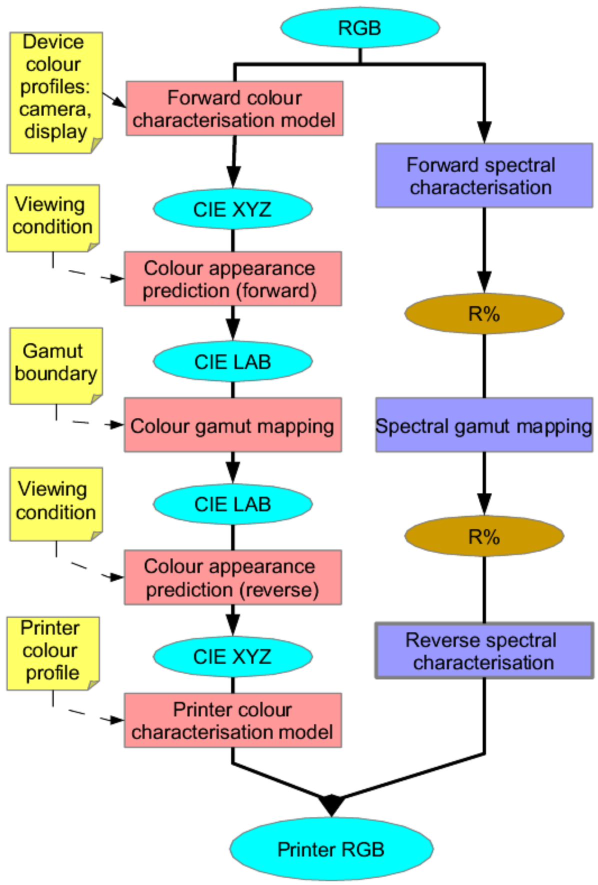

Figure 2. Colour management for 3D colour printing

Although a spectral based colour reproduction system has huge potential to be used in 3D colour printing industry, the system and algorithm for spectral based approach is much more complicated and under developed than the colorimetric approach. Moreover, due to complexity of 3D printing system, a large system error for colour reproduction is difficult to avoid. A post corrections need to be performed and those corrections based on colorimetric values are much desired than that based on spectral data. Therefore, at this stage, the colorimetric approach probably the most widely used technology to provide general practical and improvement in 3D printing industry.

4. KEY STUDIES

4.1 Colour reproduction for soft tissue prostheses

For soft tissue prostheses application, a 3D colour image reproduction system was developed based on the six steps, in order to reproduce a 3D printed prosthesis of a human subject. The first step was 3D image acquisition, which captured a 3D image of the subject face using a 3dMD photogrammetry facial system (3dMD, Atlanta, GA, USA). The second step was to create a 3D image design for the captured subject face in order to fix bad edge, make it to solid model and eventually transform them to the 3D printer format. Simultaneously, in the third step, colour management was undertaken to convert the colour of facial image from camera RGB to printer RGB for each pixel using specified camera and printer colour profiles respectively. Then, as the fourth step, 3D texture mapping was conducted to map the printer facial image onto the manipulated 3D facial model using Materialis Magics software (Materialise, Leuven, Belgium). The next step is 3D colour printing to produce the 3D model in a starch powder using the Zcorp Z510 3D printing system (3D Systems Inc., Rock Hill, SC, USA). The final step is post processing, which includes infiltration with a medical grade silicone polymer.

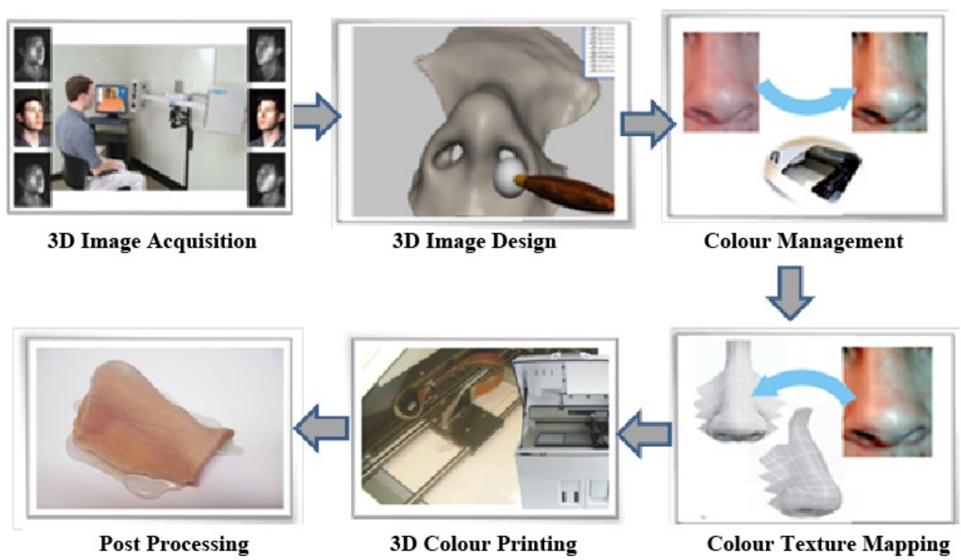

Figure 3. 3D colour image reproduction for soft tissue prostheses

Colour Management

To transform camera RGB to printer RGB, both a camera colour profile and a printer colour profile were developed. A digital Macbeth ColorCheckerDC chart (X-Rite Inc.,Grand Rapids, MI,USA) was used to provide 240 training colours (see figure 4a). The 2D colour chart was converted to a 3D model with dimensions of 200 (l)×150 (w)×3 (h) and printed using a Z Corp Z510 colour printer. Subsequently, the XYZ values for each training colour produced in the printed colour chart were obtained by colour measurement using a Minolta CM-2600d spectrophotometer (Konica Minolta Inc., Tokyo, Japan). During the measurement, a viewing geometry of di:8 (diffuse illumination, 8-degree viewing) was used, with the specular component included and the aperture size set to 3mm. The illuminant was set to CIE standard D65 to approximate skin colour under daylight conditions and the CIE 1931 standard observer was used.

Based on printer RGB and CIE XYZ tristimulus values for those 240 training colour, the printer colour profile was developed using a third-order polynomial regression. For the camera colour profile, the same chart was captured using the 3dMD camera and the camera RGB was identified for those 240 training colours. Then, based on camera RGB and CIE XYZ tristimulus values, the camera colour profile was developed using a second-order polynomial regression. Eventually, for each pixel of image, their camera RGB was first transformed to CIE XYZ tristimulus values and then transform back into printer RGB.

To evaluate the colour reproduction system for a human face, a colour test chart was designed using 14 predetermined human skin colours, including four Caucasian, two Chinese, two Asian, four African, and two Caribbean skin shades (see figure 4b) [5]. A 3D colour chart was generated using the Z Corp Z510 colour printer, with physical dimensions of 200 (l) by 150 (w) and 3 (h) mm. After post processing, this was considered as the original chart.

Through the application of the colour management and reproduction system, the new colour chart was printed and referenced as the reproduction testing chart (figure 4b). Colour in both original and reproduction testing charts were measured using a Konica Minolta cm-2600d spectrophotometer, respectively. Colour differences between the original chart and the reproduction chart, for 14 test colours, under CIE illuminant D65 were calculated using the CIELAB colour difference formula [15]. Note that D65 is a widely used illuminant for colour matching in application of soft tissue prosthesis and therefore was used here as a reference illuminant. Results shown that average colour difference for those skin colours was largely reduced from 20.8 ΔE^*ab (without colour management) to approximately 4.5 ΔE^*ab (with proposed colour management process). It clearly indicates that a significant improvement in colour reproduction can be achieved using 3D colour image reproduction systems [6]. For its successful application in the production of facial soft tissue prostheses, an acceptable colour difference for the 3D printed objects is approximately 3–4 ΔE^*ab.

(a) Training (b) Testing

Figure 4. 3D models of training and testing chart

4.2 Colour uniformity correction across different orientations

Due to some unwanted mechinical and physical effects, a powder-binder based colour 3D printer normally cannot provide consitstant colour for all sides of a 3D print. To minimize the colour variations across different orientations, a multi-directional colour management system has been developed for evaluating and compensating the colour differences [7]. It includes the measurement of a multi-directional colour target, estimating the multi-directional colour differences and conpensating the differences in the input 3D model. They will be introducd next:

A multi-directional colour target

A Multi-directional Colour Target was designed to estimate the same colour patches in 26 surface directions (Figure 5). The target is just like a puzzle. The patented target combines with 13 pieces, and each piece has two sides with several colour patches on it. The biggest piece, which is printed on top and bottom, has 225 colour patches for general ICC-based colour management. The other pieces have 4 or 14 colour patches and can represent the colour differences in various surface normals. 4 pieces of 4-colour patches are consist of CMYK colours for 8 corner directions. 8 pieces of 14-colour patches are consist of 100% CMYKRGB colours and 50% CMYKRGB colours for 16 different directions, including front, back, right, left, and other 45 degrees oblique angle directions. Each colour 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 (Figure 6). Each piece has a unique shape to avoid mistakes in assembling [8].

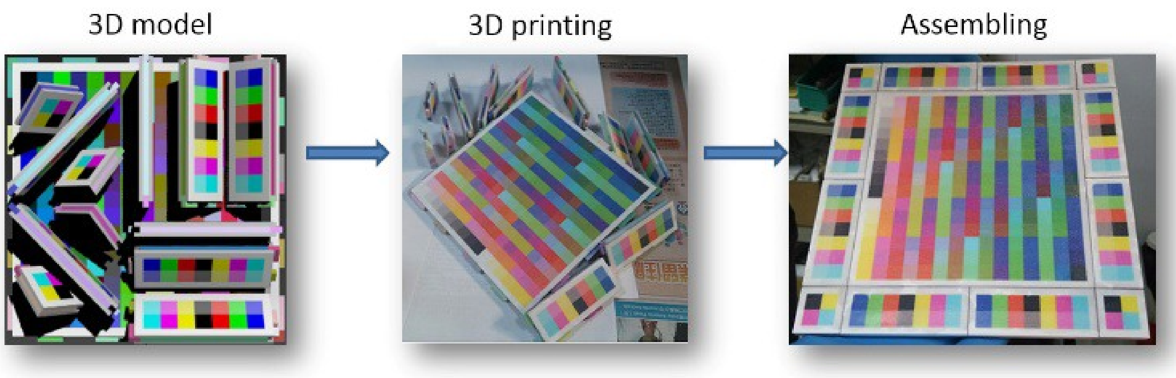

Figure 5. Left: the arrangement of each pieces in Autodesk 3DsMax modeling software. Each piece is arranged to face particular direction. Middle: printed sample after post-curing process. Right: the printed sample after puzzle-like assembling.

Figure 6. 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 colour patches.

Estimation the multi-directional colour differences

A powder-binder based 3D Systems ProJet 460 Plus Colour 3D printer was used in this study. The printer support RGB 3-channel colour input and have CMY inkjet heads to print full-colour 3D model. After we measured the spectral reflectance of every colour patches of the target using i1iO automatically, and plot the colour in CIELAB space, we found the colour variations is roughly a linear scaling between white point and the LAB values measured on the top surface (z-direction). The mean and maximum colour difference across different orientations is up to 6.71 and 22 ΔE00 [9] respectively, which is noticeable by human eyes (Figure 7).

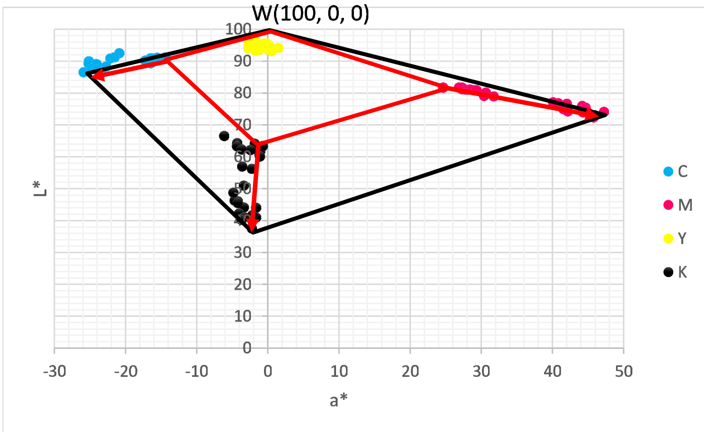

Figure7. The colour variations of 100% CMYK patches are roughly a linear scaling between white point and the z-directional LAB values.

Multi-directional colour compensation

Based on the above measurement, a 2D LUT which stores the scaling factors for each of the 26 orientations is generated before the compensation. A multi-directional colour-compensation is done by first converting the RGB value of each voxel to LAB space (using sRGB standard as an example). Afterward, calculating the surface normal of each voxel, and then correcting the LAB value by interpolating the scaling factor of the 2D LUT in LAB space. Finally, the ICC-based B2A 3D colour LUT is used to convert the corrected LAB values into RGB space. Our test on the ProJet 460 Plus showed that the colour variations can be reduced to a half by applying the above approach.

5. CONCLUSION

Full colour 3D printing technology has developed dramatically and accurate colour reproduction for 3D objects is highly desired. To faithfully reproduce colour in 3D printed objects, a colour image reproduction framework is developed as a give stage processing. Within the framework, colour management processing is specified. When the framework is applied into 3D printing facial soft tissue prostheses, colour quality of printed prostheses has been significant improved. With proposed post correction processing, an improvement of 3D colour uniformity has been achieved for 3D printed objects. Results all shown that colour image reproduction framework is essential and effective for 3D colour image printing.

ACKNOWLEDGMENTS

This project was partially supported by the EPSRC grant EP/K040057/1 and Verivide Limited, UK, National Natural Science Foundation of China Grant (61575090).

REFERENCES

[1] Stopp S, Wolff T, Irlinger F, Lueth T., " A new method for printer calibration and contour accuracy manufacturing with 3D-print technology," Rapid Prototyp J. 14(3),167–1726 (2008).

[2] van Noort R., " The future of dental devices is digital," Dental Materials. 28, 3–12 (2011).

[3] Mavili M E, Canter HI, Saglam-Aydinatay B, Kamaci S, Kocadereli I., " Use of three-dimensional medical modeling methods for precise planning of orthognathic surgery," J Craniofac Surg.. 18(4),740-7 (2007).

[4] CIE S 014-3/E:2011 (ISO 11664-3:2012), Colorimetry - Part 3: CIE Tristimulus Values, STANDARD by Commission Internationale de L'Eclairage, 05/01/2012.

[5] Xiao K, Yates JM, Zardawi F, Sueeprasan S, Liao N, Gill L, Li C, Wuerger S., " Characterising the variations in ethnic skin colours: a new calibrated data base for human skin," Skin Research and Technology. In press (2016).

[6] Xiao K, Zardawi F, van Noort R, Yates JM., "Developing a 3D colour image reproduction system for additive manufacturing of facial prostheses," International Journal of Advanced Manufacturing Technology, 70, 2043-2049 (2014).

[7] Sun, P. L. and Sie Y. P., "Colour Uniformity Improvement for an Inkjet Colour 3D Printing System", Proc. of IS&T Electronic Imaging 2016, San Francisco, USA, Colour 342.

[8] Sie Y. P., Sun, P. L. and Su Y. C. "Developing Test Targets for Colour Management in Full Colour Three-dimensional Printing", Proc. of AIC2015 TOKYO - Colour and Image, 664-669.

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