Developing a 3D Colour Reproduction System for Additive Manufacturing of Facial Prostheses

Kaida Xiao[1,2], Faraedon Zardaw[1], Richard van Noort[1], Sophie Wuerger[2] and Julian M Yates[3],*
[1] School of Clinical Dentistry, the University of Sheffield, UK;
[2] School of Psychology, University of Liverpool, UK;
[3]School of Dentistry, University of Manchester

Abstract

A new 3D colour image reproduction system is proposed for automatic and accurate additive manufacturing of facial prostheses. The general framework of colour image reproduction was defined and a protocol for each sub-process was developed for this specific application. Prototypes of both nose and ear prostheses were produced using the proposed system. The produced facial prostheses are capable of providing accurate shape, fine texture and improved colour reproduction, with significant savings in both time and cost.

Introduction

Maxillofacial prostheses are constructed to correct facial disfigurement caused by surgical ablation due to cancer, severe facial trauma and congenital craniofacial anomalies [1]. The number of patients requiring facial prostheses has increased over the last few decades. Conventionally, the manufacture of these soft tissue prostheses is a lengthy and technically demanding process, and the outcomes are heavily dependent upon the skill of a small number of highly experienced technologists. An accurate colour match between the subject's skin and the prosthesis is always highly desirable. However, as colour matching is achieved by subjectively assessing the patient's skin colour and manually mixing colour pigments in the conventional technique, it can be extremely difficult to achieve a sufficiently accurate match.

Additive manufacturing, including three dimensional (3D) printing is being increasingly used to produce three dimensional solid objects from a digital/virtual model. One of the biggest advantages of 3D printing systems is their ability to directly interconnect with advanced manufacture techniques and allow custom-based production, with excellent accuracy and savings in both time and cost. This technique has been utilised extensively for rapid prototyping and is gaining popularity in medicine and dentistry [2]. Automatic additive manufacture of facial prosthetics using 3D image capture and 3D image printing has been recognised as an important innovative manufacturing process that may have a significant impact on the delivery of these prostheses to patients [3]. However, comparing with conventional image devices, although 3D image devices are capable of generating full 3D models, their processing are much more complicate. For example, both printing setting and posting printing processing can affect 3D printing results significantly. It makes their processing become less reliable and accuracy without a specific protocol. Moreover, methods for image reproduction between 3D camera to 3D printing can be very different, although there is no any method has been defined and evaluated for this application. Further more, accurate colour reproduction and fine texture of facial prostheses are affected the overall quality of facial prostheses significantly and therefore need to be fully addressed in the proposed system.

In this study, for the first time, a new and innovative method for manufacturing facial soft tissue prostheses that prioritises accurate 3D colour image reproduction was developed. The frame work and protocol for specific processing was described. The evaluation of processing in term of colour reproduction was conducted.

Methodology

Framework of 3D imaging reproduction

The framework of the 3D colour image reproduction was developed based on six steps as demonstrated in Figure 1. The first step is 3D image acquisition, which captures a 3D image for the target object under controlled viewing conditions using 3D image capturing devices, such as 3D camera and 3D scanner. The output for this step can be directly saved or transformed to a monochrome 3D model and a 2D colour image. The second step is to create a 3D image design for the monochrome 3D model in order to edit and fix the 3D images and transform them to the 3D printer format. Simultaneously, in the third step, colour management is undertaken to convert the 2D colour image from camera RGB to printer RGB for each pixel using specified camera and printer colour profiles respectively. Then, 3D surface texture mapping is conducted to map the newly generated colour image onto the designed 3D model as the fourth step. The next step is 3D colour printing to produce the 3D model in a starch powder using the Zcorp Z510 printer. The final step is post processing, which includes infiltration.

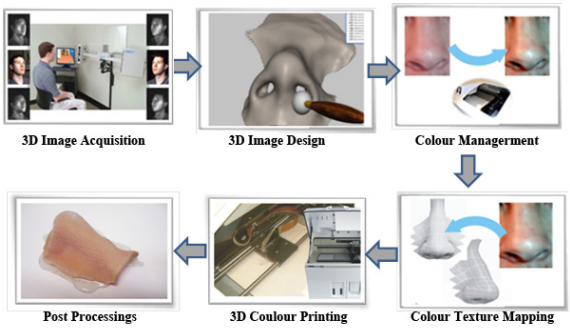


***Figure 1**. 3D imaging reproduction system for Facial prostheses*

A 3dMD facial system was adopted in this study to capture 3D images for a human face. The 3D Photogrammetry system consisted of a set of cameras in a 'pod'; a 3 pod camera system was

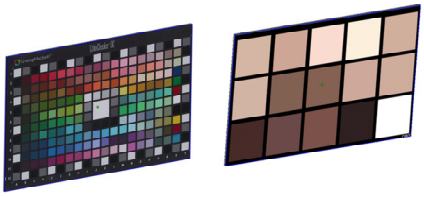
used for data capture (Figure 2a). The camera was set up in an arc with a radius of 1.1m from the target object, with the left and right cameras positioned approximately 80 degrees from the central unit. Before data capturing, camera calibration was conducted in line with the manufacturer's guidelines. The only lighting used during the data capturing process was the cameras' own built-in flashes. After 3D image capture, the 3dMD patient software (3dMD LTD, Atlanta, USA) was adopted to transform the 3D colour model into the monochrome 3D model and one colour bitmap image.

(a) 3 pod 3dMD facial system (b) Zcorp Z510 printer

Figure 2. *3D image Devices*

The 3D data manipulation was performed in this stage for the monochrome 3D mode to process the captured appropriate 3D data and output a specified print ready 3D model. This process included: importing a captured 3D image and transforming it to a standard 3D model format; fixing all the bad edges on the 3D image that was generated by data capturing and optimising it to achieve better image quality; 3D image editing and design to select and design the target object; exporting the 3D image to a 3D model to achieve a printable format. At this stage, it is still very difficult to automate all the processing with an algorithm and it is more fe asible to perform the task using 3D image processing software. In this study, the processing was refined from a series of unique steps provided in Materialise 3Matic (Materialise LTD, Leuven, Belgium) and Freeform (Sensable LTD, Wilmington, USA) software packages.

For colour management processing, the conventional colour management technique [4] was applied to transform the 2D colour image from camera RGB o the corresponding printer RGB through human colour appearance attributes [5]. To achieve this result, a number of different training colour samples need to be defined and a specific colour profile needed to be developed for each 3D imaging device respectively in order to connect the device dependent RGB systems to device independent CIELAB colour appearance attributes [5]. Subsequently, the colours in the captured image can be firstly transformed from camera RGB to CIELAB values using a camera colour profile and then transformed back to printer RGB using a printer colour profile. In this study, 240 training colours were selected using a Macbeth ColorChecker DC chart and converted to a 3D model with dimensions of 200(l) x 150(w) x 3(h) as demonstrated in Figure 3a. For each of the training colours, a digital RGB was achieved in Adobe Photoshop (Adobe Inc., San Jose, USA) and their CIELAB values were obtained by colour measurement using a Minolta CM-2600d spectrophotometer applying SpectraMagic NX Colour Data Software under a CIE standard D65 lighting source. A polynomial regression with least square fitting [6] was adopted to predict both the camera and printer colour profiles. Ultimately, the second order polynomial regression model for the 3dMD camera and the third order polynomial regression model for the Zcorp Z510 printer achieved the best performance and were therefore adopted in this study. Colour Image processing was performed using MATLAB (MathWorks, Inc., Natick, Massachusetts).



(a) Training colours (b) Testing colours

Figure 3. *Colour charts for 3D image reproduction*

Then, in the colour texture mapping stage, the new generated print image was mapped into the newly designed 3D model. In this study, the colour texture mapping for the 3D model was performed manually using the function in Materialise 3matics software.
Subsequently, the 3D model was printed using a 3D colour printing system. In this study, a Zcorp Z 510 3D printer was adopted (Figure 2b). A 3D colour image was sent to the 3D colour printer for the printing of a 3D object using starch powder (Z15e, 3DSYSTEMS Limited). A resolution of 0.5 mm was selected to generate a medium range of thickness for each layer. During printing, printer heads released coloured inks and a binder onto the powder foundation according to the prescribed layers within the 3D digital images. This allowed printing in a cross sectional 2D layer. The process was then repeated to produce a new 2D layer on top of the previous layer. The process of printing continued until a full 3D colour object had been built up.

In this final step, the post processing was performed for the printed 3D colour object. For this study, the 3D coloured object was removed after printing within 20 minutes of completion and any excess powder removed. It was then left for 30 minutes in an airtight storage container. Next, infiltration processing was conducted in order to infiltrate the 3D object with a clear medical grade silicone polymer (Silskin 25). Previously it was determined that 1.4 mm infiltration could be achieved from each side of a 3D sample, thus indicating that the 3D sample could be fully infiltrated up to a thickness of 2.8-3.0 mm. Finally, the 3D object was left for 24 hours to completely dry and allow the silicone to set.

Colour Measurement

In this study, a Minolta CM-2600d spectrophotometer using SpectraMagic NX Colour Data Software was employed to take colour measurements in CIELAB values. The illuminant was set to CIE standard D65 to simulate skin colour in daylight conditions. During the measurement, a viewing geometry of d/8 (diffuse illumination, 8-degree viewing) was used, with the specular component included and the aperture size set to 3mm. The instrument provide a consistent (repeatability $\leq$0.04 ΔE*ab) and reliable colour measurement (inter instrument agreement <0.2 ΔE*ab).

Colour Profiles Development

Colour profile for each device, more specifically, represents a mathematical model that can calculate the relationship of colour responses between the human eye and a specific colour device. One relatively straightforward methods of developing a colour profile is to use a number of training colour samples that are recorded in terms of both device RGB values and CIE XYZ tristimulus values. Then, based on this set of training data, standardized modelling techniques can be employed to derive a transformation between the CIE XYZ tristimulus values and device dependent RGB values.

The development of the Zcorp Z510 colour printer colour profile requires both printer RGB and CIE XYZ tristimulus values. A digital Macbeth colour chart was adopted to provide 240 training colours and their RGB values for the 240 colour patches were extracted in Adobe Photoshop. To achieve their corresponding XYZ tristimulus values, the 2D colour chart was converted to a 3D model with dimensions of 200(l) x 150(w) x 3(h) and produced using Zcrop Z510 colour printer and post processing. Subsequently, their XYZ values of each of training colours the printed colour chart was obtained by colour measurement using a spectrophotometer.

The printed 3D training chart was also adopted for developing camera colour profile and their CIE XYZ tritimulus values had been obtained. To achieve the camera RGB, the chart was placed on a grey background and captured using 3dMD camera. Then, RGB for the captured chart was extracted in Adobe Photoshop.

In this study, second order and third order polynomial regression and a direct 3 x 3 matrix were used to address the relationship between device RGB and CIE XYZ tristimulus values for developing both printer colour profile and camera colour profile.

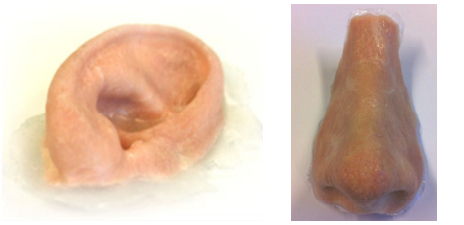
System Evaluation

In this study, by applying a colour management system, a new 3D imaging reproduction system was developed. To evaluate the colour reproduction performance of the process, a test colour chart was prepared using 14 pre-determined human skin colours including 4 Caucasians, 2 Chinese, 2 Asians, 4 Africans, and 2 Caribbean skin shades. As before the colour chart was generated into a printed 3D model with a physical size of 200(l) by 150(w) and 3(h) mm and printed by the Zcorp Z510 printer. After post processing, this was considered as the original chart.

Two reproduction charts were then reproduced using two 3D imaging reproduction systems. For the first, the original chart was captured by the 3dMD camera and the data sent to the Zcorp Z510 printer directly with only minor corrections in 3D geometry undertaken. This printed colour chart was referred to as reproduction chart 1. A second processing was then undertaken using the proposed 3D imaging reproduction process. This colour chart was printed and referred to as reproduction chart 2. To quantify the performance, colour patches within the original colour chart and the two reproduction colour charts were measured using a spectrophotometer. Data was measured in terms of CIE LAB values respectively [5]. The CIELAB colour difference between the different colour charts (Original vs. Reproduction 1, Original vs. Reproduction 2) for each skin colour patch was calculated and indicate the colour reproduction performance.

Results and Discussions

Prototypes of ear prosthesis and nose prosthesis (Figure 4) were produced using the proposed 3D image reproduction system. The whole process lasted less than two days. The produced prostheses were assessed for accuracy of size using Digital Dial Callipers and the system error was within 0.5 mm. The texture of the prostheses was visually assessed by comparing the prostheses with the original subject's skin and these results were also satisfactory.



(a) *Ear Prostheses* *(b) Nose Prostheses*

Figure 4. *Output of facial prostheses*

In order to evaluate the colour reproduction of facial prostheses for a wide range of ethnics groups, a test colour chart was prepared using 14 human skin colours including 4 Caucasian, 2 Chinese, 2 Asian, 4 African, and 2 Caribbean skin shades together with a clear shade (see Figure 3b). As before, the colour chart was generated into a printed 3D model with a physical size of 200(l) by 150(w) and 3(h) mm and printed by the Zcorp Z510 printer. After post processing, this was considered as the original chart.

Two reproduction charts were then reproduced using two 3D image reproduction systems. For the first, the original chart was captured by the 3dMD camera and the data sent to the Zcorp Z510 printer directly, with only minor corrections made to the 3D geometry. This printed colour chart was referred to as reproduction chart 1. The process was then repeated using the proposed 3D colour image reproduction process. This colour chart was printed and referred to as reproduction chart 2. To quantify the performance, colour patches within the original colour chart and the two reproduction colour charts were measured using a spectrophotometer in terms of CIE LAB values respectively. The CIELAB colour differences between the different colour charts (Original vs. Reproduction 1, Original vs. Reproduction 2) for each skin colour patch were calculated. The mean, maximum, minimal and standard deviations of the colour differences for the 14 skin colours were calculated and the results are given in Table 1. To illustrate the colour reproduction performance of the two systems for each skin shade, Figure 5 was also plotted.

Table 1. Colour difference between original colour chart and reproduction colour charts

CIEΔE*ab	Mean	Max	Min	STDEV
Org vs. Rep1	20.8	27.8	8.0	5.5
Org vs. Rep2	4.5	11.1	2.5	2.3

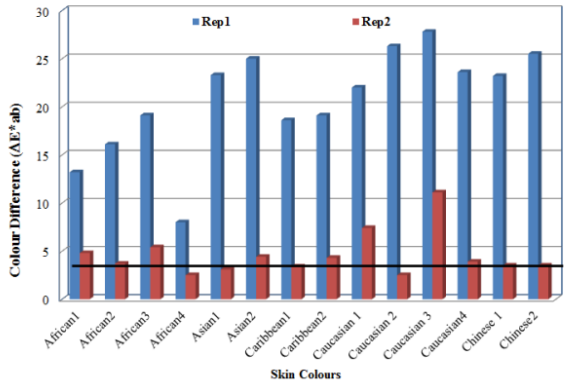


Figure 5. *Performance of Colour reproductions in proposed 3D imaging reproduction*

Both Table 1 and Figure 5 demonstrate that a significant improvement in colour reproduction was achieved using the proposed 3D colour image reproduction system. For facial prostheses application, the acceptable colour difference for skin colour reproduction has been subjectively evaluated and it was found that threshold of acceptable reproduction error is approximately 3 ΔE*ab [7]. Therefore, a solid black line was plotted in Figure 3 to demonstrate the acceptable colour difference in skin colour reproduction. It can be seen that although the average colour difference lies above 3 ΔE*ab, most skin tones are very close to this value, indicating that the colour reproduction is acceptable.

From Figure 5, it can be seen that performances of skin colour reproduction are of difference for different testing ethnic groups. In order to further investigate whether the performance of reproduction affected by lightness of testing skin colours, Figure 6 was plotted to illustrate relationship between lightness and predictive error for 14 testing skin colours. It can be seen that apart from 1 colour (Caucasian 3), there is no clear trends that predictive error dependents on lightness of testing skin colours.

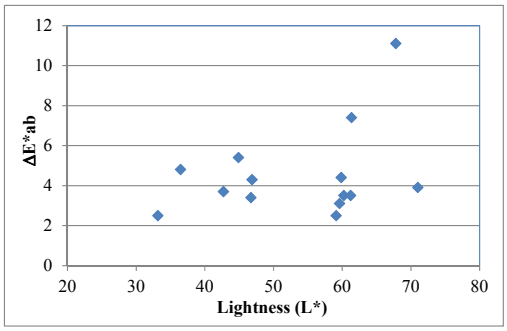


Figure 6. *Relationship between lightness and predictive error for 14 testing colours*

Conclusions

In conclusion, a 3D colour image reproduction system is proposed in this letter for automatic and accurate additive manufacture of facial prosthetics. It provides accurate shape and fine texture information, with significant savings in time and cost. The colour reproduction for facial prostheses was evaluated using human skin colours, and the performance was significantly enhanced. The 3D colour image reproduction system could be extended to other applications, such as the rapid prototyping industry and computer graphics.

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Author Biography

Kaida Xiao received his PhD in colour science from the Colour and Imaging Institute, University of Derby (2007). Since then he worked in the Samsung Advanced Institute of Technology, Tru-Colour Limited, The University of Sheffield and now he is working in University of Liverpool as a Senior Research Fellow. His research interest covers colour appearance, image quality enhancement, 3D colour image reproduction and colour and appearance in medicine and dentistry.