Developing a 3D colour image reproduction system for additive manufacturing of facial prostheses

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Abstract In this study, a new 3D colour image reproduction system is proposed for the automated and accurate additive manufacturing of soft tissue facial prostheses. A framework of 3D colour image reproduction was defined and a protocol for each sub-process was developed for this specific application. Colour management processes were developed and integrated into the proposed 3D image reproduction system; colour profiles for both the 3dMD photogrammetry system and the Z Corp Z510 3D printer were established utilising conventional colour reproduction techniques for 2D images. The soft tissue prototypes of both nose and ear prostheses were produced using the proposed system. The quality of prostheses was evaluated. The results show that the protocol used in the 3D manufacturing process was capable of producing accurate skin colour with fine textures and 3D shape, with significant savings in both time and cost.

Keywords 3D image reproduction · Facial soft tissue prostheses · Advanced manufacture · 3D colour printing

1 Introduction

Maxillofacial prostheses are constructed to correct facial disfigurement caused by surgical intervention 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. The manufacture of these soft tissue prostheses by conventional means is a lengthy and technically demanding process, and the outcomes are heavily dependent upon the skill of a small number of highly experienced technologists. Furthermore, the process can involve direct contact with the patient with impression-taking techniques that can be painful and inconvenient. An accurate colour match between the subject's skin and the prosthesis is also highly desirable [2]. However, it can be extremely difficult to achieve a sufficiently accurate match using the conventional technique as colour matching is achieved by subjectively assessing the patient's skin colour and manually mixing colour pigments.

The technology of additive manufacturing, including three-dimensional (3D) printing, is being increasingly developed to produce three-dimensional solid objects in many different materials [3, 4]. One of the biggest advantages of 3D printing systems is their ability to directly interconnect with advanced manufacturing techniques and allow custom made production, with excellent accuracy [5] and savings in both time and cost. This technique has been utilised extensively for rapid prototyping and is gaining popularity in medicine and dentistry [6]. With the evolution of various 3D imaging capturing techniques, another milestone has been to achieve accurate acquisition and transformation of target object geometric data into 3D digital models using 3D sensors. This technique has been utilised in medical applications to readily and non-invasively capture 3D images of patients. The captured digital 3D model has great accuracy [7, 8] and has been effectively used for soft tissue diagnosis and surgical planning [9–11]. By combining 3D image capturing and 3D printing technique, there has been the huge potential to develop 3D imaging reproduction systems for WYSIWYG
processing for any object. In medicine, the automatic additive manufacture of facial prosthetics using 3D image capture and 3D printing has been recognised as an important innovative manufacturing process that may have a significant impact on the delivery of these prostheses to patients [12].

However, when compared with conventional image capturing devices, 3D image devices have much more complicated working processes. Furthermore, the quality of 3D printed product is not only affected by the quality of the captured image but also the printing itself including binder/substrate interaction and the infiltration method in the post printing processing. Without a specific protocol, 3D objects can often be produced with poor reliability and quality using 3D image/manufacturing devices. Moreover, in terms of 3D image reproduction, image processing methods to transform 3D images from a 3D camera to a 3D printer are far less well developed than other processes that use 2D technology. To date there is no method that has been developed and evaluated for the proposed application. Furthermore, the colour reproduction required for facial prostheses can be significantly affected by the overall quality of the facial prostheses produced, and therefore any colour management processing not only needs to be specially designed in the proposed system, but also needs to run in parallel with the specific 3D manufacturing processes.

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 and a framework and protocol for specific 3D processing was designed. Conventional colour management processing was successfully applied to 3D imaging devices. A working prototype of both nose and ear prostheses was produced in a “non-contact” method and evaluated to provide satisfactory results.

2 Materials and methods

2.1 Framework for 3D colour image reproduction

A framework for the 3D colour image reproduction system was developed for the production of soft tissue facial prostheses, based on the six steps illustrated in Fig. 1. The first step was 3D image acquisition, which captured a 3D image of the target object under controlled viewing conditions using 3D image capturing devices, such as a 3D camera or 3D scanner. The output for this step can then be saved directly or transformed to a monochrome 3D model and a 2D colour image. The second step was to create a 3D image design for the monochrome 3D model in order to edit and manipulate the 3D images and transform them to the 3D printer format. Simultaneously, in the third step, colour management was 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, as the fourth step, 3D surface texture mapping was conducted to map the newly generated colour image onto the manipulated 3D model. The next step is 3D colour printing to produce the 3D model in a starch powder using the 3D printing system. The final step is post processing, which includes infiltration with a medical-grade silicone polymer. The specific protocol for each step was designed and described below.

A 3DMD photogrammetry facial system (3DMD, Atlanta, GA, USA) was adopted in this study to capture 3D images of a human face. The 3D photogrammetry system consisted of a set of cameras in a “pod”; a three-pod camera system was used for data capture (Fig. 2a). The camera was set up in an arc with a radius of 1.1 m from the target object, with the left and right cameras positioned approximately 80° from the central unit. Before data capture could be undertaken, 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 was utilised to transform the 3D colour model into the monochrome 3D model and a one colour bitmap image.

The 3D data manipulation for the monochrome 3D model was then performed at this stage to process the captured 3D data and output the specific printer-ready 3D model. This process included importing a captured 3D image and transforming it to a standard 3D model format, manipulating and smoothing any bad edges on the 3D image that were generated by the data capturing process and optimising it to achieve improved image quality. 3D image editing to select and design the target object, and exporting the 3D image to a 3D model to achieve a printable format. At this stage, it was still very difficult to automate all the processing with an algorithm and therefore it is more feasible to perform the task using 3D image processing software. In this study, the processing was refined and performed using a series of unique steps provided in bespoke 3-matic (Materialise, Leuven, Belgium) and Freeform (Sensible, Wilmington, DE, USA) software packages.

For colour management processing, a conventional colour management technique [13] was applied to transform the 2D colour image from camera RGB to the corresponding printer RGB through human colour appearance attributes [14]. To achieve this result, a number of different training colour samples are needed to be defined and specific colour profiles are needed to be developed for each 3D imaging device in order to connect the device-dependent RGB systems to device-independent CIELAB colour appearance attributes [15]. Subsequently, the colours in the captured image were 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, colour management processing was performed using MATLAB (MathWorks, Inc., Natick, MA, USA).

The texture mapping was a procedure similar to pasting a picture to the surface of an object. Three digitised colour portraits with the "third" dimension from reconstructed soft tissue were blended into a cartograph as a texture map. For the colour texture mapping stage, the newly 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 a bespoke function in the Materialise 3-matic software.

Subsequently, the 3D model was printed using the 3D colour printing system. In this study, a Z Corp Z510 (3D Systems Inc., Rock Hill, SC, USA) 3D printer was used (Figs. 2b). A 3D colour image was sent to the 3D colour printer for printing of a 3D object using starch powder (Z15e, 3D Systems) and a binder. 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 produced.

In the final step, post processing infiltration was performed for the printed 3D colour object. In this study, the 3D coloured object was removed after printing within 20 min of completion and any excess powder removed. It was then left for 30 min 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 had been determined that 1.4-mm infiltration could be achieved from each side of a 3D printed sample, thus indicating that the 3D sample could be fully infiltrated up to a thickness of 2.8–3.0 mm. Finally, once infiltrated the 3D object was left for 24 h to completely dry and allow the silicone to set.

Due to the different ways in which colour communication for and between 3D image capturing and 3D image printing systems is utilised, there is often a significant colour discrepancy between the printed and original objects when using this type of manufacturing process. To achieve an accurate colour reproduction through 3D image devices, specific colour profiles for the 3D image devices need to be developed in order to link the colour system of a specific device to the human visual system.

The colour profile for any given device represents a mathematical model that can calculate the relationship of colour responses between the human eye and a specific colour.

Fig. 2 3D image devices. a Three-pod 3dMD facial system. b Z Corp Z510 printer
device. CIELAB uniform colour space has been widely used for more than 30 years to predict three-dimensional colour attributes of human perception, whereas device-specific RGB colour systems drive colour outputs in terms of digital RGB values. One relatively straightforward method 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 CIELAB values. Then, based on this set of training data, standardised modelling techniques can be employed to derive a transformation between the CIELAB values and device-dependent RGB values.

The development of the Z Corp Z510 printer colour profile requires both printer RGB and CIELAB values. A digital Macbeth ColorChecker DC chart (X-Rite Inc., Grand Rapids, MI, USA) was used to provide 240 training colours (Figs. 3a) and their respective RGB values. These were then 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) × 150 (w) × 3 (h) using a Z Corp Z510 colour printer and post-processing. Subsequently, the XYZ values for each training colour produced in the printed colour chart were obtained by colour measurement using a spectrophotometer.

The printed 3D training chart was also used for developing the camera colour profile (the CIELAB values had been obtained previously). To obtain the camera RGB values, the chart was placed on a grey background and its image was captured using the 3DMD camera. Then, RGB values from the digitally captured chart were extracted using Adobe Photoshop.

Following capturing of the relevant data, polynomial regression based on the least-squares method was then used to drive both printer and camera colour profiles due to its optimal performance and ease of implementation [15]. For these transformations, the original matrix was represented by $O$, the target matrix by $T$, and the least solution by $M$ (Eq. 1):

$$M = (O^T O)^{-1} T$$  \hspace{1cm} (1)

where $O^T$ denotes the transposition of $O$, and $O^{-1}$ represents the inverse of $O$. The idea underpinning this simple linear transformation was that each column of $T$ can be written as a linear combination of the columns of $O$. Therefore:

$$T = \alpha O_1 + \beta O_2 + \gamma O_3$$  \hspace{1cm} (2)

Fig. 3 Colour charts for 3D image reproduction. a Training colours. b Testing colours

Fig. 4 Relationship between normalised CIE XYZ tristimulus values and corresponding relative printer RGB (a, b, c) for Z Corp Z510 3D printer
where $\alpha$, $\beta$, and $\gamma$ are scalars. In a second-order polynomial function, each column of $T$ can be represented as a linear combination of not just the columns of $O$, but also the columns of $O^2$ ($O_1^2$, $O_2^2$, $O_3^2$). Moreover, cross-column and translational terms can also be added into the function. So the $N \times 3$ matrix can be expanded to the $N \times 10$ matrix. Similarly, a third-order polynomial function consisting of 20 terms as listed in Eq. 4 was also investigated:

$$O^T = \begin{bmatrix} O_1 & O_2 & O_3 & O_1^2 & O_2^2 & O_3^2 & O_1 O_2 & O_1 O_3 & O_2 O_3 \\ 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 \end{bmatrix}$$

(3)

$$O^T = \begin{bmatrix} O_1 & O_2 & O_3 & O_1^2 & O_2^2 & O_3^2 & O_1 O_2 & O_1 O_3 & O_2 O_3 & O_1^2 O_2 \end{bmatrix}$$

(4)

In theory, there is no limit to the order and number of terms within the polynomial; in practice, it is constrained by the accuracy required, the computational cost, and the number of samples available. In this project, second-order and third-order polynomial regression (Eqs. 3 and 4) and a direct $3 \times 3$ matrix were used to address the relationship between device RGB and CIELAB values for the development of both the printer colour profile and camera colour profile.

In order to place the two data sets within the same numeric scale, both sets of data were converted. CIELAB values were transformed to CIE XYZ tristimulus values, RGB values were divided by 255, and CIE XYZ tristimulus values were divided by 95, 100, and 108 respectively, in order for normalisation to a CIE D65 standard light source to be undertaken.

2.2 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° viewing) was used, with the
specular component included and the aperture size set to 3 mm. The instrument provides a consistent (repeatability < 0.04 $\Delta E_{ab}^*$) and reliable colour measurement (inter-instrument agreement < 0.2 $\Delta E_{ab}^*$).

2.3 System evaluation

In this study, by integrating a colour management system, a new 3D image reproduction system was developed for producing facial soft tissue prostheses using a unique and innovative method of production. To evaluate the colour reproduction potential for the human face, a colour test chart was prepared using 14 predetermined and accepted human skin colours, including four Caucasian, two Chinese, two Asian, four African, and two Caribbean skin shades (Figs. 3b). As before, 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.

Two reproduction charts were then produced using two 3D imaging reproduction systems. For the first, the characteristics of the original chart were captured using the 3dMD camera and the data was sent to the Z Corp 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 from all the charts was measured in terms of CIELAB values [14]. The CIELAB colour difference between the different colour charts (original vs. reproduction 1, original vs. reproduction 2) for each skin

| Table 1 Colour difference between original (Org) colour chart and reproduction (Rep) colour charts |
|----------------------------------|------------|------|-----|-----|
| CIE $\Delta E_{ab}^*$ | 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 |

colour patch was then calculated and the colour reproduction performance was determined.

3 Results and discussions

3.1 Colour profiles

When developing a colour profile for the Z Corp Z510 3D colour printer, the best performance was achieved when the third-order polynomial regression model was applied [16]. Figure 4a-c was plotted to demonstrate the relationship between printer RGB and CIE XYZ tristimulus values in red, green, and blue colour channels, respectively. In each sub-figure, a dot represents one of 240 training colours; the best-fit line using third-order polynomial regression was also plotted in each sub-figure. It can be seen from $R^2$ values that the model for the blue channel gave the best performance, whereas the worst model performance was achieved for the red channel.

The colour profile of the 3dMD camera was developed using the second-order polynomial regression model due to its inherently improved performance. Figure 5a-c was plotted to illustrate the relationship between camera RGB and CIE XYZ tristimulus values for the 3dMD camera system. Again for each sub-figure, camera RGB and CIE XYZ tristimulus

**Fig. 7 Performance of colour reproductions in proposed 3D imaging reproduction**
values were plotted for all the 240 training colours. The best-fit line was plotted using a second-order polynomial regression and indicated in each sub-figure. As with the printer, it was also found that the blue channel demonstrates best performance, while the red channel had the worst model prediction results.

3.2 Prototypes of prostheses

Prototypes of ear and nose prostheses (Fig. 6) were produced using the proposed 3D image reproduction system, with the whole process lasting less than two days. The produced prostheses were assessed for accuracy of size using digital dial calipers. Subsequently, the system error was determined to be within 0.5 mm. The texture of the prostheses was visually assessed by comparing the prostheses with the original subject’s skin; these results were also clinically satisfactory.

3.3 Evaluation of colour reproductions

The maximum, minimum, mean, and standard deviations of the colour differences for the 14 skin colours were calculated for the two 3D image reproduction system and the results given in Table 1. The colour reproduction performance of the two systems is shown in Fig. 7 for each skin shade.

Both Table 1 and Fig. 7 demonstrate that a significant improvement in colour reproduction was achieved using the proposed 3D colour image reproduction system. For its application to produce facial soft tissue prostheses, an acceptable colour difference for the 3D printed objects is approximately 3–4 \( \Delta E^*_{ab} \) [17]. A solid black line was plotted in Fig. 7 to demonstrate the acceptable colour difference in skin colour reproduction. It can be seen that although the average colour difference lies above 3 \( \Delta E^*_{ab} \), most skin tones are very close to this value, indicating that the colour reproduction is acceptable.

4 Conclusions

In conclusion, we propose a 3D colour image reproduction system for the automated manufacturing of facial prosthetics using 3D additive manufacturing techniques. This unique and innovative method of producing such prostheses 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 compared to standard models. The 3D colour image reproduction system could be extended to other applications, such as other branches of rapid prototyping industry and computer graphics.

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