Image to Geometry Registration for Virtual Dental Models

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Abstract—**In computer-aided design and manufacturing (CAD/CAM) for dentistry, the digital dentition model is usually acquired using intraoral scanner or impression model scanning before further processing. Both tooth shape and shade play important role in treatment planning for patient satisfaction with dental esthetics. However, most of current intraoral scanners cannot generate good enough color texture information. For impression model scanning, tooth shade is even lost when making impression. In the paper we consider the technique using the image-to-geometry registration method to map color intraoral photographs onto the virtual models. We investigate the automatic technique to accurately find correspondences of the digital model and the color intraoral photographs. This eliminates manual placement error of correspondence for the registration.**

Keywords—Image to geometry registration, Tooth shade, Optimization

I. INTRODUCTION

In esthetic dentistry, the goal is to create beautiful smile. One of the most important factors in determining the outcome is tooth shade [1]-[4]. Treatment planning for restorations/prostheses in the esthetic zone should include a thorough assessment of patient's tooth shade such that it should be either matched or blend with natural teeth. Conventional photographs are used in dental treatment planning for decades, two dimensional (2D) photographs only allow the smile design in one viewing angles. It means that positioning of prostheses can only be guessing and it need further manual fine tuning in its printing or milling. Recently, three dimensional (3D) facial photographs are advocated for better digital planning with unlimited viewing angle [5]-[8]. Prostheses can then be precisely positioned in 3D and directly exported to milling for clinical use.

To enable digital smile design, patient's 3D face and high-resolution teeth scans need to be combined to form a digital "virtual patient model" (VPM). Their 3D positions can be related using the virtual facebow techniques [9]-[12]. 3D facial scan is a well-established technique. Current commercial active and passive stereophotogrammetry devices can capture facial surfaces within mini-seconds with very high accuracy and resolution [13]-[15]. Since the lighting can be controlled to a very repeatable condition, the captured color textures are photo realistic. Although the acquired colors are usually not calibrated in these commercial devices, it is possible to correct for use in dental color matching.

For digitizing the dentition shape, traditional method is impression model scanning. Rubber impression is firstly taken from the patient. Then a gypsum model is derived from the impression and hence perform scanning on it. Color is lost in the very first step when taking the impression. Recent years, digital impression methods are becoming more popular [16]. The 3D shape is acquired using teeth brush size 3D sensor which continuously stitching the acquired 3D surfaces pieces. Depends on the technology, some commercial scanners require applying powder on tooth surface. This kind of intraoral scanners can deliver higher accuracy because of the better teeth surface condition. Some other types of intraoral scanner such as confocal technique can also capture color along with shape and hence match shade color. But they are less accurate than those using powder. Due to limited spaces and other complicated factors in the oral cavity, such as saliva, the tooth shape/shade may not always be successfully acquired.

For the problem, it is proposed in this paper to acquire color using traditional intraoral photography and map it onto the 3D shape scanned using intraoral scanner or impression model scanning. This allows much better control in lighting and color calibration for tooth shade matching [17][18].

Before the 3D mesh model can be colored with 2D photos, it need to be transformed to a view angle which is optimally matched to the 2D photos according to some criteria. This process is referred as "Image to geometry registration" [19]-[22]. Its solutions can be roughly classified as: correspondence based [23], feature based and statistic correlation based [19]-[21] methods. Correspondence based methods try to locate correspondence which is the same as in camera calibration [23]. The image feature based approaches further include features found in the image and mesh model such as silhouette and projected 3D mesh model contour. Statistic correlation based approach make use of statistic measure to analyze the correlation, such as mutual information [24]. In [20], correspondence points can be manually added to combine with mutual information approach. The registration can be very accurate but the placement and selection of correspondence is time consuming and exhibits repeatability problem. The key to the success is the robustness and accuracy of finding correct features, correspondences or the statistic measure.

Since human dentition have some unique properties, such as color and corner points, the corresponding features can be used for alignment. In next section, the protocol of data acquisition is firstly described, then features for finding correspondences in 3D mesh model and 2D photographs for the alignment are developed. Finally, the proposed method is applied on a healthy subject.

II. MATERIALS AND METHODS

A. *Platform*

In this study, the process for correspondence detection of 3D mesh model and photos are done in Matlab. The detection results are then loaded into Meshlab [25] to perform the final raster alignment and color mapping.

Fig. 1 – Standard intraoral photograph in frontal view.

B. *Intraoral dentition model and photos*

Standard intraoral photograph in frontal view was taken using a single lens reflex (SLR) camera (EOS 500D Canon) with a macro lens (EF 100mm f/2.8, Canon) and a ring flash (Macro Ring Lite MR-14EX, Canon) (Figure 1). Stone cast of the subject (one of the authors) was scanned using a structured light 3D scanner (DAVID SLS-3, Hewlett-Packard). The vertex resolution is 0.1mm. The stone model and the photograph are taken in the same day such that it can minimize the inconsistency between them. The 3D mesh model is then further cleaned and cut into appropriate size.

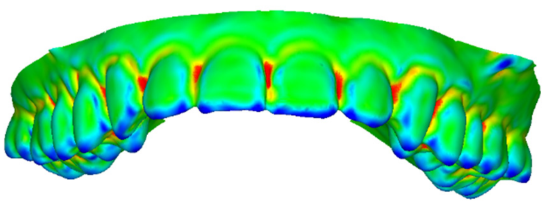

Fig. 2 – Upper teeth colorized by mean curvature. Red-green-blue color encode curvature values from minimum to maximum. Vertices with smallest curvature value are clustered at gingival papilla.

C. *3D shape features extraction*

Each human tooth sits on the maxillary and mandibular bones which are covered by gingiva, as shown in Fig. 1. In scanned 3D mesh model, the gum-tooth margins appear as groove and local valleys. These valleys are the results of jointing three surfaces: gingiva and two adjacent teeth. They are known as gingival papilla. This geometric singularity can be characterized with signed mean curvature (denote as K) in Algebraic point set surfaces (APSS) framework [26]. For the valleys, the mean curvatures of their vertices are of negative values which can easily be filtered out from other. For other valleys in the dentition, such as the buccal gingival papilla, they can be discarded using their average vertex normal vector or limited with the region of interest (ROI).

The following summarizes the procedures to extract mesh model feature using mean curvatures:

<u>Compute mesh model feature points</u>

1. Compute mean curvature of the mesh model with filter scale 10.
2. Select vertices with mean curvature value $K < -1$.
3. Select vertex patches pointing away from face.
4. Centers of the selected vertices patches are computed and used as correspondence points.

In Fig. 2, it shows the upper teeth colorized with mean curvature. Red-green-blue color encode mean curvature [25][26] values from minimum to maximum. It is shown that the valleys have minimum curvature while the tooth tips have maximum curvature values. The resulted selection of gingival papilla area by filtering the vertices with mean curvature value was shown in Fig. 3 in green. Centers of the vertex patches were then identified as the correspondence points from 3d mesh model, which are shown as red circle in Fig. 3. It can be seen that mean curvature offers very good indication of the gingival papilla centers.

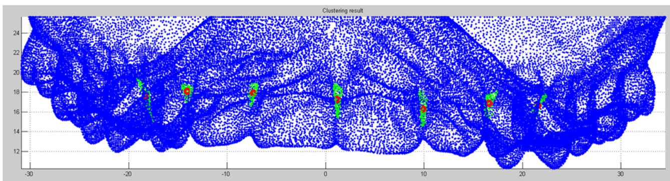

Fig. 3 – Upper teeth clustering result: Blue, green and red dots are respectively 3D mesh model vertices, filtered vertices according to mean curvature and clustered center of the filtered vertices.

D. *Image features extraction*

Consider the standard intraoral photo as shown in Fig. 1, the gingival papilla appears as turning points on the color edge of the gum to tooth. Since the color of the gum and tooth are very different (red vs white), we suggest to firstly segment the tooth based on color and look for the turning points on the boundary. Without loss of generality, the color of gum can be sampled from the upper or lower half rows of 2D photos. In CIELAB color representation, the gum and tooth can then be segmented easily. For other noise pixels, they can be removed using median filter and morphological operations. With the segmentation mask derived, as shown in Fig. 4, the groove lines of gum boundary can be easily located.

To detect turning points on an image, one approach is to firstly convert the image pixels to ordered sequence. Then the turning points can be detected by the peaks. In this application for aligning dentition, the photograph was taken in a standardized way such that the tooth location of central incisors and occlusal line are more or less at the center and horizontally aligned to image frame respectively. It suffices to adopt a simple approach to convert the segmented mask image to a 1D sequence in a way that the sample values refer to the vertical distance to the image lower ROI edge. In Fig. 5, the converted 1D sequence derived from the gum-tooth boundary is shown. Gingival papilla appears as sharp peaks (flipped vertically). Using the Matlab peaks finding function developed by Thomas C. O'Haver [28], they can be automatically located, as shown in Fig. 5 in red circle.

The following summarizes the procedures to extract image feature using mean curvatures:

Compute image features points

1. Convert input image into CIELAB (L*ab) color space [27].
2. Segment the tooth using color of gum with *ab* color angle tolerant 0.34 rad, as shown in Fig. 4.
3. 2D Median filter and morphological opening filters are applied to further clean the segmentation mask.
4. From region of interest of the detection, the boundary points are extracted to form a 1D sequence. The peaks are detected using a Matlab peaks finding function developed by Thomas C. O'Haver [28].

In Fig. 5, it shows the segmentation and peaks found from the derived gum-tooth margin curve with the above steps. The extracted coordinates are then used as correspondence points.

Fig. 4 – Segmentation of gum and tooth using CLELAB color.

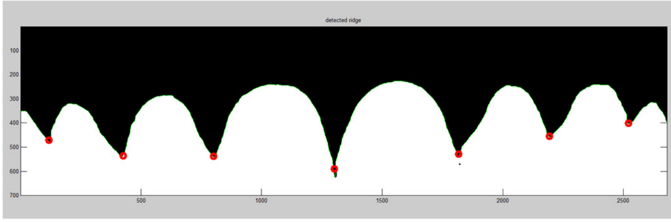

Fig. 5 – Upper teeth gingival papilla detection result (red circles).

E. Image to geometry registration with correpsondence

The 3D mesh model and raster image were then imported into Meshlab [25]. Raster image alignment was applied to look for the matching of the mesh model and image with the computed correspondence found in the previous subsections, as shown in Table I. The alignment is to minimize the following objective function [20],

$$MC_{I_A,I_B(C)} = k(-MI(I_A, I_B(C)) + (1-k)E(Corr, C)$$

where $C = (\theta, \phi, \psi, t_x, t_y, t_z, f), 0 \leq k \leq 1$;

θ, ϕ, ψ are Euler's angle; t_x, t_y, t_z are translation; and f is the focal. The two terms are respectively:

$$MI(I_A, I_B(C)) = -\sum_{a,b} p(a,b) \log\left(\frac{p(a,b)}{p(a)p(b)}\right)$$

and

$$E(Corr, C) = \frac{1}{N} \sum_{\forall cor_i} \sqrt{(x_{pi(C)} - x_i)^2 + (y_{pi(C)} - y_i)^2}$$

In the current application, k may be set to higher value to emphasize the matching of correspondence points. On the contrary, mutual information is not very useful in this case as human dentition color looks very similar.

TABLE I. DETECTED COORESPONDENCE POINTS

Points	3D			2D	
	X	y	Z	x	y
1	21.5474	16.6457	14.6196	1118	1897
2	-14.05	18.1207	21.1385	1427	1832
3	-7.3437	17.9217	26.3238	1800	1830
4	1.1708	17.277	28.1966	2302	1779
5	16.5713	16.8889	21.1354	2816	1840
6	9.8585	16.3011	26.3116	3194	1914
7	-18.2112	17.6344	14.7781	3522	1966

Fig. 6 – Alignment result.

Fig. 7 – Color mapping result.

III. Conclusion

In this paper, an automatic feature extraction for the image to geometry registration of dentition is proposed. It searches the vertex points characterized with mean curvature from 3D mesh model and the corresponding gingival papilla points of 2D photograph. Their properties are well defined and can be detected accurately and automatically. Based on this framework, further geometry and image features can be developed to enhance the performance such as the tooth tips.

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