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A dental vision system for accurate 3D tooth modeling

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Abstract - **This paper describes an active vision system based Reverse Engineering approach to extract the three-dimensional (3D) geometric information from dental teeth and transfer this information into Computer-Aided Design/Computer-Aided Manufacture (CAD/CAM) systems to improve the accuracy of 3D teeth models and at the same time improve the quality of the construction units to help patient care. The vision system involves the development of a dental vision rig, edge detection, boundary tracing and fast & accurate 3D modeling from a sequence of sliced silhouettes of physical models. The rig is designed using engineering design methods such as a concept selection matrix and weighted objectives evaluation chart. Reconstruction results and accuracy evaluation are presented on digitizing different teeth models.**

1. INTRODUCTION

For decades, attempts have been made to use ceramics for fabrication of crowns and inlay material in restorative dentistry. However, it was only a few years ago that technologies became available that could be used successfully in dental practices. Two crucial obstacles made it intractable to use ceramics as an inlay/crown material:

- Appropriate adhesive technology to enable a lasting connection between the inlay or crown and the tooth.
- Capable systems that enable well-fitting inlays and crowns to be fabricated [1].

The second obstacle triggered a research trend towards the importance of 3D tooth modeling. It has been recognized that resistance to restoration failure is not solely a biological concern (e.g. toxicity), but that the cavity shape, dimensions, and the state of stress must all be taken into account [2, 3]. There has been interest in the use of reverse engineering in tooth modeling for a number of decades. However, traditional reverse engineering scanning technologies such as the laser scanner and the Coordinate Measuring Machine (CMM) both have their own limitations [4], especially in restorative dentistry. Their data capturing process is slow, because they scan the surface line-by-line and point-to-point and the high energy light source of the laser scanner also needs to be treated with care. Computer vision techniques have enabled automatic, non-contact and fast reconstruction from multiple photos of dental objects. However, existing techniques mostly concentrating on 3D scene reconstruction and virtual reality applications are not capable of accurate reconstruction for engineering in dentistry. In this paper, we describe the development of a dental vision system approach of obtaining precise 3D measurement from 2D photographs, including the design of a vision system rig and 3D shape reconstruction from sliced silhouettes technique.

Methods of shape reconstruction from turn-table motion [5] have shown the potential of accurate modeling in the last decade. Volumetric modeling from silhouettes [6] based on turntable motion has been able to convert visible contours to a visual hull. However, volumetric modeling usually cannot generate a detailed enough data set (e.g. point cloud) for engineering applications. In this paper, we describe a 3D modeling vision system for reconstruction of real models under controlled imaging environment using silhouette based dense slices intersection method. The modeling accuracy evaluation is shown on the comparison of real teeth models and digitized models. The aim is to extract the geometric information and transfer this information into CAD/CAM systems to improve the quality of 3D models and at the same time lower manufacturing costs by simplifying the method and reducing the production time.

2. OVERVIEW OF THE APPROACH

In particular, this paper involves a development of an automatic vision system 3D modeler: silhouettes & turn-table motion based reconstruction. The modeler utilizes single-view method recovering curved shapes from a sequence of profile views of teeth models using the volume intersection techniques. In order to obtain highly reliable silhouette, active vision technique is applied using a set of light sources over the object to eliminate the environment light reflection. In our experiment, a vision system rig was built according to 3D depth recovery principles to accommodate up to 3 CCD cameras and a turntable holding teeth for image acquisition. The turntable allows user to take a series of profile views of the object by rotating it around a single axis with known angles.

3. VISION SYSTEM CONFIGURATION

The system diagram and rig overview is shown in Figure 1. The horizontal camera was used at this stage for Slicing Method Algorithm (SMA) which is discussed in the remaining section of this paper. Due to our acquisition setup, the rotation axis and distance from the camera center to this rotation axis remain the same during the turns of the table. The structure is able to support at least

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2 cameras at any one time; for greatest accuracy the structure is extremely stable so there is no movement when the cameras are taking images. The cameras are able to move towards and away from the object in both the vertical and horizontal planes and are able to move to any distance from the object up to the constraints of the rig size which improves the accuracy, and aids the automation process. The turntable has the ability to rotate in small increments (c. 4.5º) that allows an accuracy of ±0.5º after rotation through 180º. The rig not only completely controls the light (by means of an enclosed structure) but is also flexible enough to hold several different types of light at various positions to optimize the image of the object. For the Slicing Method the ideal image is a silhouette of the object with sharp edges and no shadow.

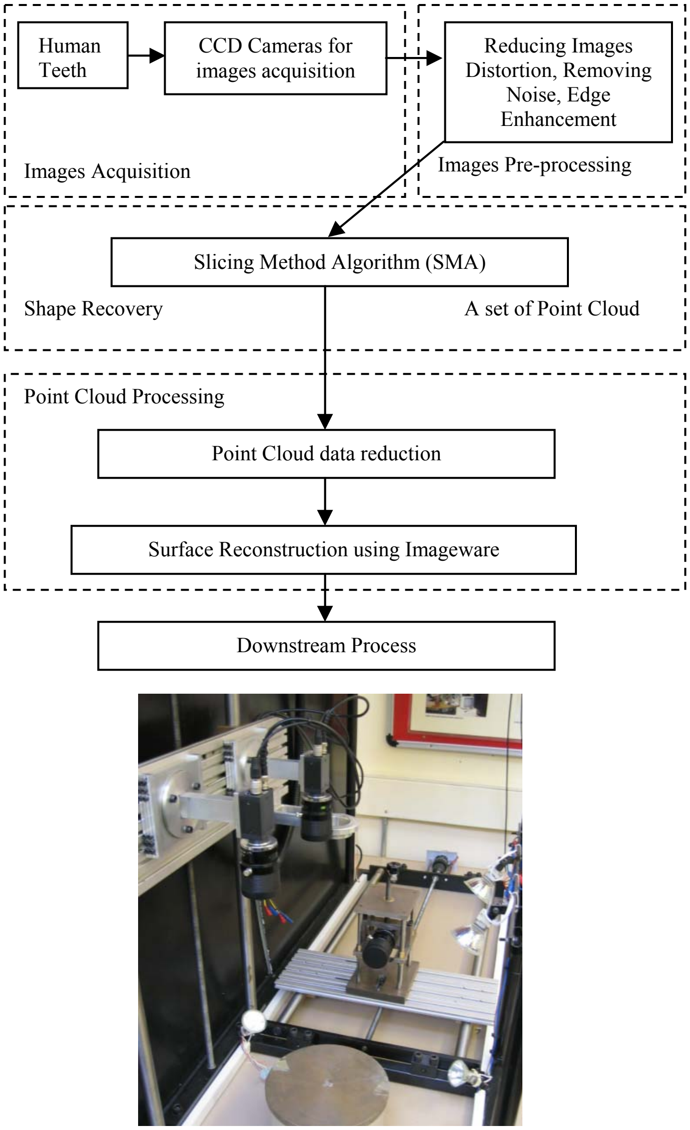
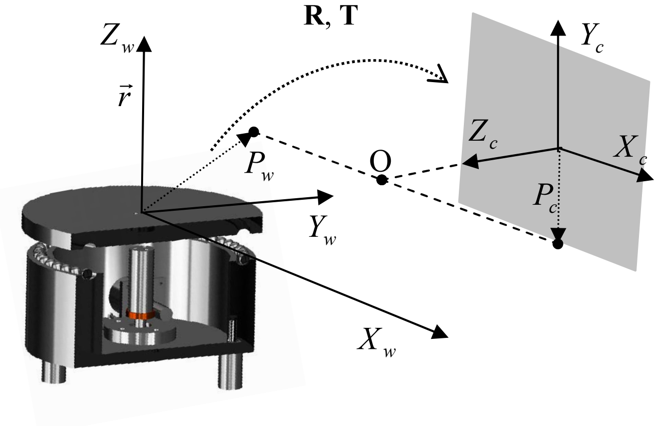


Fig.1. Vision System diagram and overview

3.1. System Calibration

The vision system must be calibrated to obtain the interior and exterior parameters of the camera. This is to find out the position and orientation of the camera and the focal length.

In a setup consisting of a rotary table with a fixed camera, we use at least three images of the calibration pattern to determine the rotation axis position with respect to the fixed camera geometry. Bouguet's [7] camera calibration method is used to determine the parameters of the camera. The relation between the object rotation axis (set as world reference frame) and the camera reference frame is shown in Figure 2.



X_w, Y_w, Z_w : World reference frame (WRF)
X_c, Y_c, Z_c : Camera reference frame (CRF)
P_w : Object surface point in WRF
P_c : Corresponding Image point in CRF
O: Projection center
R, T: Extrinsic parameter of the camera
$\vec{r}$: Rotation Axis vector

Fig.2. Rotation axis with respect to camera frame

One major concern in turntable-motion reconstruction is to find the rotation axis accurately. Rotation axis of the turn-table with respect to the fixed camera coordinate frame can be defined by a unit vector $\vec{r}$ in the direction of the rotation axis, corresponding to the projection center O of the camera onto the rotation axis as shown in Figure 2. Once the camera parameters are known, this vector can be computed using the rotation axis translated from CRF to WRF. In our study, we use the extracted rotation axis to estimate the initial bounding box, divided into slices, of the object in the silhouette-based reconstruction procedure.

3.2. Shape Modeling from Sliced Silhouettes

Occluding Boundaries (OB) technique and its derived method, Slicing Method, were the two 3D shape recovery methods used in this project.

Figure 3 shows the visual perception process of the Slicing Method. In the Slicing Method process many profile views of an object are captured from different angles. As per all Occluding Boundaries techniques these images are then edge detected/boundary traced, so that each image of the object is a silhouette. Each silhouette is then 'sliced' into one pixel high segments, which can then be projected onto a new image. This new image is a cross sectional slice at a specific height of a particular view. Once a complete set of slices exists for each view, a union operation can be performed on corresponding slices from all the views. When all union operations have been completed a final set of slices will have been produced that contain the data for the 3D model of the object. The vision system was calibrated [7] to obtain the interior and exterior parameters of the camera in order to find out the position and orientation of the camera and the turntable rotation axis r. The following operations are used to extract the point cloud from the profile images:

1. Read the profile images as matrices $I_k[i,j]$, $k \in [1,n]$ where n is the number of the profile image, i and j are the row and column number of the point on the profile image respectively;

2. Determine edge points using the edge detector or boundary tracing operator depending on the properties of images for each profile image to generate edge/boundary points matrix $E_k[i,j]$, with 1's where the detector finds edges/background in I and 0's elsewhere/the object;
3. For each $E_k[i,j]$, find the points $D_k(i)$ on each row which represent the object as shown in Figure 4;
4. Generate a square slice image $S_{k,i}[m,m]$ as in Figure 4 according to the object points $D_k(i)$, where the pixels representing the object are set to black with the value 0 and others are set to white with the value 1 and rotate this image by $180 \bullet k/n$ degrees. The centre point of the slice image is on the rotation axis r, which was determined during the calibration process.
5. For each i (the same height at all the profile images), apply a union operator to the set of $S_{k,i}[m,m]$. The final slice i can be written as $SLICE_i[m,m] = \sum_{k=1}^{n} S_{k,i}[m,m] = \begin{cases} 1 & Tooth \\ 0 & Background \end{cases}$
6. Apply the edge detector to $SLICE_i[m,m]$ to extract the surface points $P(x,y,z)$ of the object, where $z = i$, (x,y) is the coordinate of the edge points in $SLICE_i[m,m]$.

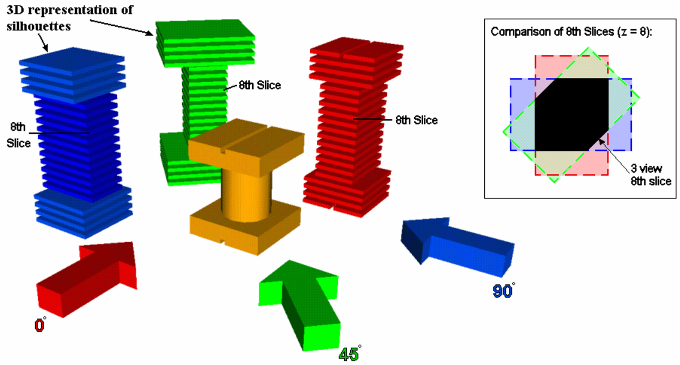


Fig.3. Visual representation of the Slicing Method, the boxed section shows an example union operation with the 8th slice.

The basic idea of dividing an object into pixel based slices is derived from the visual hull theory. When the camera intrinsic and extrinsic parameters are known, a solid outline cone can be back projected from every profile image. 3D models resulting from silhouette intersection are limited by the visual hull effect hence the surface of complex objects can be roughly recovered. In order to obtain more detailed model so the object is divided into slices to obtain small region features, which are important in modeling tooth because of its small dimension and complex curved shape. We intersect each divided slice from all the views, called Slicing Method Algorithm. The pixel height based dividing method can make the system easily determine the coordinate of the object surface point and the dimension value of the object.

4. VISION SYSTEM APPLICATIONS EVALUATION

To evaluate the vision system accuracy, a tooth preparation model provided by Renishaw and an additional cracked 7-year-old child incisor by the second author, were digitized by the vision system using the SMA to demonstrate the vision system ability in bioengineering applications. These two samples were also scanned by Renishaw's Triclone dental system with 10 µm accuracy. The Triclone accuracy was compared with the vision system. This comparison was demonstrated with the vision system point cloud and the surface generated from the Triclone point cloud.

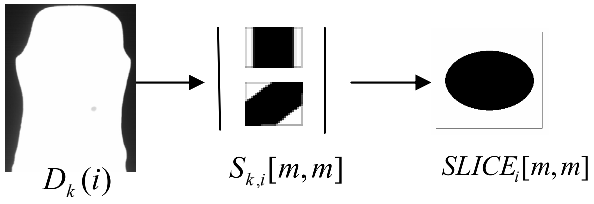


Fig.4. Process on slice generation (tooth preparation model)

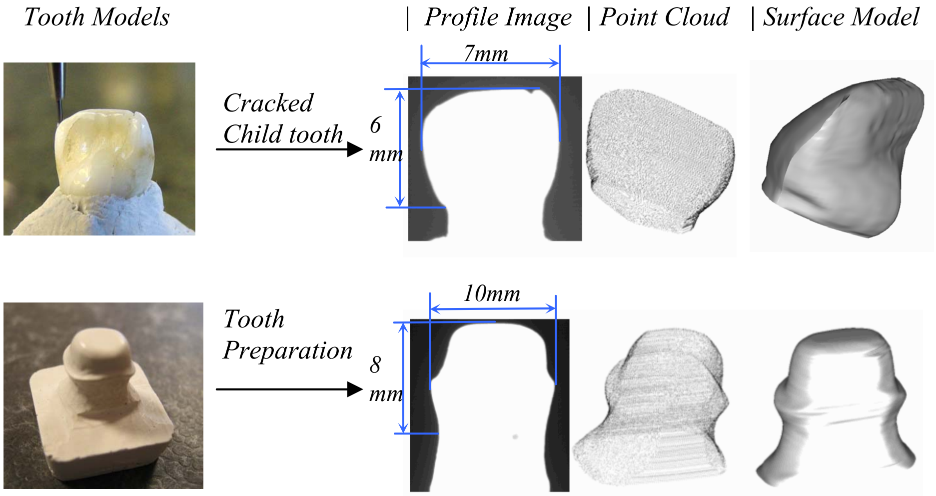


Fig.5. SMA on processing tow typical dental tooth models

4.1. Image Acquisition

40 profile images were captured using a SONY XC-ST70 CCD camera with a Computar TEC M55 lens. The angle increment between each pair of neighbourhood images was 4.5º. The captured images had a resolution of 640 × 480. The CCD camera here had effective pixels of 768 × 494.

4.2. Image Optimization

Firstly, in order to reduce the distortion caused by the lens, the calibration process described by Bouguet [7] was used. Secondly, the scale factors in both horizontal and vertical directions of profile images were applied.

4.3. Evaluation of the results

Figure 5 illustrates the 3D modeling process from the profile images to the 3D surface model. The tooth preparation and child's tooth models have 139,498 and 113,450 points respectively, which can be enough for both visualization and engineering applications. Sliced point cloud has organized properties and has the advantage when used in dental/engineering applications because the format of the point cloud (slice by slice) is the same as traditional CMM scanners (line by line).

This comparison result has been very promising for restorative dentistry. The vision system was proved to have an accuracy of within *100* µm on the child's tooth cracked region and within *50* µm on the tooth preparation model. The point cloud successfully recorded the surface details of the two teeth models. The vision system digitizing accuracy can be improved by a) introducing higher resolution cameras while current CCD camera only has effective pixels of 768 × 494 and b) increasing the precision of the turntable rotation.

5. CONCLUSIONS AND FUTURE WORK

A vision rig prototype has been designed, fabricated and tested being capable of scanning different types of objects, especially in the area of restorative dentistry. The rig prototype functions have been demonstrated on two typical samples used in dentistry. The point clouds obtained by the vision system had a good density compared to Triclone. SMA has shown its potential in processing a single tooth. The results were very promising and can be improved by various methods. Current development concentrates on a final integrated system, incorporating the Stereo Vision technique and LED structure lighting devices.

ACKNOWLEDGMENT

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