Dental Robotics: A Method to Automate Veneer Preparation

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***Abstract*—The current trend of automation in modern prosthodontics has reached significant maturity since its conception in the context of the fabrication of the constructive components, such as dental bridges and dental crowns. However, the procedure of preparing the tooth in order to place a dental crown has yet to be automatized. As a preliminary study to achieve such goal, this paper presents a series of methods that generate a trajectory for a robot to prepare an incisor to fit a dental veneer from a 3D scan. As of the current state of the research, a preliminary demonstration and results are presented. A more thorough numerical analysis of the result is currently a work in progress, and a referral to the newest article is presented in the conclusion.**

I. Introduction

An increasing interest to integrate CAD/CAM(Computer Aided Design/Manufacturing) into modern prosthodontics have stimulated the development of practical automated fabrication of dental crowns[1]. However, automation of the tooth preparation has yet to develop and therefore must be completed manually by the dentist using several tools to guide the preparation of the tooth[2]. A significant disadvantage of the manual preparation is that a wax casting of the prepared tooth must be first sent to a lab in order to fabricate the dental crown, and in the mean while a provisional crown is placed on the prepared tooth. Automating the preparation process will eliminate the need of a provisional crown, as the shape of the finished tooth is determined before the preparation is completed, and the dental crown could be fabricated preoperatively and placed immediately after the tooth preparation. The purpose of this paper is to develop a method to generate a trajectory for an automated crown preparation for the incisor, or a dental veneer preparation based on a 3D scan of the incisor and a method to evaluate the preparation completed by a robot. A preliminary implementation of the preparation on a plastic maxilllary incisor model using a general purpose 6DOF robotic arm and an evaluation of the performance are presented as a result.

II. Methodology

Clinically, a veneer preparation consists of removing a specific depth of enamel from the surface, adding chamfers at the priximal of the incisors, and removing 1.5mm of the incisor from the incisal edge. Additionally, the finished surface man not contain undercuts, as the placement of the veneer will be impossible. The core of the methodology of automatizing the veneer preparation is to generate a trajectory for a robot holding a dental drill that will reduce the incisor into the designed shape that will satisfy the clinical requirements. The trajectory is generated from cross sectional geometry of the 3D scanned image of the incisor and input parameters that will specify the boundary on the incisor surface to apply the preparation.

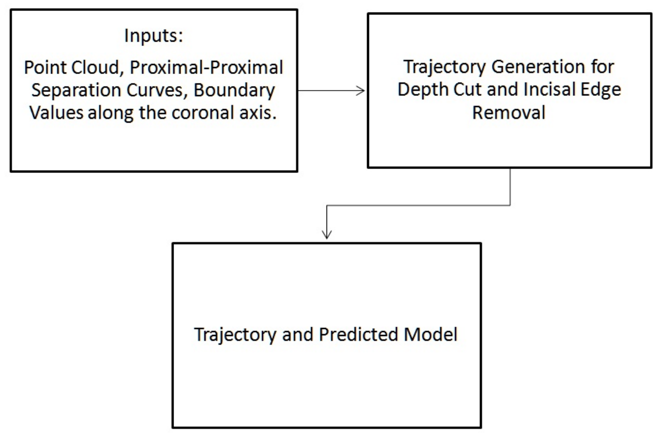


Fig. 1: Block Diagram of the Workflow

A. *Quantified Clinical Specifications of Veneer Preparation*

The specification of the veneer preparation is summarized below.

1) Surface Depth: Clinical study[3] suggests an optimal amount of enamel to be removed at different coronal positions, and therefore the depth of enamel to be removed must be fully controlled as a function of the location along the coronal axis. The trajectory generated must remove a uniform depth of enamel specified at each cross section from the surface of the incisor must be removed. The specified depth is 0.3mm at the most apical crosssection, 0.5mm at 3/5 th of the length of the incisor, and linearly interpolated inbetween. The specified depth is a 0.5mm beyond 3/5th of the length of the tooth.

2) Chamfer: Even though there are several conditions[4] on the proximal ends of the finished surface, for this paper the end curves are chosen to have chamfers due to the quantifiability by approximating the shape as a quarter circle that has a radius equal to the depth of enamel removed at the cross section.

3) Undercuts: The precense of undercuts make the placement of the veneer impossible. Therefore, the resulting configuration of the finished incisor should contain no undercuts.

4) Incisal Edge Removal: A specified length from the incisal edge along the apical direction is removed to create space for the veneer to be placed.

B. Input Parameters

The trajectory will be computed based on the following parameters: (Fig. 2).

1) Scan of the Incisor - Image obtained from a 3D scanner that containts the surface geometry of the tooth. For simplicity, the orientation of the image is adjusted such that the z-axis is parallel with the coronal direction.
2) Proximal to Proximal Separation Curves - A discrete curve specified by design that is used to parametrically specify the proximal to proximal boundary of the incisor in which enamel is removed, as a function of the length along the coronal direction.
3) Top and Bottom Value - The length along the coronal direction that the top value determines the length from the incisal edge to be removed, and the bottom value determines where the gingival margin is.

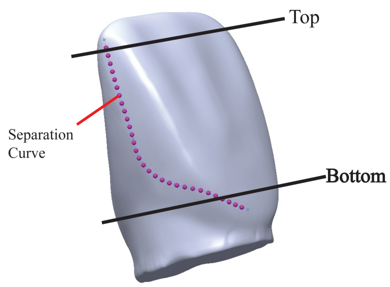


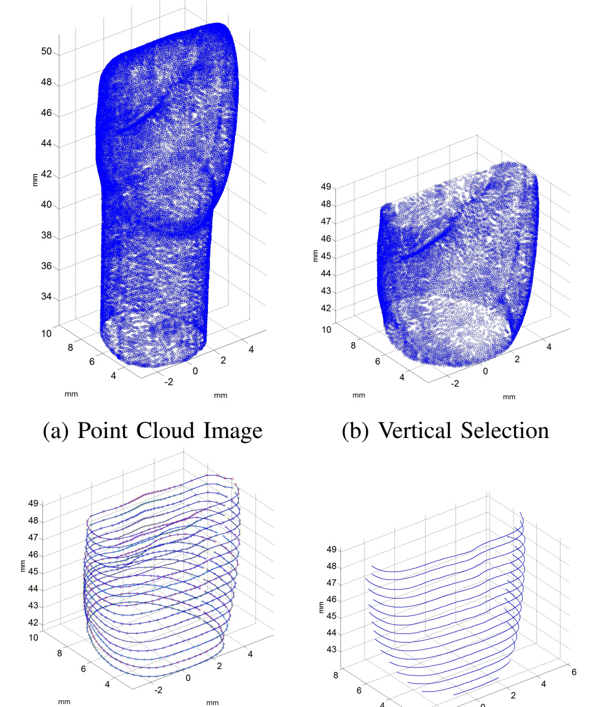
Fig. 2: Separation curve, top and bottom defined with respect to the scan

C. Depth Cut Trajectory Generation

1) Surface Reduction into Rectangular Map: The most general form of a 3D scanned image is the point cloud format, where the image of the object is represented as an unordered collection of points(Fig 2. 3a). However, in order to compute the trajectory for the veneer preparation using 2 dimensional geometry, the image of the incisor must be reduced into intervals on the cross sectional contours by the following steps:

1) Select points contained within the interval of the gingival margin and the length from incisal edge to be removed. (Fig. 3b)
2) Sort the points into containers corresponding to intervals of cross sections along the coronal direction of the incisor, while modifying the coronal position to be uniform within each container.
3) On each cross section, collapse points in an angular interval to their mean, specified by the imported separation curves. 3c)
4) Truncate the cross sections by the specified angular boundaries.

The process is illustrated by Figure 3, and the resulting set of curves is referred as outer reference curves (Fig . 3d).



(a) Point Cloud Image (b) Vertical Selection

(c) Vertical and Angular Reduction (d) Outer Reference Curve

Fig. 3: Generation of Outer Reference Curves

2) Inner Reference Curves: Once the outer reference curve of the surface of the incisor has been obtained, the inner reference curves are computed by translating the points of the outer reference curve along the normal of the tangent line by the specified depth at each cross section, as illustrated by Figure 4.

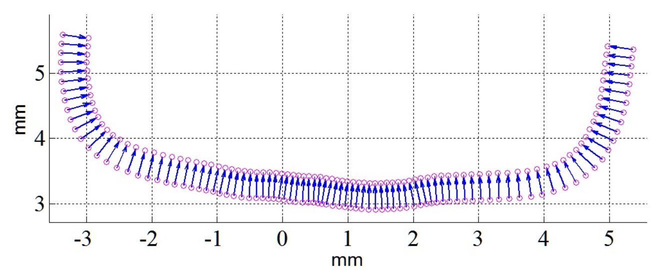


Fig. 4: Determination of inner reference curve

3) Adding the Chamfer: The trajectory to follow the chamfer is determined by a parametrized quasi-quarter circle that has a radius of the specified depth of the cross section, departs the end of the outer reference curve orthogonally, and merges into the inner reference curve in parallel. The end of inner reference curves are replaced with this quarter circle as illustrated in Figure 5.

4) Undercut Removal: Undercuts are detected by traversing the inner reference curve and observing the direction vector

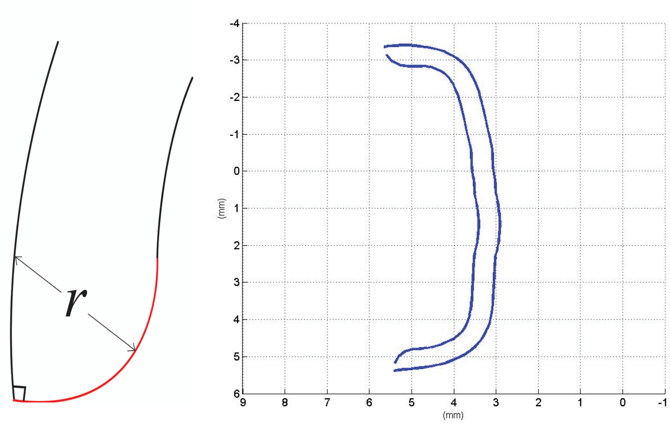


Fig. 5: Replacing the end of the inner reference curves with the computed chamfer

from. An undercut is detected when the following condition occurs.

$$(\vec{inner}_{i+1} - \vec{inner}_i) \cdot \vec{axis\_h} < 0$$

Where $inner_i$ and $inner_{i+1}$ are two consecutive points traversing the inner reference curve, and axis_h is the direction vector from the first point to the last point on the inner reference curve. When an undercut is detected, $inner_{i+1}$ could be translated along axis_h to resolve the undercut. The direction of translation is chosen to increase the depth of the veneer and remove more enamel, as the veneer requires thickness to retain mechanical resilliance. The method is illustrated in Figure 6.

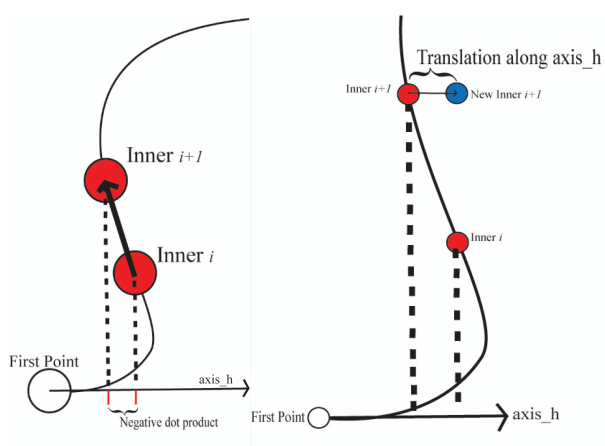


Fig. 6: Undercut Detection and Rectification

D. Incisal Edge Removal

The trajectory to remove a length from the incisal edge is computed by straight lines that span the bounding rectangle of the proper cross section. The cross section is the cross section from the peak of the tooth minus the desired height to be removed. The trajectory is illustrated in Figure 7.

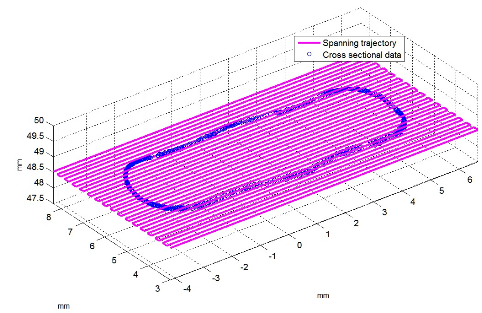


Fig. 7: Trajectory for removing a length from the incisal edge

E. Generating The Predicted Model

By combining the computed trajectory and parts from the original pointcloud removed earlier in the process, the predicted model can be generated, as illustrated in Figure 8. This model is used as a reference for assessing how well the robot drilled the surface compared to the specified design.

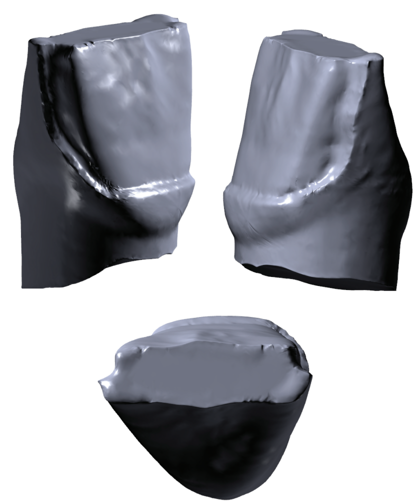


Fig. 8: The predicted model rendered from the original points and the computed trajectory

III. Results

A preliminary implementation of the procedure was carried out with the Denso VM-G general purpose industrial robotic arm, and we were able to demonstrate that the surface was formed into the shape specified in the design stage (Fig. 10). A more thorough testing comparing the performance of the robot to a human dentist is currently in progress.

IV. Conclusion

A large part of demonstrating that a robot is capable of carrying out the veneer preparation procedure is currently under progress as of April 6th, 2014 and therefore it is stated here that the newest version of this article including the supporting results will be available at http://people.ucsc.edu/~ikanuma/dental_robotics.html in the nearest future. The work

Fig. 9: The robot executing the trajectory on the incisor model

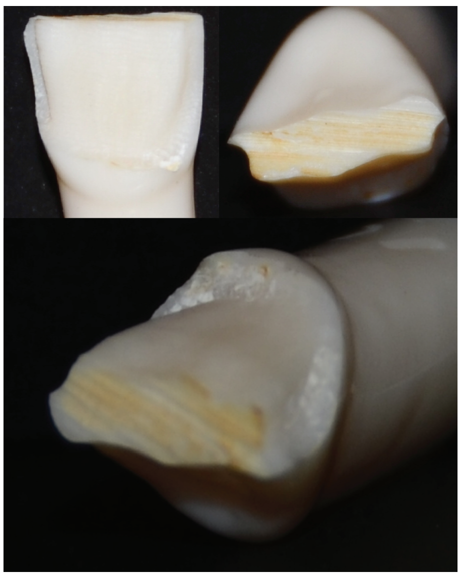


Fig. 10: Incisor after preparation by robot. The prepared tooth features chamfers and a uniformely reduced surface.

presented in this paper is the development of the techniques to generate a trajectory for a static incisor from a scanned image. Future works necessary to bring the techniques developped in this paper in a clinical setting are dynamic position tracking of the moving patient and a demonstration that a dental veneer could be created beforehand the procedure. Even though only the procedure was tested on the incisor only, the technique presented in this paper could easilly be applied to other teath as long as the scanned images are available.

Acknowledgment

Ikuru would like to thank Dr. Takafumi Otani, Dr. Ariel Raigradski, and Professor Jacob Rosen for their patience for the maturity of this project. Additionally, Ikuru would like to thank Daniel Lavell for the countless hours assisting the project.

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