HAVE 2008 – IEEE International Workshop on
Haptic Audio Visual Environments and their Applications
Ottawa – Canada, 18-19 October 2008

Mixed Reality Software for Dental Simulation System

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***Abstract*—This paper presents a dental simulation system. This is prepared for students in the faculty of dentistry so as to examine skills of dental surgery operations. The mixed reality system is for cutting human STL-based teeth by a STL-based bar mounted on a turbine. All STL-based data is captured by the computed tomography (CT) scan. It uses X-rays to make detailed pictures of the structures in and around a human oral for each patient. As a result, we expect a personal-oriented treatment. Furthermore, the system has visual, tactile, and sound realities. The visual reality is supported by the OpenGL, the velocity of bar tip is an output and the tactile reality is an input in the OpenHaptics. In addition, the sound reality is controlled by the OpenAL, which is directly monitored from a wonderful microphone. All are combined by Microsoft Foundation Class (MFC) as a human interface. Finally, we can feel a tactile force on the basis of the penalty method using penetration depth and relative velocity between STL-based bar and teeth. To calculate the penetration depth quickly, we use the Quickhull and Gilbert, Johnson and Keerthi (GJK) algorithms.**

I. INTRODUCTION

For student education in the faculty of dentistry, we build a novel dental mixed reality system for cutting a human tooth by a dental bar located on a turbine tip, which are completely captured from the CT scanner as STL. Before constructing this system, we investigated three previous works. One is the FreeForm software provided by the SensAble Technologies Inc. [1] (shown by the middle LCD (Liquid Crystal Display) in Fig.1). In the FreeForm, we comfortably scrape or deform many kinds of materials including teeth. However in the software, we cannot freely design any bar and also do not have any possibility to combine many kinds of tooth parts such as decayed tooth, enamel and ivory qualities, dental pulp and so on. Another is VRDTS (Virtual Reality Dental Training System) (illustrated by right LCD in Fig.1). In the system, we can virtually drill a decayed tooth including enamel quality, ivory quality, and dental pulp. This prototype is being developed by the Harvard School of Dental Medicine, and successively Novint is developing the VRDTS prototype [2]. Unfortunately, we did not understand how the VRDTS is implemented since Novint did not provide further information. In the classic version, we cannot retrieve any real tooth data scanned by CT scanner, and also cannot renew old shapes and abilities of bar and turbine. The other is Kim's approach [3], [4], [5]. In his approach, volumetric implicit surface is used for surface modeling and haptic rendering while sculpting. The main defective points are as follows: (1) Each virtual tooth is roughly approximated. It is not a real data which is captured from a real CT scanner. (2) Each pair of bar and turbine is roughly expressed by combination of bigger ball and circle pillar. This approximation generates the lack of tactile and visual realities. On the observation, we decide to develop a new dental simulation system (described by left LCD in Fig.1).

Fig. 1. A comparative photograph of FreeForm, VRDTS, our dental haptic simulator.

In order to feel a force artificially, we firstly construct the convex hull of teeth sequence by the **Quickhull** algorithm [6], [7]. **Qhull** computes the convex hull of some complex concave object [6]. The Qhull also computes volumes, surface areas, and approximations to the convex hull. Secondly, we calculate penetration depth between bar and teeth by the **Gilbert, Johnson and Keerthi (GJK)** algorithm [7]. The GJK algorithm tracks the vector of penetration depth between a pair of convex polyhedrons in time that is expected to be bounded by a constant. Thirdly, using in the **Kelvin-Voigt**

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material based on the depth vector and the velocity before contact as the penalty method, we generate an artificial force [8], [9], [10].

The **penalty** method introduces restoring forces when objects inter-penetrate [8],[9]. It produces highly realistic animation between rigid non-penetrating bodies. Interpenetration was prevented in both papers by introducing arbitrary penalty forces that acted to separate penetrating bodies; a natural solution method, since dynamical correctness of these forces was not a focus of either paper. The original method introduced spring forces to prevent bodies in resting contact from penetrating. As contrasted with this, this system selects the **Kelvin-Voigt** material whose forces are simultaneously made by spring and damper. Finally, using the Haptic Device API (HDAPI), we feel an adequate force by a popular haptic device PHANToM (The SensAble Technologies Co.).

This paper uses OpenGL, OpenAL, OpenHaptics, and MFC to construct a teeth simulation system through a haptic audio visual environment. This is explained in section 2. In section 3, we focus on software of the proposed system. The flowchart and performance evaluations are presented. Finally in section 4, we conclude our research and also evaluate some drawbacks.

II. Our Dental Simulation System

In this paper, we explain our dental simulation system. First of all, we focus on PHANToM haptics device which flexibly manipulates a 3-D CG environment and simultaneously controls an arbitrary tactile feeling between encountered virtual objects (Fig.2). In our dental system, if we put the upper blue button, we can cut a STL-based tooth by a STL-based bar located on the top of a turbine.

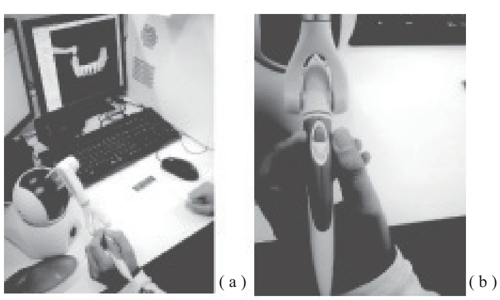

Fig. 2. (a) All the teeth, bar, and turbine are virtually described as STL in a 3-D CG environment. (b) A human operator can manipulate blue and white buttons in the haptic device PHANToM OMNI.

As shown in Fig.3, our basic software roughly consists of three procedures such as calculating collision check, doing penetration depth (right middle), and generating a force (right bottom). The last force can be felt by the force feedback device PHANToM OMNI (right bottom) under the OpenHaptics (HDAPI). In addition, our application software has three procedures as monitor display (right upper) by OpenGL, sound propagation (left middle) by OpenAL, and human interface based on bar, turbine, teeth data (left bottom) via keyboard and mouse, which are controlled by Microsoft Foundation Class Library (center upper).

In order to capture real shapes of teeth, bar, and turbine in a dental hospital, we use a computed tomography (CT) scan. It uses X-rays so as to make detailed pictures of structures in and around a human oral. Therefore, we can exactly and individually capture teeth, maxilla, mandible bone, lips, and muscles as several kinds of data structures as Bitmap, JPEG, TIFF 16bit including STL format. The STL format is one of standard formats for the exchange of surface shape data, especially in rapid prototyping field, which replaces the original surface with a collection of triangulated surface segments. In our system, we precisely approximate all data from the CT scanner with high precision as triangular polyhedrons (STL).

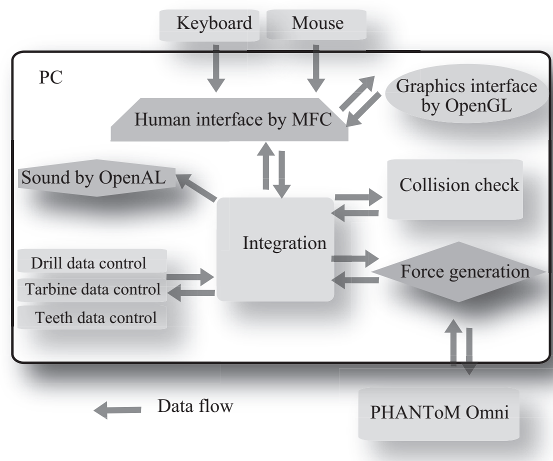

Fig. 3. Architecture of our dental simulation system.

As illustrated in Table I, we can see shape complexities of bar and turbine. While changing many kinds of bars located on the tip of turbine, a dental doctor adequately cuts a STL-based tooth by a STL-based bar in our dental mixed reality system (Fig.4).

TABLE I
Vertex and surface numbers of STL-based bar and turbine.

Parts	Vertex number	Surface number
Bar	170	333
Turbine	11458	20988

Moreover, as shown in Table II, we can see complexity of teeth sequence according to the resolution of CT scanner. Here, the highest resolution model (100 percentages) cannot be used because it is too heavy to be operated rotationally or parallel by a human operator in a popular desktop PC.

Finally, in Fig.5, we explain how to use our dental simulation system according to the initial display image. In the initial image, we can access six blocks such as menu bar, file bar, drill bar, tool bar, sound control, and parameter box. The rest is the center block which controls the whole CG image supervised by OpenGL. The others are basically combined

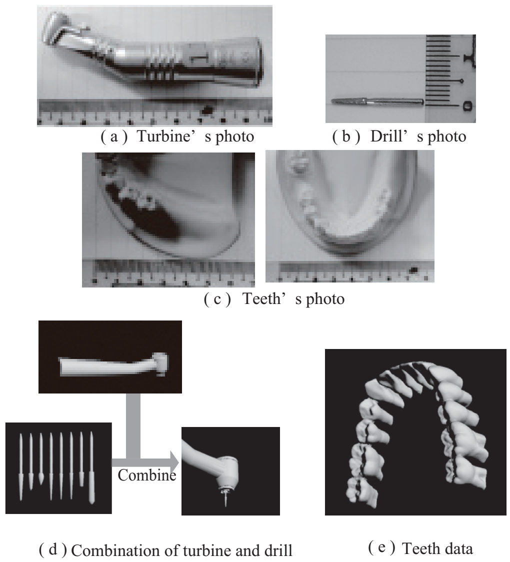

Fig. 4. Comparison between real (a) and virtual (b) dental surgery data.

TABLE II
VERTEX AND SURFACE NUMBERS, RETRIEVING AND DRAWING CALCULATION COSTS OF TEETH REPRESENTED BY STL WITH SEVERAL RESOLUTIONS.

Resolution	Vertex number	Surface number	Retrieving time (ms)	Drawing time (ms)
Plane	169	288	79	12
6%	4882	9760	109	15
12%	9762	19516	219	31
25%	20335	40656	485	47
50%	34273	68151	843	48
100%	162672	325312	4406	183

by Microsoft Foundation Class (MFC). In file bar, we can retrieve one of teeth data whose resolutions are 6, 12, 25, 50 and 100 percentages. In the drill bar, we can pick up one of many types of bars whose shapes and performances are quite different. Moreover in the tool bar, we can adequately moderate the mixing sound ratio of motor rotating and teeth cutting. Finally in the parameter box, we can flexibly adjust physical parameters of damper and spring in the **Kelvin-Voigt** material.

A. VISUAL REALITY by OpenGL

The OpenGL is the most popular programming interface for developing a 3-D computer graphics environment. The OpenGL is the API (Application Programming Interface) which prepares image rendering, texture mapping, special effects, and other powerful visualization functions.

B. SOUND REALITY by OpenAL

The OpenAL (Open Audio Library) is the audio of cross-platform API. Using the OpenAL, we obtain sound realities such as motor rotating and tooth drilling (Fig.6). The OpenAL efficiently makes rendering of multichannel three dimensional

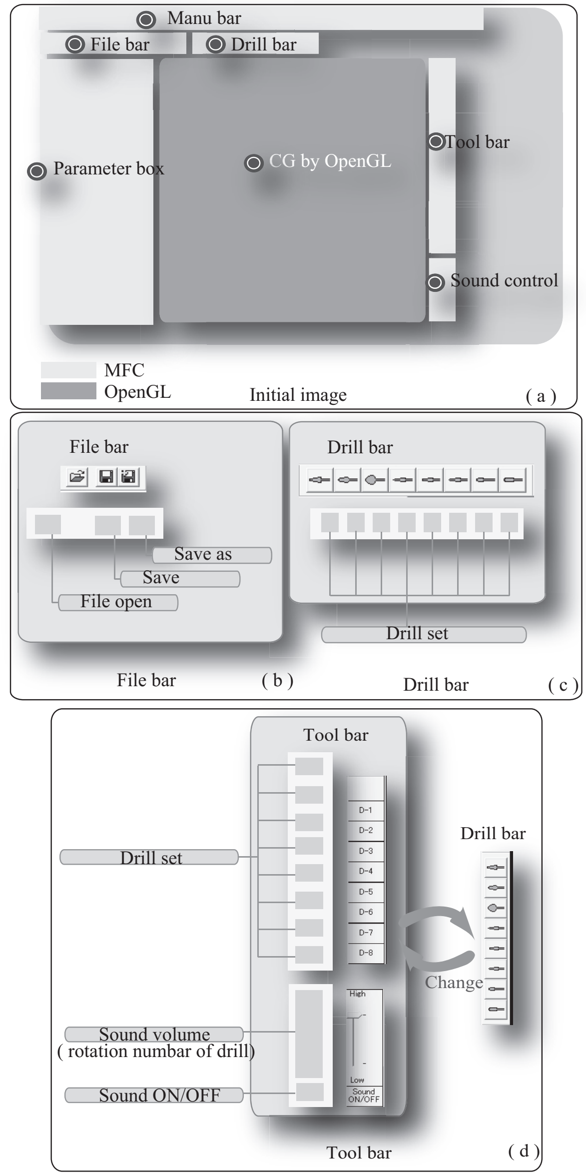

Fig. 5. Our system includes many kinds of blocks.

positional audio. The style and the custom of API are intentionally modeled with OpenGL.

C. TACTILE REALITY by OpenHaptics

The OpenHaptics directly controls all the PHANMToM devices to feel an arbitrary force artificially. That for making tactile reality is directly connecting with the OpenGL for generating visual reality. It can also simulate haptic material properties such as friction and stiffness. The toolkit mainly includes the Haptic Device API (HDAPI) - low level access to the haptic device - and the Haptic Library API (HLAPI) - high level access to the haptic device -. In this research, we use the HDAPI which enables haptic programmers to render forces directly.

D. HUMAN INTERFACE by MFC

In our system, we should prepare many kinds of windows and buttons (switches) as shown in Fig.5. For this purpose, we use MFC (Microsoft Foundation Class Library). The MFC is a library that wraps portions of the Windows API in C++ classes. The classes are defined for many of the handle-managed windows and also for predefined windows and common controls. It mainly controls many bars concerning to human computer interaction. For example, the sound control adequately mixes sounds and their volumes of cutting teeth and rotating motor. This is achieved by the OpenAL.

Furthermore, by using parameter box, we can moderate contacting or cutting a force against a STL-based tooth by the OpenHaptics (HDAPI). Finally, if a human operator changes his eye position, the total image including all the teeth, dental bar, and dental turbine is smoothly changed by the OpenGL.

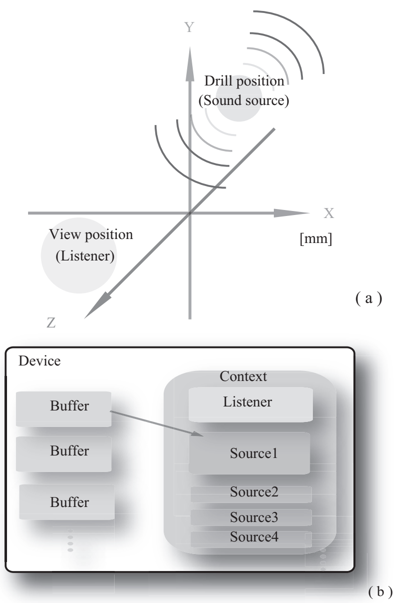

Fig. 6. (a) Relation of sound source and listener. (b) Architecture of OpenAL.

III. FLOWCHART AND PERFORMANCE EVALUATIONS OF OUR SYSTEM SOFTWARE

In this section, we describe details of our dental simulation system. First of all, the flowchart is illustrated in Fig.7. As mentioned previously, the system consists of three procedures as visual procedure, tactile procedure, and sound procedure. In succession, the three procedures are combined by the human interface procedure.

Firstly, we describe a stroboscope for cutting STL-based teeth by a STL-based bar. As illustrated in Fig.8, we drop a STL-based bar on STL-based teeth vertically along the y-axis. Therefore, the distance between bar and teeth decreases monotonously. In this situation, we check precision of penetration depth calculated by the **GJK** algorithm. As shown

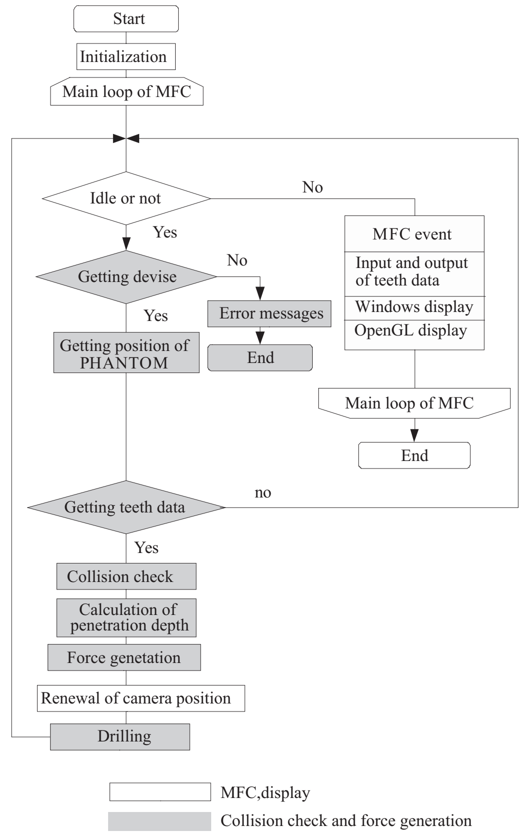

Fig. 7. Flowchart of our dental simulation system.

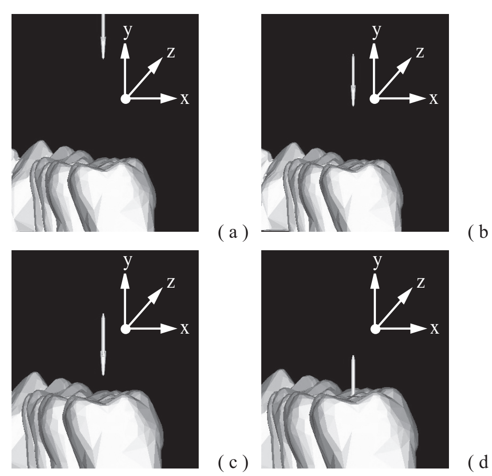

Fig. 8. Stroboscope for drilling STL-based teeth by a STL-based bar along the y-axis.

in Fig.9, we can understand two properties: (1) The collision between bar and teeth is exactly detected. (2) The penetration depth increases monotonously as the distance between bar and teeth decreases monotonously. They are wonderful characteristics for generating a tactile force exactly and continuously.

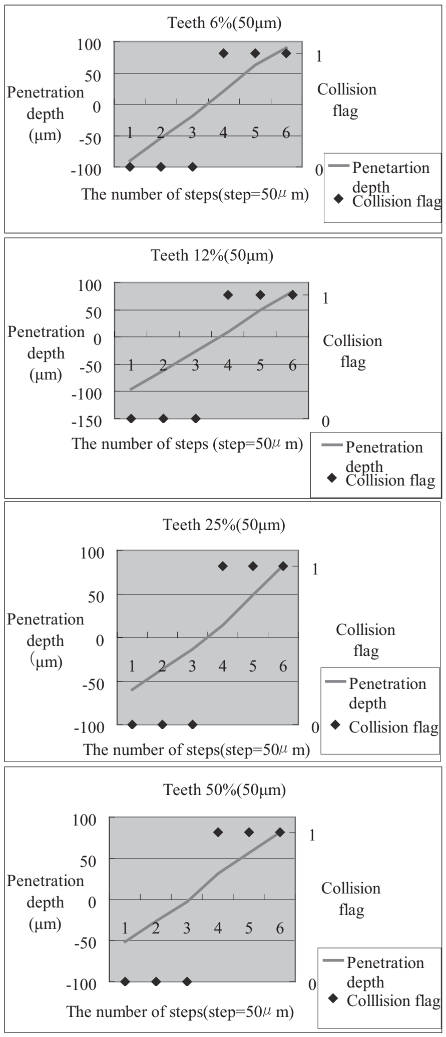

Fig. 9. Precision check of penetration depth between STL-based bar and teeth whose resolutions are 6, 12, 25, 50 percentages, respectively, (a), (b), (c), (d).

In addition to this, we describe calculation time of contact detection and penetration depth in Table III. The algorithm quickly identifies every non-contact state, but unfortunately it is a little bit time consuming to identify every contact state and penetration depth between bar and turbine.

In order to check whether the penetration depth is precisely calculated or not, we drop a bar on the xz-plane along the y-axis. The stroboscope is illustrated in Fig.10.

In this simulation, the distance between bar and plane decreases monotonously. Especially, from the contact state between bar and plane, the bar intersects the plane per each movement whose resolution is between 100 μm and 0.1 μm. As described in Table IV, we can see the minimum resolution

TABLE III

CALCULATION TIME FOR CUTTING OR NON-CUTTING A STL-BASED TOOTH BY A STL-BASED BAR, WHOSE RESOLUTIONS DIFFER FROM EACH OTHER.

Resolution	Cutting (ms)	Non-cutting (ms)
plane	1.0875	0.2625
6%	154.9	0.95
12%	326.8	0.85
25%	632.2	0.9
50%	1193.65	0.95
100%	871.5454545	22535.16667

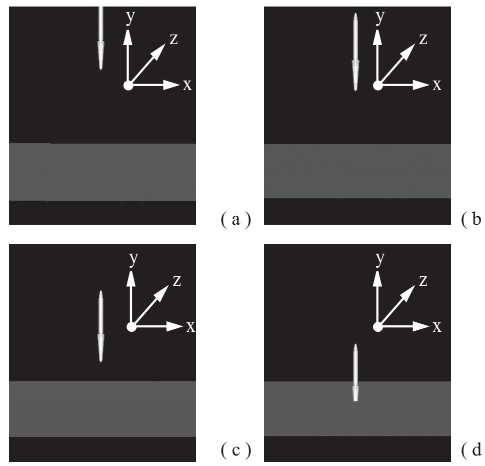

Fig. 10. Stroboscope for contacting a plane by a bar.

to identify the intersection is always smaller than or equals to 20μm. In dental surgical simulation, this is an acceptable resolution because the diameter of human hair is between 18μm $\sim$ 180μm, which a human being can see an intersection by biting it.

TABLE IV

INTERSECTION CHECK PER MOVEMENT PRECISION BETWEEN BAR AND PLANE. DP MEANS IDENTIFICATION POSSIBLE, AND IP MEANS IDENTIFICATION IMPOSSIBLE.

μm	100	50	25	20	15	10	5	1	0.1
6%	DP	DP	DP	DP	DP	DP	DP	DP	DP
12%	DP	DP	DP	DP	DP	DP	DP	DP	DP
25%	DP	DP	DP	DP	DP	DP	DP	IP	IP
50%	DP	DP	DP	DP	IP	IP	IP	IP	IP

Finally, we will give examples of force sequences for cutting and touching STL-based teeth by a STL-based bar. The stroboscope is illustrated in Fig.11. For such a normal operation, we can feel adequate sequences of tactile forces as follows: In Fig.12, we can see different tactile feeling in cutting or touching teeth by a bar. Moreover in Fig.13, we can understand different tactile feeling if a STL-based bar contacts with a STL-based teeth by low or high speed. Here, we should note that all the forces can be adequately adjusted by coefficients of spring and damper in the **Kelvin-Voigt** material, and they are limited to be felt under the upper bound 3.3[N] of the force feedback device PHANMToM OMNI.

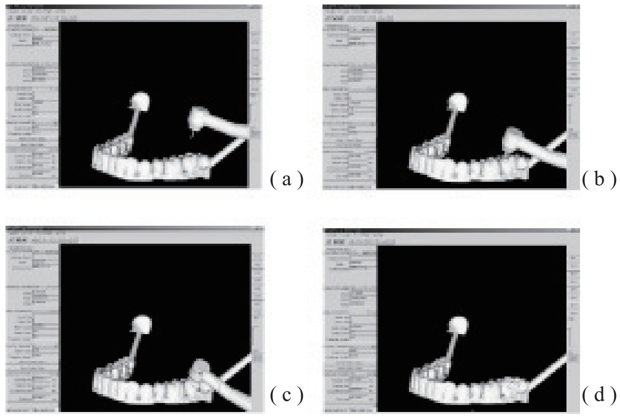

Fig. 11. Stroboscope for cutting STL-based teeth by a STL-based bar.

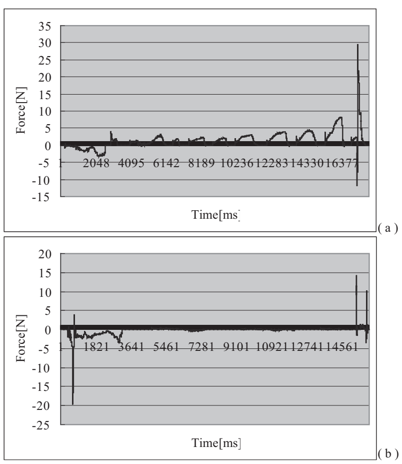

Fig. 12. Force sequences for (a) cutting or (b) touching STL-based teeth by a STL-based bar.

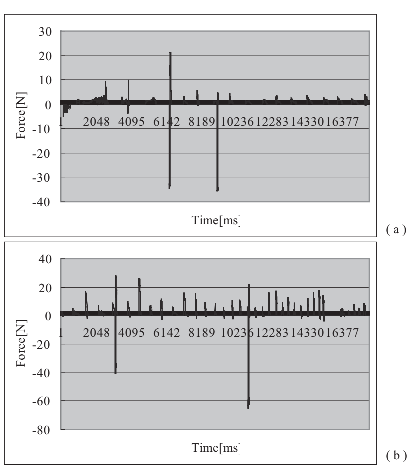

Fig. 13. Force sequences for touching STL-based teeth by a STL-based bar whose speed is low (a) or high (b).

IV. CONCLUSIONS AND ONGOING WORKS

For the student education in the faculty of dentistry, we proposed a novel mixed reality system for cutting human STL-based teeth by a STL-based bar mounted in a turbine. All data are captured by the CT-scanner as STL. The system consists of four parts, human interface by MFC, visual part by OpenGL, tactile part by OpenHaptics, and sound part by OpenAL.

Moreover, by using **Quickhull** and **Gilbert, Johnson and Keerthi (GJK)** algorithms, we efficiently calculate the penetration depth between bar and teeth. Therefore, based on the **Penalty** method using the penetration depth and contact velocity of turbine tip, we can calculate an artificial force. By using the PHANToM OMNI, we can adequately feel a tactile force.

Furthermore concerning to the resolution of teeth's STL, we deeply investigated precision of interference check between bar and teeth, and also precisely did precision of the penetration depth. Moreover, we exactly checked calculation time to check the intersection and also penetration depth between STL-based bar and teeth. As a result, we understand our system is wonderfully used by dental doctor and its candidates.

Finally, in future, we should modify our dental surgical system in order for us to touch or cut concave tooth by a convex bar quickly and exactly without the loss of visual and tactile realities.

V. ACKNOWLEDGMENTS

This is supported in part by 2006 Grants-in-aid for Scientific Research (No.18360128) and also is supported in part by the 2007 Modern Good Practice, from the Ministry of Education, Culture, Sports, Science and Technology, Japan.

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