Construction of Dental Simulation System with Mixed Visual, Tactile, and Sound Realities

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Abstract

The paper presents a novel dental simulation system by a smart combination of the existing software such as OpenGL, OpenHaptics, OpenAL, and also the auxiliary data structure for AABB trees and GJK-based penetration depth computation. They offer many comfortable human interfaces. Especially, all the algorithms are running under STL-based teeth and dental bars which are straightforwardly captured for a real patient and his environment in a dental hospital with the help of a dental CT-scan system. Using the proposed system, each undergraduate student learning in the faculty of dentistry can acquire many kinds of surgical operation skills.

1. Introduction

In this paper, we construct a smart dental simulation system with mixed realities, and especially check its tactile reality for touching or cutting a human tooth by a dental bar located on a turbine tip. The tactile reality is basically computed from the popular **AABB** interference check and simultaneously the famous **GJK** penetration depth algorithms. The system is used to acquire many kinds of operation skills in dental surgeries by undergraduate students in the faculty of dentistry. This is a mixed system of visual, tactile, and sound realities. All human teeth and dental bars are completely captured as triangular polyhedrons (STL) by a popular dental CT-scan system with high precision.

Our dental simulation system is a kind of multisensory interaction, a bridge between real and virtual worlds [1] (Left view in Fig.1(a)). The reality of this system comes from the following three aspects. One is a visual reality designed by the OpenGL. The OpenGL is the most popular API for computer graphics. Another is a sound reality which motor and drill sounds are directly memorized by a high-quality microphone. According to the speed of turbine motor, we can hear a mixture of rotating motor and scraping tooth, which is controlled by the OpenAL. The other is a tactile reality made from the OpenHaptics. The OpenHaptics, especially, HDAPI (Haptic Device API) is the API for controlling completely a force feedback device PHANToM provided by SensAble Technologies Inc. Finally, all are combined by Microsoft Foundation Class (MFC) as a human interface.

There are a few of software for dental surgical simulation. FreeForm software provided by SensAble Technologies Inc. is a 3-D design tool for many kinds of materials and many types of shapes. This can be applied for dental surgery (Right view in Fig.1(a)). As mentioned previously, we can approximately build many kinds of materials whose softness and hardness are selected as less than ten levels. Also in the FreeForm, we can basically design many types of tools by a set of typical shapes such as Constructive Solid Geometry (CSG). Therefore, dental bar and turbine are expressed by a set of bigger balls and circle pillars. As a result,

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we feel artificial shape and force via such approximations as black boxes since the FreeForm is not open source. Also in the software, we cannot unfortunately combine many kinds of tooth parts such as decayed tooth, enamel and ivory qualities, dental pulp and so on. The other possibility is Virtual Reality Dental Training System (VRDTS) (Fig.1(b)). In the VRDTS, we can combine a decayed tooth, enamel and ivory qualities, dental pulp as one tooth. This prototype (β-version) was developed by the Harvard School of Dental Medicine. Recently, we heard that the Novint Co. is developing the VRDTS new version [2]. Unfortunately, we cannot see how to revise the VRDTS, and whether Novint provides a new version or not. The classic β-version is running only in not PHANToM OMNI (cheaper haptic device) but PHANToM Desktop (more expensive haptic device). Furthermore in the β-version, we cannot use any real teeth data captured by the dental CT-scan, cannot add a new surgical operation, and also cannot renew classic shapes and abilities of dental bars and turbines. On the observation, we plan to construct a smart dental simulation system (Left view in Fig.1(a)).

Figure 1. (a) (Left) Our new system, (Right) FreeForm. (b) Virtual Reality Dental Training System (VRDTS).

In order to feel force sequence artificially, we always calculate the intersection between STL-based tooth and bar with the help of the **AABB** collision check algorithm. Even though both polyhedrons are to be concave and complicated shapes, the **AABB** algorithm determines their intersection quickly [3]. Furthermore, we calculate penetration depth between STL-based tooth and bar by the **GJK** algorithm [4]. The **GJK** algorithm always tracks the vector of penetration depth of the intersection in time that is expected to be bounded by a constant. Needless to say, there are many interference check and penetration depth calculations such as [5],[6]. However, their software are not open or are not be frequently used. The software **AABB** and **GJK** are to be open source and therefore can be easily revised for the academic usage. Finally, we note that the pair of **AABB** and **GJK** is popularly used in the digital game and amusement fields. Consequently the pair is quite stable because it has few programming bag via many experiences.

The **penalty** method that introduces restoring forces when objects inter-penetrate have also been presented [7],[8],[9]. It produces highly realistic animations between rigid non-penetrating bodies. In this research, we calculate the penetration depth between tooth and bar under the pair of **AABB** and **GJK**. In addition, using the Haptic Device API (HDAPI) under a haptic device PHANToM OMNI and its OpenHaptics toolkit, we can obtain a tip velocity of dental bar. Then, using the **Kelvin-Voigt** material based on the penetration depth multiplying spring coefficient and contact velocity multiplying damper coefficient, we make an artificial force as the **penalty** method.

Moreover, there are a few of similar works [10],[11],[12]. In these approaches, volumetric implicit surface is used for surface modeling and haptic rendering. The main defective points are as follows: (1) Each virtual tooth is roughly approximated. Also, it is not a real patient data which is captured from a real CT scanner. (2) Each bar or turbine is roughly expressed by combination of bigger ball and circle pillar. This contact approximation is far from the real kinematic relationship between STL-based dental bar and tooth which are really used by a dental doctor in a hospital. Finally, another type of dental operation was proposed in a dental surgical simulation [13]. In the system, a human feels contacts for teeth by a hand scaler and also observes teeth inside a mouse by a hand mirror. Both are achieved by the haptic devices PHANToM. The differences against our research are as follows: The proposed system is for us to investigate ideal virtual teeth by a scaler via a hand mirror. On the other hand, our system is for us to scrape patient's teeth by dental bars, which are captured from the CT-scanner in a hospital.

In this paper, we explain our dental simulation system in section 2. Especially in section 2, we explain many roles of software used in our system. Then in section 3, we describe several abilities concerning of computation, kinematic, and dynamic results in our mixed reality system. Finally in section 4, we conclude this research and also give an ongoing work.

2. Our Dental Simulation System

A multimodal system is proposed for a dental surgical simulation in this section. First of all, the simulation software is composed of three procedures such as calculating collision check (right bottom), investigating penetra-

tion depth (right middle), and generating a force (right top) (Fig.2). An artificial force can be felt by the force feedback device PHANToM OMNI (right top) under the OpenHaptics (HDAPI). In addition, our application software consists of three procedures as monitor display (left middle) by OpenGL, sound propagation (left bottom) by OpenAL, and human interface based on dental bar and turbine, teeth data (right middle) via keyboard and mouse, which are controlled by Microsoft Foundation Class Library (center upper). Finally, we use a computed tomography (CT) scan to capture STL-based teeth, dental bar, turbine, and mirror in a dental hospital. The STL format is a polyhedron with triangulated patches.

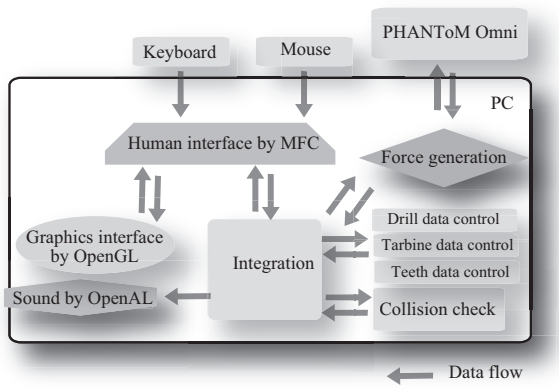


Figure 2. Architecture of our dental simulation system.

In Table 1, we can see shape complexities of dental bar and turbine. While changing many kinds of dental bars located on the tip of turbine, a dental doctor adequately cuts a tooth (Fig.3). As contrasted with this, we can see complexities of teeth in Table 2.

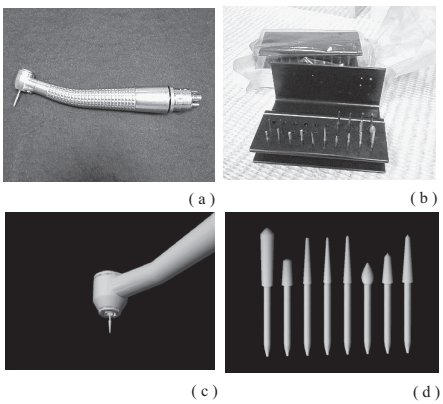


Figure 3. (a) A real turbine, (b) real bars, (c) a virtual turbine, (d) virtual bars.

Table 1. Vertex and surface numbers of STL-based dental bar and turbine.

Parts	Vertex number	Surface number
Drill	170	333
Turbine	11458	20988

Table 2. Vertex and surface numbers, retrieving and drawing computation costs of STL-based teeth.

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

2.1. VISUAL, SOUND, TACTILE REALITIES by OpenGL, OpenAL, OpenHaptics

First of all, on the basis of the OpenGL, we can easily display a 3-D environment in a PC monitor. Therefore, it is a kind of CG programming toolkit under C++ programming language. The OpenGL is strongly connected with the OpenHaptics explained later. For this reason, a human operator easily picks up and manipulates one of objects in the 3-D CG environment. Secondly, with the help of the OpenAL (Open Audio Library), we can flexibly control many types of sounds for cutting a tooth by a bar and rotating a motor of dental turbine (Fig.4). The OpenAL efficiently makes rendering of multichannel 3-D positional audio. Moreover, we can manage an artificial force directly by a PHANMToM haptic device under the OpenHaptics. In our dental surgical simulation, we use the Haptic Device API (HDAPI) which enables haptic programmers to render forces directly.

2.2. HUMAN INTERFACE by MFC

In Fig.5, we watch a whole 3-D CG world including teeth, bars, turbine and mirror smoothly in the center block of our dental simulation system by the OpenGL. In the sound control, we manipulate sounds and volumes for cutting tooth and rotating motor by the OpenAL. Then, based on the parameter box, we can moderate contacting or cutting force against a tooth by the OpenHaptics (HDAPI). Finally, this interface equips the other four blocks such as menu, file, drill, tool bars. All windows are mixed by the Microsoft Foundation Class (MFC).

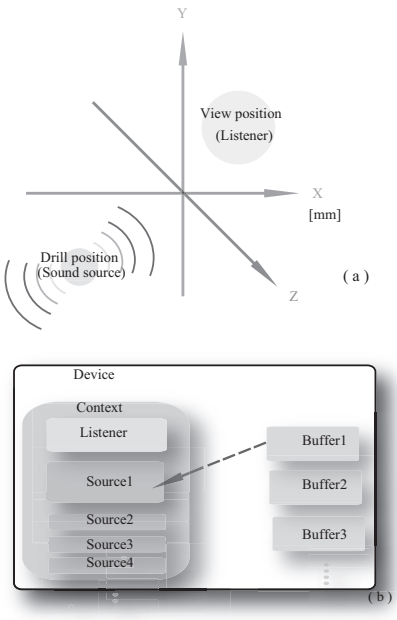


Figure 4. (a) Relation of sound source and listener. (b) Architecture of OpenAL.

3. DETAILS OF OUR SYSTEM SOFTWARE

Our dental surgical system consists of visual, tactile, and sound procedures. The procedures are combined by the human interface procedure. In this section, we mainly describe details of our dental simulation system. The relationship between world (camera), haptic, and mirror coordinate systems is illustrated in Fig.6. In addition, the sequence of initialization, pedal procedure to increase turbine rotation, collision check calculation, penetration depth calculation, scraping a tooth by a bar, generating an artificial force, drawing teeth, bar, turbine, mirror is illustrated in Fig.7.

Moreover, in our dental surgical system, we use dental bar, turbine, and mirror (Fig.8). The PHANToM haptics has blue and white buttons, and a human operator pushes one of buttons. In our system, a human operator selects one of dental mirror and turbine by the white button, and successively he switches touching and scraping a tooth by a bar by the blue button (Fig.9).

In order to check whether the penetration depth can be precisely calculated or not, we prepare a quite simple concave object whose number of patches is ten as illustrated in Fig.10. In succession, we show the penetration depth in Fig.11, which is calculated by the twin algorithms when a dental bar is vertically dropped onto the object surface with the same velocity at the positions A, B, C, respectively, in Fig.10 (a),(b), and (c). From all the simulation results illustrated in Fig.11, the penetration depth between encountered objects is always and precisely acquired as long as the tip speed equals to or is less than 8000 μm / 80 $msec$ = 10 cm/sec. The speed is fast enough to cut a tooth via a dental bar by a doctor. For this reason, the pair of algorithms is quite useful for our dental task.

Furthermore, in order to check whether these properties are accepted or not in a real pair of tooth and bar, we use STL-based tooth and bar as described in Fig.12. As described in these simulation results of Fig.13, the penetration depth between encountered objects is always and precisely calculated as long as the tip speed equals to or is less than 400 μm / 6 $msec$ = 6.6 cm/sec. The speed is also efficient enough to cut a tooth via a dental bar by a doctor. For this reason, the pair of algorithms is quite useful for our dental task.

Moreover, as illustrated in Table 3, we can see the combination of **AABB** and **GJK** algorithms is very efficient, which is always less than the time step (1ms) of PHANToM OMNI. From there properties, we can use the combination of the **AABB** and **GJK** algorithms is wonderful in order for us to feel a reactive force by the haptic device PHANToM OMNI.

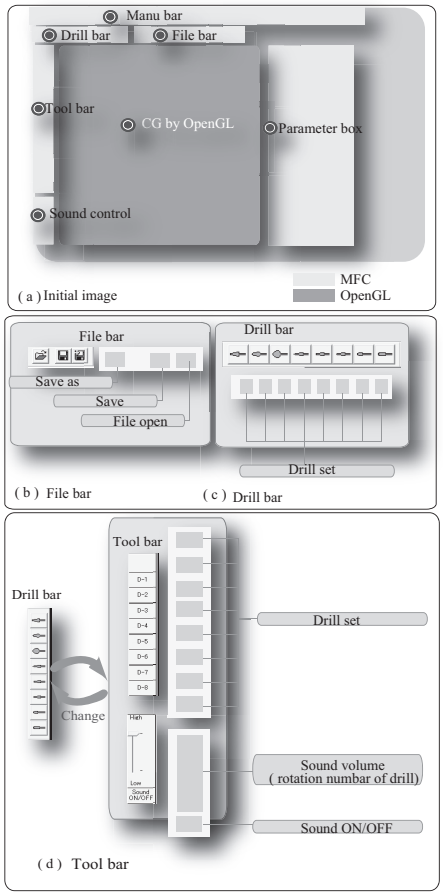


Figure 5. Our system includes many kinds of blocks.

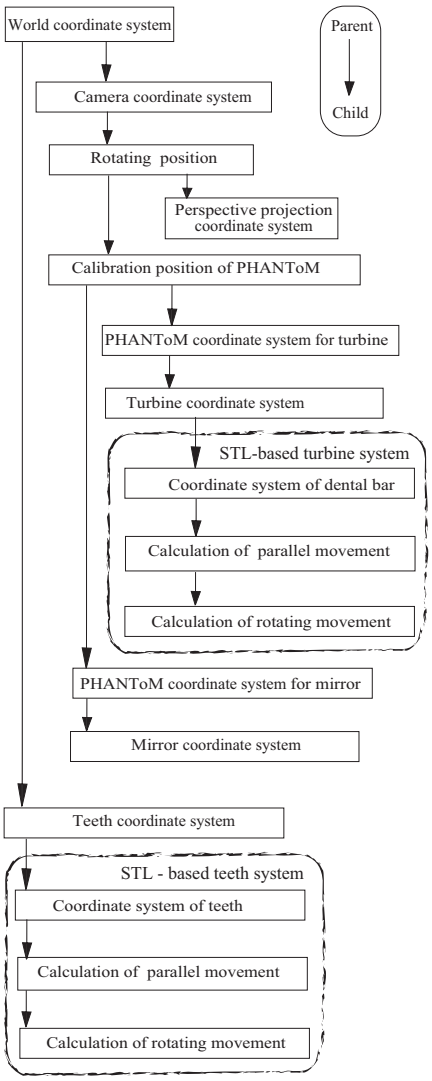


Figure 6. The world (camera), haptic, and mirror coordinates are combined in our dental simulation system.

Table 3. Calculation time for generating artificially an arbitrary force.

Contacted by a bar tip	Front tooth	Molar tooth	Dog tooth
High-velocity (ms)	0.0081	0.0119	0.0026
Low-velocity (ms)	0.01	0.0081	0.0016

Finally, we check minimum resolution of penetration depth as we change the resolution of STL. As described in Table 4, we can see the minimum resolution is always smaller than 0.5μm. This is an acceptable resolution because the diameter of human hair is between 18μm $\sim$ 180μm, which a human identifies by biting it.

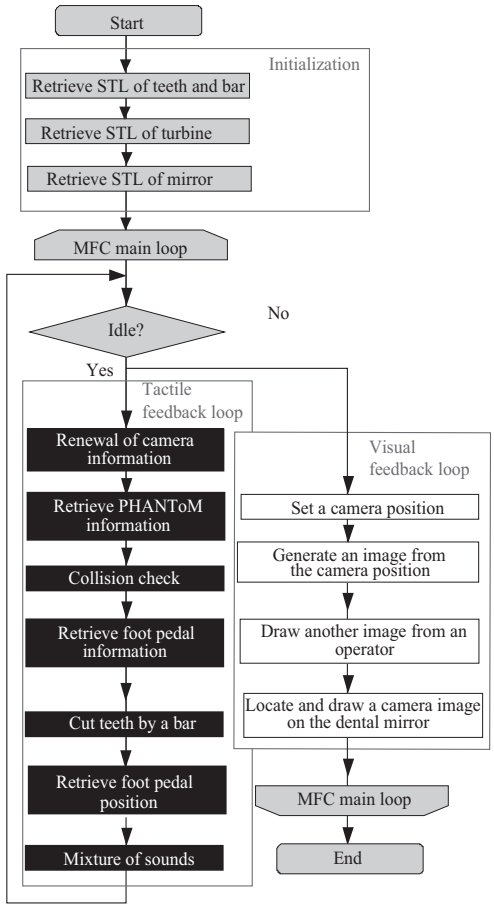
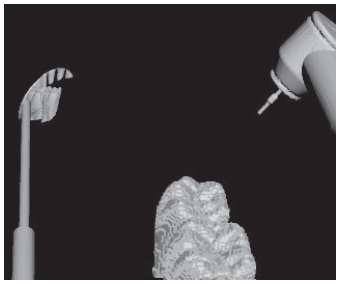


Figure 7. Initialization, a pedal procedure to increase turbine rotation, collision check calculation, penetration depth calculation, scraping a tooth by a bar, generating an artificial force, drawing teeth, bar, turbine, mirror in our dental simulation system.

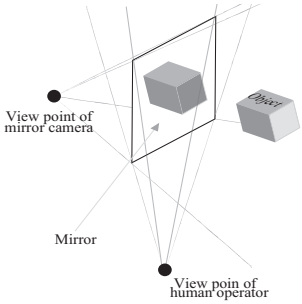
Table 4. Collision detection between STL-based tooth and movement precision of the tip of dental bar. DP means collision identified, and IP means collision non-identified.

μm	100	50	25	20	15	10	5	1	0.5	0.1
6%	DP	DP	DP	DP	DP	DP	DP	DP	DP	DP
12%	DP	DP	DP	DP	DP	DP	DP	DP	DP	DP
25%	DP	DP	DP	DP	DP	DP	DP	DP	DP	IP
50%	DP	DP	DP	DP	DP	DP	DP	DP	DP	IP

On these observations, we try to simulate many types of contacts in our dental surgical system. First of all, a human has many types of teeth, for example, front tooth, dog tooth, and molar as illustrated in Fig.14. For this reason, we try to contact each of teeth by a dental bar, and then we check to calculate an encountered velocity, and a penetration depth. Consequently, we feel sequence of artificial forces during some surgical operation. We ascertain two kinds of surgical

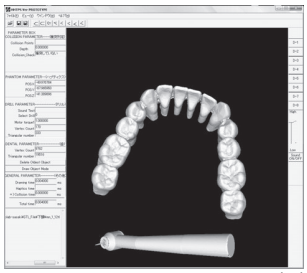


(a)



(b)

Figure 8. A human operator can use dental turbine or mirror independently.



(a)

(b)

(c)

Figure 9. (a) All the teeth, dental bar, dental turbine, dental mirror are virtually described in a 3-D CG environment. (b) A human operator selects one of the turbine and mirror by blue and white buttons in the haptic device PHANToM OMNI. (c) A human operator steps on a pedal to increase or decrease rotation of motor.

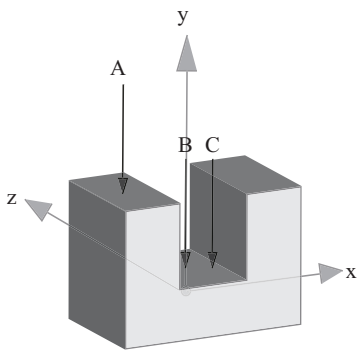
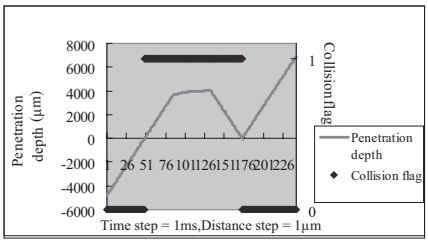
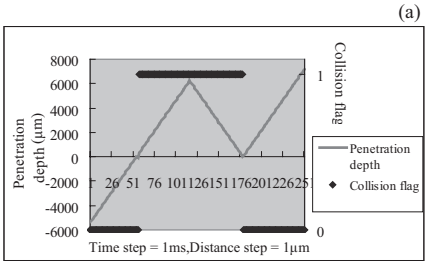


Figure 10. A simple concave object with ten patches, and its three positions A, B, and C to be pushed by the tip of dental bar (a),(b),(c), respectively.



(a)



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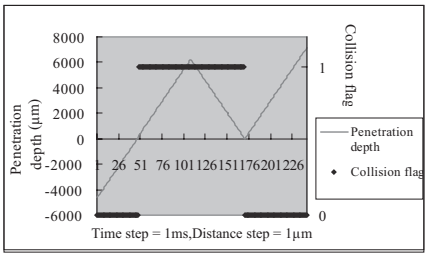


(c)

Figure 11. Penetration depth is monotonously and exactly changed as long as the tip of dental bar trusts a concave object at three positions A, B, and C whose speed is smaller than a tip speed in several popular surgical operations (a),(b),(c), respectively.

operations whose tip speeds are high and low.

In Fig.15(a),(b), we illustrate contact velocity, penetration depth, and artificial force if we touch the tip of dental bar to a front tooth by high and low speeds, respectively. In Fig.16(a),(b), we show contact velocity, penetration depth, and artificial force if we touch the tip of dental bar to a dog tooth by high and low speeds, respectively. In Fig.17(a),(b), we describe contact velocity, penetration depth, and artificial force if we touch the tip of dental bar to a molar by high and low speeds, respectively. As illustrated in these surgical results, we can get adequate force sequences in all

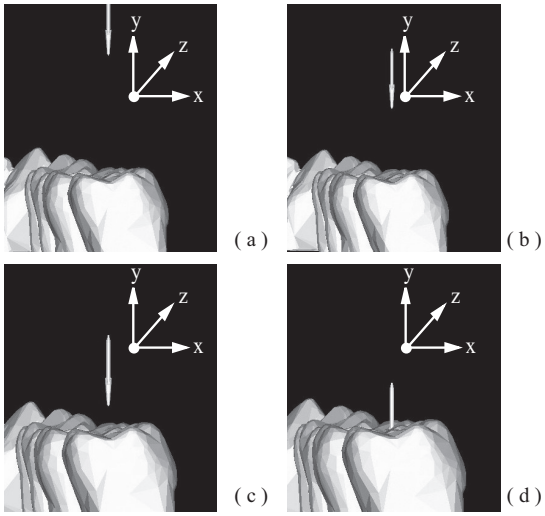


Figure 12. Stroboscope when the tip of dental bar trusts a tooth vertically along the y-axis.

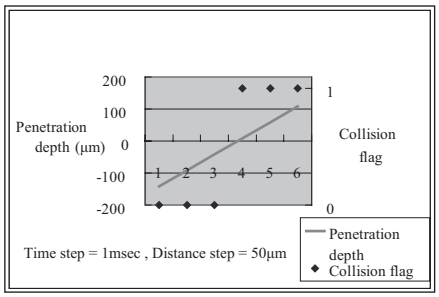


Figure 13. Penetration depth is monotonously and exactly changed as long as the tip of dental bar trusts captured teeth whose speed is smaller than a tip speed in several popular surgical operations.

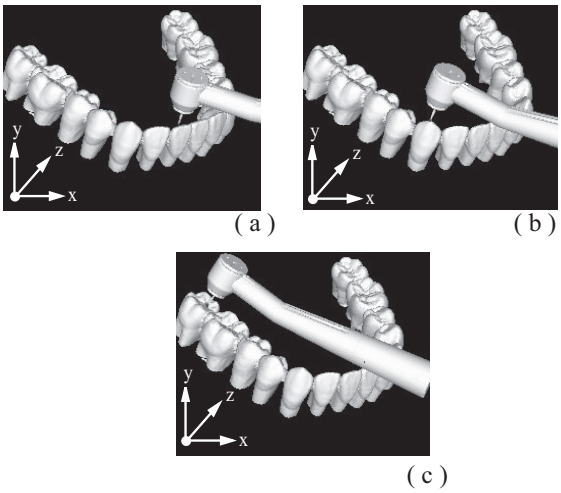


Figure 14. Front, dog and molar teeth are contacted by the tip of dental bar which is operated by a human, respectively (a),(b),(c).

operations, which are felt by a human operator via the haptic device PHANToM OMNI.

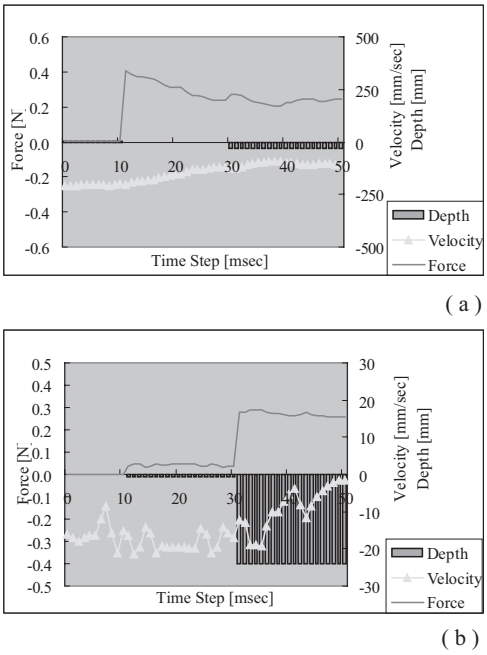
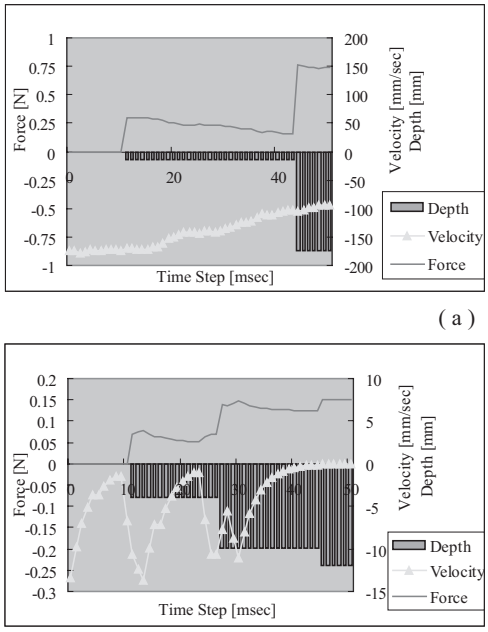


Figure 15. (a) Three sequences of penetration depth, tip velocity of dental bar and contact force when a front tooth is operated by the tip of bar under high speed. (b) Three sequences of penetration depth, tip velocity and contact force when a front tooth is operated by the tip under low speed. The task is described in Fig.14(a).

4. CONCLUSIONS AND FUTURE WORKS

This paper described our dental simulation system as a mixed environment of visual, tactile, and sound realities. The merit of our system is to use real shapes of teeth, bars, and turbine really used by a dental doctor in a hospital. All the data of teeth, bars and turbine are captured as STL (triangular polyhedrons) via CT-scanner with high precision. Moreover, in order to obtain a virtual force from a kinematic relationship between encountered bar and tooth, we use the **Kelvin-Voigt** material as the classic **Penalty** method. As input data in the **Kelvin-Voigt** material, we consider penetration depth and contact speed. The former can be automatically calculated by the **AABB** collision check calculation and simultaneously the **GJK** penetration depth calculation. The latter can be always obtained from the haptic device PHANToM OMNI via the OpenHaptics HDAPI.

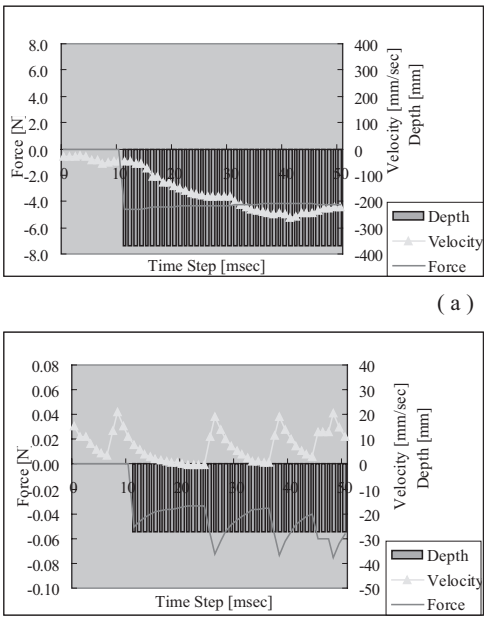
Based on several kinds of simulation results, we ascertained that each sequence of reactive forces is reasonably responsible for haptic rendering in our dental surgical operation. Needless to say, the sequence is comfortably and stably felt by the haptic device PHANToM OMNI. The total calculation time is small enough for using the haptic device.



(a)

(b)

Figure 16. (a) Three sequences of penetration depth, tip velocity of dental bar and contact force when a front tooth is operated by the tip of bar under high speed. (b) Three sequences of penetration depth, tip velocity and contact force when a front tooth is operated by the tip under low speed. The task is illustrated in Fig.14(b).



(a)

(b)

Figure 17. (a) Three sequences of penetration depth, tip velocity of dental bar and contact force when a front tooth is operated by the tip of bar under high speed. (b) Three sequences of penetration depth, tip velocity and contact force when a front tooth is operated by the tip under low speed. The task is shown in Fig.14(c).

Finally as an ongoing work, we evaluate some difference between student and doctor skills with the help of the difference between two teeth operated by student and doctor.

References

[1] D.K.Pai, "Multisensory interaction: Real and virtual", *Springer Tracts on Advanced Robotics, Springer Berlin / Heidelberg*, vol. 15, 2000. 1

[2] "Virtual reality dental training system (vrdts)", http://www.novint.com/VRDTS.htm. 2

[3] G.Bergen, "Efficient collision detection of complex deformable models using aabb trees", *Journal of Graphics Tools*, vol. 2, no. 4, pp. 1–13, 1997. 2

[4] G.Bergen, "A fast and robust gjk implementation for collision detection of convex objects", *Journal of Graphics Tools*, vol. 4, no. 2, pp. 7–25, 1999. 2

[5] Y.J.Kim, M.C.Lin, and D.Manocha, "Fast penetration depth estimation between polyhedral models using hierarchical refinement", *International Workshop on Foundations of Robotics (WAFR)*, 2002. 2

[6] Y.J.Kim, M.A.Otaduy, M.C.Lin, and D.Manocha, "Six-degree-of-freedom haptic display using localized contact computations", *Proc. of 10th IEEE Symposium on Haptic Interfaces For Virtual Environment and Teleoperator Systems*, pp. 209–216, 2000. 2

[7] D.Terzopoulos, J.C.Platt, and A.H.Barr, "Elastically deformable models", *Computer Graphics (Proc. SIGGRAPH)*, vol. 21, pp. 205–214, 1987. 2

[8] J.C.Platt and A.H.Barr, "Constraint methods for flexible models", *Computer Graphics (Proc. SIGGRAPH)*, vol. 22, pp. 279–288, 1988. 2

[9] M.Moore and J.Wilhelms, "Collision detection and response for computer animation", *Computer Graphics (Proc. SIGGRAPH)*, vol. 22, pp. 289–298, 1988. 2

[10] S.G.Sukhatme L.Kim and M.Desbrun, "A haptic rendering technique based on hybrid surface representation", *IEEE Computer Graphics and Applications*, vol. 24, no. 2, pp. 66–75, 2004. 2

[11] H.T.Yau, L.S.Tsou, and M.J.Tsai, "Octree-based virtual dental training system with a haptic device", *Computer-Aided Design and Applications*, vol. 3, no. 1-4, pp. 415–424, 2006. 2

[12] L.Kim and S.H.Park, "Haptic interaction and volume modeling techniques for realistic dental simulation", *The Visual Computers*, vol. 22, no. 2, pp. 90–98, 2006. 2

[13] H.Kato N.Hashimoto and K.Matsui, "Traning of tooth scaling by simulator - development of simulator and investigation of its effectiveness -", *Proc. of the 17th Int. Conf. on Artificial Reality and Telexistence*, pp. 251–257, 2007. 2