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# Six Degree-of Freedom haptic rendering for dental implantology simulation

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**Abstract.** Dental implantology procedures are among the most complex surgical procedures executed by dentists. During the critical part of the procedure, the jawbone is drilled at the location of the missing tooth (or the missing group of teeth). This asks for specific skills from the dentists, who need to be well trained.

In this paper we present a virtual reality based training system for implantology and we mainly focus on the simulation of drilling. We have two main contributions: The first one is a method for precise haptic rendering of contacts between the drilling tool and the jawbone model issued from a CT-scan. The second one is the real-time simulation of the jawbone erosion during drilling which is compatible with the haptic rendering of contacts.

**Key words:** medical simulation, training, haptic feedback, contact response, drilling simulation

## 1 Introduction

During a dental implant procedure, the tooth root is replaced by an artificial one, in order to support restorations that resemble a tooth. The technique requires a planning, often based on a 3D CT scan, to identify the vital structures and to choose the appropriate orientation for the implants. The main difficulty during the surgery is the precise drilling of the bones. Drilling into jawbone usually occurs in several separate steps while taking care to avoid the vital structures. A first pilot hole is expanded by using progressively wider drills (typically between three and seven successive drilling steps, depending on implant width and length).

The surgical placement of implants requires specific formation and training and the risk of complication decreases with the dentist experience [?]. The training usually begins by acquiring drilling experiences on some artificial jawbones made of plastic. Then, the training quickly switches to companionship training with real patients. In between, the only current possibility is an uncomfortable training on a human dead head which is not always proposed. Artificial jawbones are not sufficiently realistic for the drilling and the training does not include important visual obstructions and anatomical obstacles due to the cheeks and the tongue. Even when trained with human cadavers, the dentist can not execute a repetitive rehearsal to gain sufficient experience. This lack of realism and

training creates a lack of confidence among dentists when they face their first patients during companionship.

By designing a simulator based on virtual reality, we aim at providing a better alternative to training on cadaver, after the training on artificial jawbones and before the companionship. Our simulator includes a comprehensive virtual environment which includes the obstructions and obstacle previously mentioned with a more realistic haptic feedback than drilling on artificial jawbones. Using our simulator, the dentist can do the rehearsal as many time as necessary. As the simulation is based on real patient data, the dentist has also access to a large variety of pathologic cases.

During training, dentists focus on increasing several of their surgery skills, especially for drilling. They must be able to drill into jawbone while holding on the accurate direction decided during the planification. If the dentist slightly changes the tool direction during drilling, the section of the obtained hole could be oval. This could be problematic afterwards for the fixation of the dental implant. The density of the bones is non homogeneous. The surface of the jawbone is often harder than the inside. Thus, when the surface is about to be pierced the dentist must be careful that he do not apply an excessive force that would quickly drive in the drill tool too deeply. Sometimes the inhomogenities inside the bones could also deviate the drill tool from its right direction. So, one important skill si to be able to drill a precise hole even while being pertubated by these inhomogeneities. Several successive drilling steps are used to expand progressively the diameter of the hole. This must prevent from breaking the jawbone. At each step, the dentist must be able to evaluate the quality of the hole and, when necessary, he has to take a slightly different direction. While drilling, he has to take care of the elevation of the temperature, because the bone can burn. This would create a necrosis that would prevent from fixing the implant. Finally, as the view on the operative field is partially obstructed by the tools, the dentists naturally use haptic feedback to realize the procedure.

Accordingly, our training system, that should allow for acquiring these skills, must satisfy complex technical specifications. The system includes six Degree-of-Freedom (DoF) haptic device (3 translation forces and 3 rotation torques) for the rendering of all forces that are applied to the drilling tool. The virtual environment includes a precise drilling simulation and an accurate collision response. After drilling, the dentist often reinsert the tool without machining, to verify that the hole is straight and the section is not oval. The simulator will include a variety of cases based on real patient data. Thus, geometrical models of the jawbone in our simulation are based on 3D CT-scan.

To satisfy these specifications, we have two main contributions that are presented in this paper. We develop a new haptic algorithm that is based on a precise and stable modeling of contacts between the drill and a CT-scan model when it's not machining. We also propose a new method for the haptic rendering of a drilling task based on an efficient way of updating the CT-scan volume data.

The remainder of this paper is organized as follows. Section 2 summerizes previous work on 6 DoF haptic rendering and on drilling simulations. Section

3 presents the new algorithm for 6DoF haptic rendering of contacts based on jawbone models from CT-scan. The new method for the drilling simulation and haptic rendering is presented in section 4. Results are shown and discussed in section 5. Finally, we conclude in Section 6.

## 2 Previous Work

In this section, we only give a brief overview of previous work on 6 DoF haptic rendering, on haptic rendering of volumetric data including rendering of bone erosion.

Previous work on haptic rendering of volumetric data:

- In [?] Haptic force computed using elastic contact force based on Hertz theory. It do not prevent from interpenetration. *eux: The results of the human factors analysis indicate that, to be able to feed the appropriate sensorial inputs to the human perceptual system, the system needs to produce data at two very different time-scales: about 15 20 Hz for the visual rendering, and around 1 kHz for the haptic response [2]* - Critique sur leur papier - *They developed an analytical model of bone erosion as a function of applied drilling force and rotational velocity, which they varied with experimental data.* - ONE POINT ? A vrifier- voir ausi Agus04 (haptic symposium): M. Agus et al., Physics-Based Burr Haptic Simulation: Tuning and Evaluation, Proc. 12th IEEE Haptics Symp., IEEE CS Press, 2004, pp. 128-135.
- In [?] They use hybrid data structure: volumetric data for haptic rendering and traditional triangle arrays for graphic rendering. Only 3 degree-of-freedom (DoF) force feedback, while in our simulation we need 6 DoF. They propose a model for the erosion rate (Amount of bone removed per time unit by a given sample point on the drill tool)
- : A. Petersik et al., Haptic Volume Interaction with Anatomic Models at Sub-Voxel Resolution, Proc. IEEE Virtual Reality, IEEE CS Press, 2002, pp. 66-72. *they model a drilling instrument as a point cloud, and use a modied version of the Voxmap-Pointshell algorithm* **Copie-colle de Morris 06** We initially adopted a haptic feedback approach similar to Petersik et al.s,5in which the drill is represented as a cloud of sample points, distributed approximately uniformly around a spherical burrs surface. At each time step, the system tests each sample point for contact with bone tissue. By tracing a ray from each immersed sample point toward the tools center, the system can generate a contact force that moves that sample point out of the bone volume
- M. Renz et al., Stable Haptic Interaction with Virtual Environments Using an Adapted Voxmap-Pointshell Algorithm, Proc. Eurohaptics, 2001, pp. 149-154; <http://www.eurohaptics.vision.ee.ethz.ch/2001/renz.pdf> *to sample the drills surface and generate appropriate forces at each sampled point. This work developed into a commercial simulator (see <http://www.voxelman.de/simulator/tempo surg>). Each of these projects incorporates haptic*

*feedback into volumetric simulation environments that use computerized tomography and magnetic resonance data.*

Kusumoto06 3D haptic feedback utilise freeform et aussi VRDTS **A regarder : VRDTS, novint, NM, USA**

- Recent Paper [Ohtani09] uses FreeForm v9.1 for virtual drilling experience based on a 3D bone image.

Previous work on 6Dof haptic rendering:

- intro: A lot of haptic algorithms are based on 3 DoF rendering, which is effective for single-point interaction. Designing similarly effective methods for the complete drill tool interaction with the jawbone is not straightforward. In our simulator, we want 6 DoF haptic rendering on two types of interaction: contact and drilling. For contact, several algorithms were proposed but are mainly based on penalty-based response. For instance, Mc Neely and all. [?] proposed a penalty based computation of the contacting forces using voxel sampling. But penalty algorithms are not sufficiently accurate for our application (the use of progressively wider drills allowed virtual objects to interpenetrates in case of contact. A non-penetrating virtual object simulation is known to increase the perceived stiffness [?].

Application of haptic device to implant dentistry...

- Haptic rendering algorithms, haptic coupling, ... ok !!
- Papers on drilling

### 3 Contact rendering of CT-scan model

**Pour le moment, c'est le copie-colle d'un projet...** Contact modelling is a challenging problem for several reasons. First, the way contacts are handled plays a very important role in the overall behaviour of the interacting objects. The choice of the contact model and the inclusion or not of a friction model highly influence the post-impact motion of the interacting objects. When multiple objects are in contact, like in a joint, the solution space for the new, non-interpenetrating configuration is reduced. For this WP, we propose a new approach for contact detection and response that avoids meshing the interacting surfaces of the articulation bones, cartilages, ligaments and muscles: after a segmentation step on the patient data, we could obtain a continuous implicit description of the surface using a potential field on a distance map. Then, the algorithms used to process the steps of collision detection and collision response will be based on this continuous potential field. The SOFA architecture relies on several innovative concepts, in particular the notion of multi-model representation. In SOFA, most simulation components (deformable models, collision models, instruments, etc) can have several representations, connected through a mechanism called mapping (See Figure 8). We plan to use this multi-model representation in order to process contacts on a image-data-based representation. The advantage would be to maintain a complete freedom on the type of mechanical model used to simulate the anatomical structures of the joint.

## 4 Drilling

In this section, we present a new method for haptic rendering of virtual drilling based on CT-scan data. The method is based on a multithreaded approach: One thread is dedicated to a physics based drilling simulation and the other to haptic feedback. The jawbone machining simulation is driven by a volumetric density map issued from real CT-scans. At each time step of the drilling simulation, we compute an erosion rate according to conventional machining parameters (tool speed, material fragility, drilling force,...). Based on this erosion rate, we compute a reference 6D displacement of the drill tool inside the bone. Then, we update the bone implicit surface using an algorithm close to the CSG subtraction to obtain precise geometrical result. The algorithm is fully compatible with the contact algorithm previously described and the haptic rendering is based on the same god-object like technique.

### 4.1 Precomputed maps

Our method relies on a set of discrete 3D maps that are precomputed off-line and updated on-line at high rates during drilling. These maps are discretized homogeneously using voxels of the same size. To obtain a continuous value between the voxel centers, we use a trilinear interpolation.

Using a CT-Scan of a real patient jawbone and the method presented in ??, we compute a volumetric density map. **resolution utilisee ?** We can obtain a value of a density from this map with a very short constant time access.

Image CT-scan  $\rightarrow$  density map

From the CT-Scan, we also compute a potential field map. The objective is to obtain an implicit representation of the jawbone surface. Inside the object, the potential must be negative and outside, it must be positive. In the neighborhood of the surface, the potential field must varies continuously to be able to define the gradient. In practice, we apply a blur filter (**ajouter details !?**) to the data (**est-ce qu'il y a un autre traitement par dessus ?**).

Image CT-scan  $\rightarrow$  potential field map.

Finally, a potential field map is also precomputed for the drilling tool. This map is computed in the reference frame of the tool with two bounding boxes: The first one, which tightly bounds the drill tool, is used to reject a point when it is not inside the drill tool. A second one, which is larger, cover the 3D space where the potential field of the drill tool is defined.

Schema drill tool avec les deux boites englobantes

## 4.2 Erosion rate computation

We base our drilling simulation on CT-scan data to capture the influence of density of bone variation on haptic feedback. The algorithm begins with the computation of an intersection between the maps of both jawbone density and drill tool. As we rely on a god-object representation, we have two positions for the drill tool: one that is mapped on the position of the haptic device handle (HDH) and an other position (the god-object position (GO) ) that follows the friction contact constraints (**a revoir - ou on met ca** ). To perform the computation, we take the HDH position of the drill tool so that we found which voxels, in the density map, are about to be machined. If the erosion is total, the GO position meets the HDH position. Hence, the intersection captures somehow a maximal quantity of bone to remove during the current time step (**si c'est bien ca, il faut mieux definir et dire comment on calcul (somme integrale sur les voxels en intersection ?)**). Then, an erosion rate is computed to fix the quantity of bone that needs to be eroded versus the maximal quantity previously obtained.

This erosion rate computation relies on several machining parameters.

- tool speed :
- material fragility :
- drilling force :

When the erosion rate is obtained, it is used to compute a 6D erosion displacement of the drill tool inside the jawbone. *formule similaire a la "position secure": est-ce qu'on en parle ? sinon, mette la formule ici:*

## 4.3 Contact based haptic rendering update

The main assumption of this paper is that the haptic feedback to be restitued during drilling simulation corresponds to the contact forces between the drill tool and the hole. The main difference with "standart rigid contact" is that the surface is eroded when contact appears. If the erosion is total (erosion rate = 1), then there is no force to display.

Thus, we process, at each time step, an update of the potential field map to erode accurately the implicit surface of the jawbone.

## 5 Results

petite intro sur les results

- Le fraisage se fait sur des données issues d'un ct-scan. Depuis la carte de densité, on calcule la quantité de matière fraisée chaque pas de temps, ensuite on interpole le résultat obtenu pour mettre à jour une carte pour la détection de collision décrivant de manière implicite et continue la surface de la mâchoire (l'intérieur et l'extérieur).
- précision dans la géométrie de la surface fraisée : lorsqu'on a fraisé avec un certain diamètre, il faut qu'avec des fraises de diamètre supérieur,...
- On cherche à simuler le fait que la surface de l'os est plus dure
- Retour d'effort stable

### **5.1 the training simulator... il a un petit nom ?**

Présentation complète et rapide du simulateur, de l'environnement virtuel et de l'interface haptique. Photo-screen shot...

### **5.2 haptic rendering**

À réfléchir: comment quantifier les résultats obtenus sur le rendu haptique

### **5.3 computation times**

Tableau donnant une idée du temps de calcul nécessaire pour les différents algorithmes.

## **6 Conclusion**