Interactive Simulation of Teeth Cleaning

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In this paper an interactive simulation system for teeth cleaning is presented. This simulation system offers assistance for optimizing design and manufacturing of new toothbrushes. Data acquisition and pre-processing techniques for the model generation are shown, an editor for modelling of the elastic behaviour of the toothbrushes parts is presented and the mathematical method for modelling of flexible parts of the toothbrush is explained. After the introduction of the PHANToM haptoid and the explanation of a new approach to collision detection, first results of the project are shown.

1 Introduction

Dentists consider proper teeth brushing as the most important contribution to caries prophylaxis and plaque extinction. The efficiency of the process of teeth cleaning depends on various parameters, such as the geometry of the toothbrush, the arrangement of the bristles on the toothbrush's head and the right cleaning strategy.

In this paper we present an interactive simulation system for teeth cleaning. This simulation offers valuable assistance for optimizing the design and manufacturing of new toothbrushes. Benefit is also granted to researchers in oral health care. The simulation system allows early tests of the functionality of future brush generations and enables the engineers to estimate the effects of design changes in an early state of the manufacturing process. Furthermore, the simulation system offers a cost-efficient way to experiment with different designs and functional properties in the development process of toothbrushes. It also allows the validation of the efficiency of certain brush types and bristle configurations.

First in this paper, data acquisition for jaw and brush models and pre-processing techniques for the model generation are shown. Then, an editor for modelling of the elastic behaviour of the toothbrush handle and the toothbrushes bristles is presented. Afterwards, we explain the mathematical method for modelling of flexible parts of the toothbrush. In the next paragraph we describe the integration of the PHANToM haptoid in the simulation system and we explain the occurring difficulties and constraints using the PHANToMs GHOST library, leading to a new approach to collision detection. The paper finishes with the presentation of the results and with a view on further work to be done in future.

2 Methods

2.1 Data acquisition and conversion

For a realistic simulation of the teeth-brushing process three-dimensional models of the toothbrush and the jaws are needed. CAD models of different toothbrush handles were provided by our industrial partner, CT scans of plaster casts from individual probands were used as jaw data sets. The generation of Open Inventor models (i.e. surface models) out of the CT slice images required several data conversion tools. Nevertheless the quality of the resulting jaw data is limited through the thickness of the CT slices of about 1.4 mm.

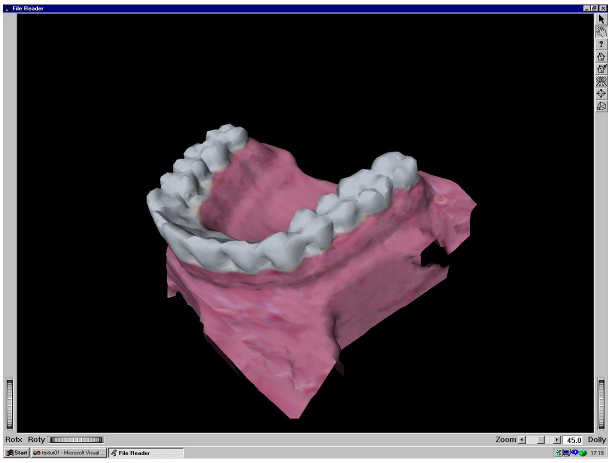

Figure 1: Textured jaw, derived from pattern scanner data through triangulation

Lateron we used different 3D-surface scanners, obtaining the best results with a pattern scanner that was developed exactly for this application (Figure 1).

2.2 Interactive cutting of the toothbrush datasets

Modelling of the elastic behaviour of the toothbrush required a tool for cutting the data sets of the toothbrush handle at desired joint points (figure 2).

Cutting a part out of a surface data set is not trivial: if the cutting plane does not lie across the edge of a triangle one has to calculate new triangles with new edges. Furthermore we decided to insert spheres at the joint points to keep the gaps that emerge when moving the segments invisible.

The cut segments are the Finite Elements for the next step: Modelling of the flexible behaviour of the toothbrush with the Finite Elements Method.

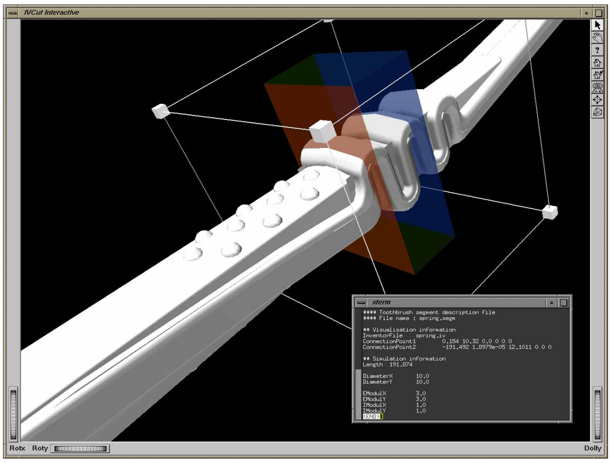

Figure 2: IV Cut tool in interactive mode with opened script file editor

2.3 *Modelling of flexible areas and bristles*

For modelling the flexible behaviour of the toothbrush's handle and bristles, a basic Finite Element model is used. First, the flexible area is divided into individual segments. Then each of these elements is modelled as a bending beam.

The analytical solution of the differential equation for one single bending beam is given by a polynomial function. Taking this polynom as an approach for the solution of the problem within the Finite Element Method, we can provide precise functional values for the contact points between the different equidistant elements.

A single bristle is currently modelled by five equidistant bending beams. Taking forces and torques as input values and positions and angles as output values, a *10*-dimensional equation system describes the relationship between these mathematical entities. Due to the dependencies between adjacent segments, a *10x10*-matrix *A*, containing the single polynomial equations, represents the Finite Element model for a bristle. Considering additional conditions to be fulfilled by these equations, the resulting matrix A is a sparse matrix.

The equation $A*x = b$ represents the solution of the Finite Element calculation for a bristle whereby b is a *10*-dimensional vector that specifies the forces and torques on each segment and x determines the new position and angle values of the segment after application of the forces and torques. The emerging system of equations is solved using the *L/U*-decomposition.

2.4 *Haptic user interface*

A fairly realistic behaviour of a simulation system can be achieved using an adequate user interface. For our work, we integrated a PHANToM haptic feedback device in our simulation system. Force-feedback can easily be simulated by programming a force field using the GHOST library delivered with the device. The force-feedback device plays the role of a virtual toothbrush. Calibration and tracking of a toothbrush using the PHANToM have been implemented.

For the tracking feature a mode called *Multitrack* allows to switch between the view of the toothbrush, the view of a simulated PHANToM with the brush or the view of the trajectory reached by the toothbrush. Furthermore, a simulation of the PHANToM´s overall functionality is available.

2.5 Collision detection between toothbrush and teeth

The detection and visualization of collisions between the toothbrush and the teeth in the simulation system is of high importance for the whole project. As we want to simulate plaque extinction in a later period of the project we need the possibility to simulate contact of a toothbrush with certain surfaces, independent of the type of these structures which may represent teeth, plaque or some kind of soft tissue which is situated in the oral area.

With the delivered software library of the PHANToM, the GHOST library, it is impossible to handle more than one collision point (i.e. one bristle), so we had to implement a new voxel-based algorithm for collision detection which is quite complex but nevertheless quite elegant:

Given a (binary) voxel representation of the teeth, one can, using the Euclidian Distance Transformation, substitute the *1* or *0* in the representation of the object (inside or outside the object) with the length of the vector pointing directly to the surface of the object. This is the force vector, describing the reverse force effecting the colliding object, in our case the toothbrush. Furthermore given a surface model-based representation of the toothbrush and letting it literally “dive” inside the teeth, one can sum up all the force vectors that point backwards and one can calculate the resulting force vector for the PHANToM user. This “diving” process has to be simulated via the FEM analysis as a bending of the bristles at the surface of the teeth. Figure 3 shows one result of this implementation; for reasons of simplicity and to speed up the application, a sphere is chosen as simple volumetric object.

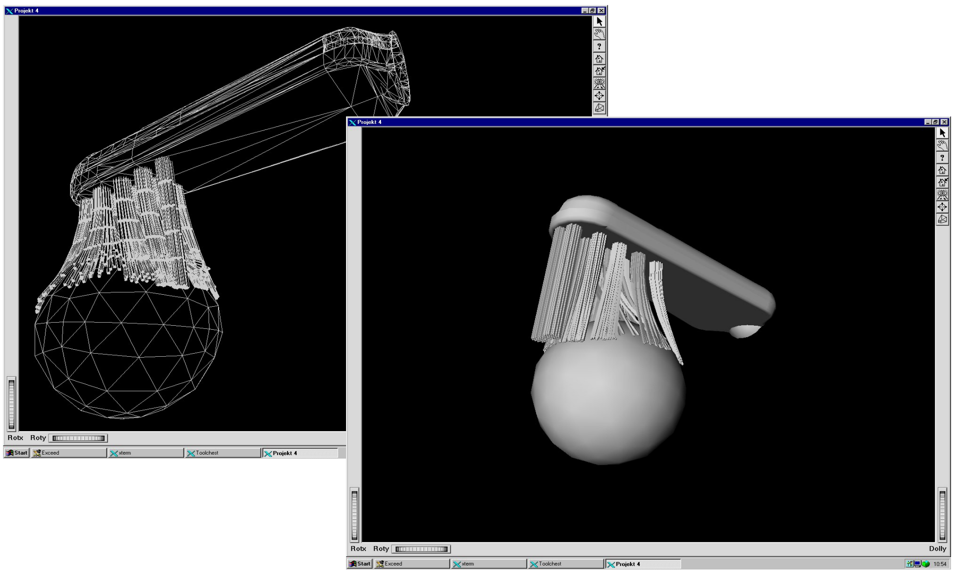

Figure 3: Bristle deformation and collision detection on simple volumetric object (sphere)

Despite of the elegance of this algorithm, it requires a lot of computing time, but these calculations can be done offline, before the simulation starts.

3 Results

A first prototype of our system has been established, using a two-processor SGI Octane SSI (400MHz, V8 graphics), together with a 1.5A PHANToM device of SensAble Technologies Inc. The software modules described above have been implemented and form a powerful simulation application. By now it is possible to simulate the movements of the toothbrush's handle and of bristle bundles on the toothbrush's head considering the material properties specified by the user.

Furthermore the system is capable of recording the trajectories of the toothbrush's head and thus recording the brushing behaviour of different users. Soon we will do test runs with probands at our university to compare different teethbrushing methods.

Figure 4: Test person using the simulation environment

The described algorithm for multi-point collision detection is implemented and is working well with simple models. Due to hardware limitations the system is in this state not capable of handling the original datasets, containing about *200.000* triangles for visualization and about *2..5* million voxels for the haptic model. A hardware upgrade is ordered already and different mechanisms for reducing the data sets and smoothing the resulting data are already implemented with good results. Multi-point collision detection in the original model dataset will be the next milestone on the way towards simulation of single bristles instead of bristle bundles.

4 Discussion

In this paper a *3D* graphical simulation system for visualization and analysis of teeth brushing has been presented. The system is based on the Open Inventor Object Library. With the given import filters, standard jaw data sets may be used as well as patient individual data. Toothbrush datasets are modelled using original CAD data and specific bristle models.

Behaviour of flexible elements of the brushes like the bristles and parts of the handle are modelled using the Finite-Element Method. The human machine interface of the system combines a haptic feedback device with a graphical user interface. First results are promising and the system will be refined.

Future work will concentrate on collision detection and contact analysis for the toothbrush and the teeth leading over towards the modeling and simulation of single toothbrush fibers and their interaction. Moreover, we will implement a reachability analysis for the brush and especially the bristles in order to control which points in the oral space are touched by the brush. Possible enhancements of the project include also the integration of this work into a pre-operative planning system for cranio-facial surgery and the combination of this work with an experimental setup for intraoperative support of surgeons.

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