A Virtual Reality Interface to an Intelligent Dental Care System

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Abstract

The design and fabrication of teeth restorations in dentistry rely increasingly on CAD/CAM techniques. We present an approach for interactive design of the occlusal surface of teeth based on simulation of jaw articulation and computer-aided diagnosis of occlusal disorders. To bridge the cognitive gap between the dentist and the computer system, we propose a virtual reality user interface, which applies the metaphors of tools and techniques known in dentistry. This makes the restoration design more intuitive for dentists. The system uses Virtual Reality Modeling Language (VRML) and HTML standards to generate a treatment report and exchange data in an electronic form.

The simulation of jaw articulation requires fast calculation of multi-point contacts and detection of collisions between surfaces of teeth and restorations. We have developed a distance maps technique which exhibits realtime performance for objects with complex geometry and is suitable for other virtual reality systems dealing with complex contacts. The characteristics of contacts between teeth acquired during lower jaw motion are compactly represented as accumulated distance maps. These maps are then used for automatic removal of interferences between the restorations and the opponent teeth, and provide the dentist with information for further manual adjustments of the occlusal surfaces.

Keywords: Jaw Articulation Simulation, Teeth Modeling and Visualization, Dental Systems, Virtual Reality.

1 Introduction

CAD/CAM techniques are increasingly used in dentistry for the design and fabrication of teeth restorations. The functionality of existing systems [DBD88] [Hof90] [Rek91]

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[vdZ93] usually fulfills the requirements for designing and manufacturing onlays, inlays, crowns, bridges and partial dentures (i.e., restorations), but efficient use of these systems involves extensive training and technical knowledge not related to dentistry. This distracts the dentist from the treatment of the patient. Hiring a trained operator helps, but significantly increases the cost of treatment.

Virtual reality technology is already applied in medical areas where treatment costs are high or where it enables to do new treatments and more safe operations (e.g., neurosurgical planning). Virtual reality extends traditional user interfaces because it simplifies navigation in 3-D space, as is often required in medical applications. In the past, the high costs of virtual reality systems could not be justified for use in dentistry, where the costs of a single treatment are relatively low. However, increasingly affordable VR systems encourage their development as a standard user interface technique in dental systems and other medical applications.

In traditional dentistry, mechanical articulators are used for design of dental restorations and articulation diagnostics. Most computer-based dental care systems [Hof90] [Rek91] poorly model the occlusal surface of restorations, because jaw articulation is ignored. In other systems an analysis of contacts/collisions between jaws is simplified, and speed of calculations is far from interactive. The quality of reconstructed occlusal surfaces is important because restoration materials used in modern dentistry are very hard (e.g., porcelain) and manual corrections of the restoration are difficult.

In this paper we present a new virtual reality user interface for simulating jaw articulation and editing of the occlusal surface of teeth, developed as a part of the ongoing project "Intelligent Dental Care System". The interaction with the dentist is based on metaphors familiar from everyday practice.

This paper also presents a method for detecting interference between existing teeth and restoration by articulation simulation [KHM+94]. Collisions and contacts can be detected staticly for jaw positions chosen by the dentist and dynamically for lower jaw movements. Also, the load distribution on the teeth is calculated [KMO+95], providing the dentist with information not available with traditional techniques. The interferences detected during articulation simulation and the load distribution on the teeth are used for the automatic adjustment of the shape of the occlusal surface of restoration. Articulation simulation and resulting shape adjustments are repeated in a loop until collisions are eliminated and the load on restored and opponent teeth meets the imposed requirements. The dentist can break this design loop at any stage, interactively edit the occlusal surface, and resume interference checking.

Motion of the mandibular jaw is simulated using 3-D measurement data, obtained using the MM-JI-E system developed at Tokushima Bunri University and Tokushima University. At present we use a mechanical scanner to measure the surfaces of the upper and lower jaws based on a plaster model.

The paper is organized as follows. In the next section we discuss our algorithm for collision detection and automatic removal of interferences between teeth and restorations. Then we present our virtual reality approaches for interactively editing the occlusal surfaces of teeth. Section 4 describes our visualization techniques of jaw articulation, motion trajectories and teeth load during grinding. In Section 5 we propose a treatment report generator which produces hypertext including virtual reality models. Section 6 gives some implementation details. Finally, we conclude and propose some directions for further research.

2 Fast Collision Detection for Virtual Reality

Fast and reliable collision detection is an important component of every virtual reality system allowing motion of the objects which cannot interpenetrate with other objects in the virtual environment. In a typical situation, the geometry of objects is simple and ordinary collision detection techniques provide a binary response indicating whether or not the objects interpenetrate for their current configuration. If any interference region is found, further calculations are abandoned and other collisions are ignored. In our application the design of occlusal surface becomes more efficient if location and depth for all collisions are known. This means that a collision detection technique must handle all (multi-point) contacts and collisions between very complex objects (over 100,000 polygons are used to build a typical model of jaws) at interactive rates. Also, the penalty for contact complexity must be negligible in order to preserve constant response time. The algorithm cannot rely on space-time coherence with interference tests performed previously because the dentist can interactively change the position of the lower jaw. The requirements imposed on the complexity of objects and latency of response preclude using traditional collision detection algorithms running on sequential computers. We formulate the problem of collision detection in terms of depth calculations which are directly supported by graphics hardware. This strategy seems to be justified by the rapid increase in performance of rendering hardware. We have developed a technique called *distance maps*, which is based on standard features of graphics hardware such as a z-buffer and stencil buffer. Distance maps provide information about distance from one jaw to the opposite jaw along a chosen projection direction for sample points located on a raster grid of graphics hardware. We propose a technique based upon *multi-projection distance maps*, which collect information such as minimal distance for various projection directions. More technical details on our general purpose multi-points collision detection algorithm can be found in [MOK95]. In our dental application we extend the notion of distance maps to *cumulative distance maps (*CDM*)*. A minimal distance can be calculated not only for multi-projection directions, but also for multiple positions of the lower jaw motion. CDM is a compact tool for representing depth and direction of all possible contacts/collisions encountered during motion of the jaw. Adjustment of the occlusal surface of restoration becomes simple with CDM. Vertices of mesh (or control points) describing a surface are moved the number of units specified in CDM in the direction of projection in which a collision is detected. Constraints imposed on the smoothness of the occlusal surface are used to prevent discontinuities and abrupt changes. Usually the sequence of CDM calculations followed by the adjustment of the surface must be repeated twice to remove completely all collisions.

The multi-projection technique can be used to accumulate more involved characteristics of contacts between teeth than the discussed minimal distance. For example, we found that the minimal distance modulated by the dot product of the normal vector to the surface with the vector in the projection direction approximates well the load on teeth. This and some more advanced characteristics useful for evaluation of the grinding process we discuss elsewhere [KMO+95]. The CDM with the load distribution on restoration are also used for adjustments of the occlusal surface until regions exhibiting too high load are removed.

The time for calculation of the distance maps for a jaw model composed of over 110,000 triangles is 0.22 sec on SGI's Indigo^2 Extreme workstation. Fig. 1 shows an example of distance maps for the upper molar and premolar teeth, calculated for jaw position close to the centric occlusal position. Regions marked by blue and green colors are those where the distance to the opponent teeth exceeds 0.8 mm; colors between yellow and red correspond to distances below 0.8 mm; zero distance, i.e., contact between jaws is pure red. Fig. 2 shows the CDM with the load distribution for a molar tooth, calculated for 5 loops of jaw motion. Regions of the highest load are marked by red and yellow colors.

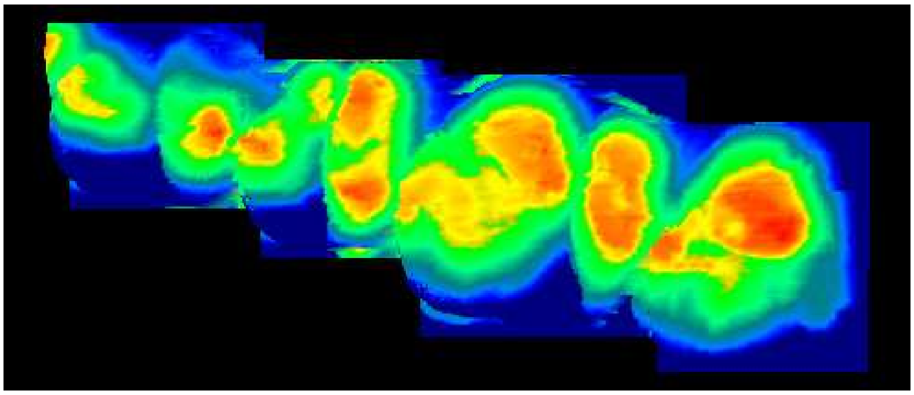

Figure 1: Distance maps

3 Interaction in Virtual Reality for Shape Design

Our system designs automatically collision-free restorations which also meet the requirements imposed on the load distribution over teeth. The shape of the occlusal surface is "reasonable", i.e., main morphological features of teeth are preserved and the rules of esthetic dentistry are respected. The dentist can examine images of a 3-D surface of a restoration, and CDM with the minimal distance to the opponent teeth and the load on

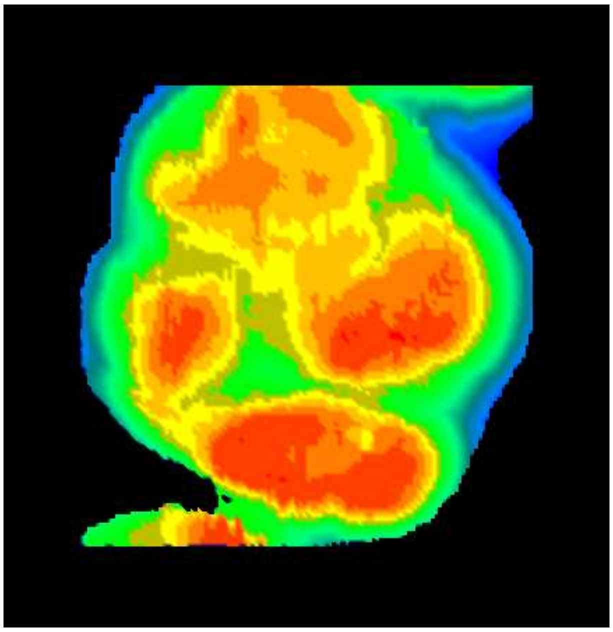

Figure 2: Cumulative distance maps

the restoration. In some cases, especially for patients with occlusion disorders further adjustments are necessary. Also, if a dentist dislikes a surface proposed by the system for, (e.g., esthetics), the designed restoration can be interactively changed.

The interaction method is inspired by the traditional wax up technique for design of crowns and dentures (Payne/Lundeen, Thomas) [Oke89]. This method is widely used by dental technicians. The modeling takes place in a mechanical articulator. The crown or denture is designed by adding wax layer by layer on a gypsum model which is gotten via imprint. The warm wax is transparent and easy to modify. As it cools (e.g., accelerated by blowing), it looses its transparency and becomes hard. During modeling the design is checked with the articulator. For visualization of the contact points a colored powder is used. The powder is sprinkled on one side of the jaw in the area of interest. If the teeth get into contact during manual sliding, the powder is transfered to the opposite tooth.

Virtual reality provides many advantages over manual design. Teeth which are not involved in the design can be hidden. As the jaw either moves along recorded trajectories or is controlled by the user, contacts and collisions are directly visible as distance maps mapped on the teeth. Also, watching the penetration from the back of a tooth or through a semi-transparent opposite tooth is possible. Only virtual reality allows us to go into rigid bodies and discover the whole nature of the articulation process.

In the modeling part of our system we simulate the behavior of wax. The dentist chooses the amount of virtual material which can be used during one step of the editing.

This limits the surface area and its relative changes. The editing process starts by touching the surface which triggers a clock. A control panel, represented as a cylinder which change its color from red (hot) to blue (cold), indicates the time (temperature). Depending on this simulated temperature, changes corresponding to mouse or stylus motion are scaled down. The process of cooling down can be speeded up (blowing) by user interaction. The previous shape is visible during editing, because the new surface layer is translucent as long as it is modifiable (see Fig. 3). An undo operation is available. After completion of the shape design, the occlusal surface is checked against collisions using the distance maps technique.

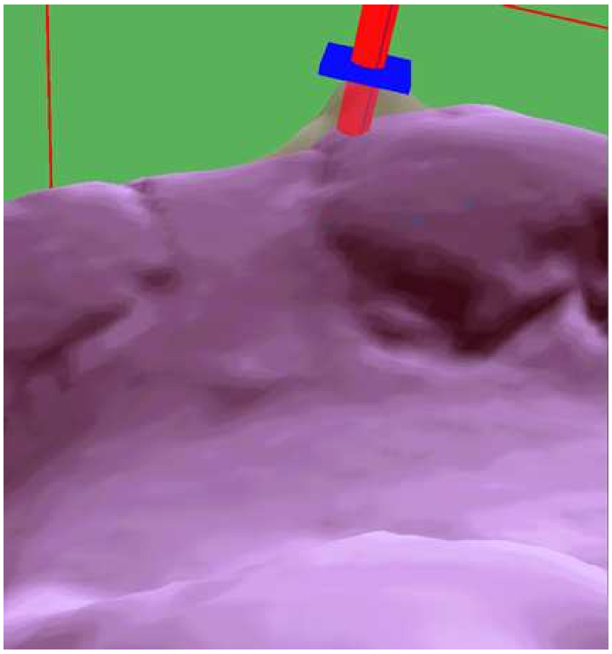

Figure 3: Surface editing

For our application, we propose specialized software (manipulators), based on direct manipulation of objects [CSH+92]. Conventionally used scrollbars, keyboard or mouse interfaces are not suitable for editing in three dimensional space. The mouse becomes more effective for editing when attached to a 3-D widget with knowledge about the modified object. The software manipulators have suitable hardware counterpart in the form of control devices (spaceball, stylus, abstract mechanical model). An abstract mechanical model of the jaw helps the dentist to determine orientation in 3-D space. A similar approach has been used to do neurosurgical planning [GHP+95]. A doll's head and stylus are input devices to control editing and visualization. This allows reduction of the cognitive distance between user and model. Our metaphors are based on traditional approaches using mechanical articulators and stylus, with a dialog technique based upon direct manipulation of objects. Disadvantages of our prototype compared to a real world approach includes the lack of force feedback and that the user sometimes loose the feeling for the size of his changes.

4 Visualization

Efficient modeling of restorations requires immediate and comprehensible presentation of current design and articulation simulation results. The dentist is trained to work and see in three dimensional space, and this impression should be conveyed as much as possible. Real-time 3-D visualization techniques offered by graphics workstations are an indispensable tool for examination of designed shape of restoration and for analysis of complex motions of the mandible. An arbitrary view of chosen teeth or whole jaws is feasible. By the default the most useful views are provided, e.g., the top view of the occlusal surface. Zoom-in and zoom-out functions are supplied and multiple windows can be opened at the same time exhibiting different views of the chosen target. All windows are simultaneously updated when articulation simulation is performed. During presentation of simulation results, we refer to metaphors used in dentistry such as *Posselt figure* which presents trajectories of the lower jaw motion, and "tapping test" [RWH89] in which the dentist marks teeth contact points by colored paper. We also provide visual information not available in the traditional dentistry such as dynamic load distribution on the occlusal surface of teeth during lower jaw movements. Visualization of contact points for sliding the lower jaw over the surface of the upper jaw is useful for evaluation of occlusal disorders (motion typically starting at the centric occlusal position).

An important issue in virtual reality systems is the speed of image display. Image quality can be traded off for speed of visual response. The level of detail of the teeth model is adjusted to the performance of workstation to avoid latency in interaction with the dentist for realtime response.

5 Report Generator for prognosis and diagnosis using VRML and HTML

Medical reports play an essential role in treatment planning, communication, presentation and decision finding. The current practice is to keep patient data as text, handwritten charts, diagnosis images (Photos, CAT, X-Rays), and cast models at different places. Usually if the patient visits a different clinic the data must be collected again. With computer technology all patient data can be put into electronic form accessible via fast growing networks. But access to this data is difficult and not available at all places using a single user interface. To overcome this situation we have developed a report generator which is part of our Intelligent Dental Care System. The output is hypertext markup language (HTML), images (in GIF and JPEG), sound, and virtual reality modeling language (VRML) [BPP95]. During a work session the data is created

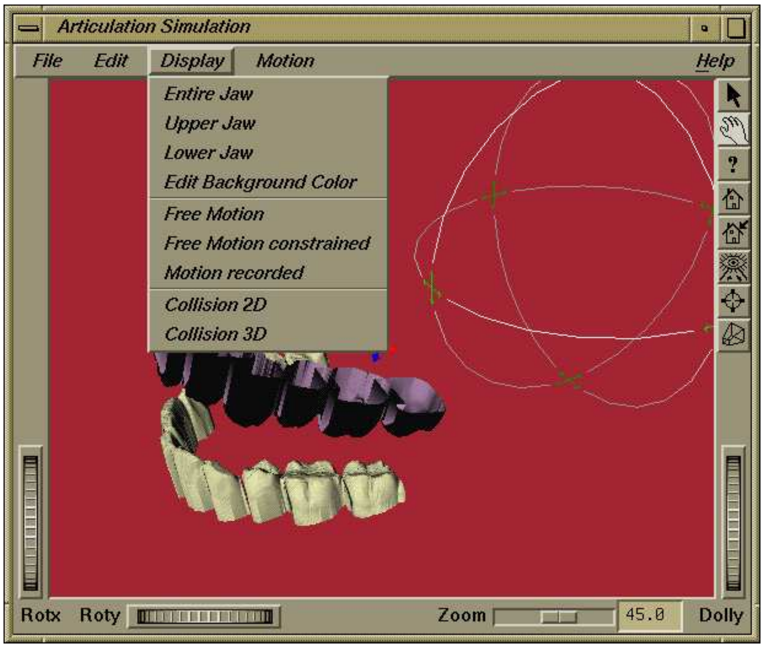

Figure 4: Articulation simulation user interface

and associated into a report with the following structure: Starting from an introduction (HTML) all other data can be accessed via hyperlinks. The models of the teeth are stored using VRML. For each tooth hyperlinks are added to distance maps and other diagnosis data. Important for the user is that a relation is specified only once. The generator creates a table of contents automatically and adds hyperlinks. The example in Fig. 5 shows the combination of 2-D hypertext document with a 3-D model. In the shown 3-D (WebSpace) browser the last molar tooth is highlighted and linked to the underlying textual description with related distance map.

6 Implementation

The prototype of our system is being developed on SGI workstations, but the target platform is not yet decided. This imposes demand of high portability of our application software. Since the main portability problems can be expected with graphics and user interface, we use standard environments for such development supported on many platforms. High level graphics operations and relevant user interface is based on Open Inventor, while low level graphics refer to OpenGL. In the near future, add-on graphics boards supporting these standards for PC class computers are expected on the market, and then our software can be run on inexpensive hardware configuration.

The generated report of the IDCS system is accessible on nearly any platform without

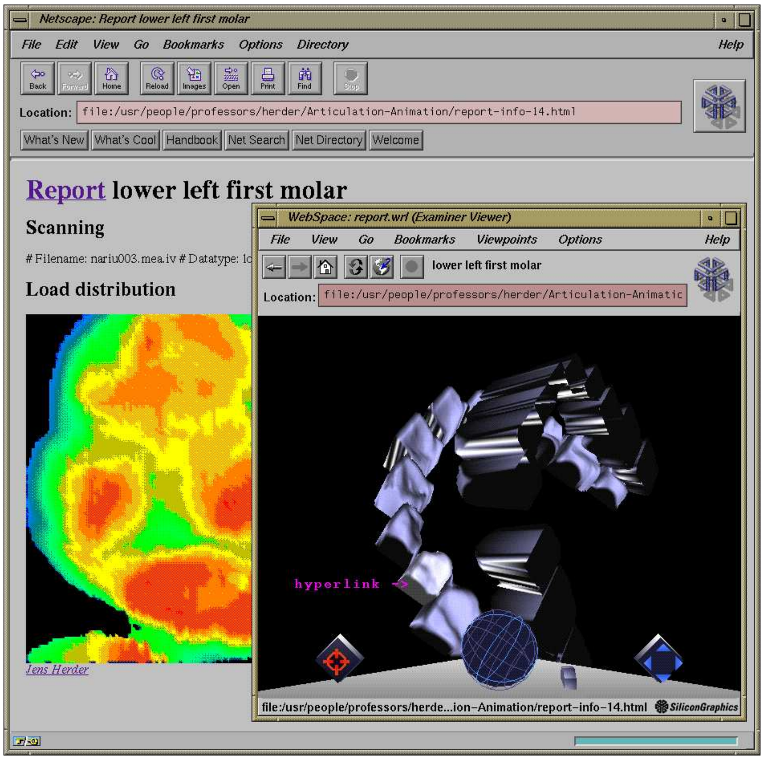

Figure 5: Report using VRML and HTML

having our specialized system because we use the emerging HTML and VRML standards. Those file formats can be processed by various viewers (e.g., Mosaic, Netscape, WebSpace, Webview, VRweb). These standards enable data exchange and preserve the context between the different (text, 2-D, 3-D) data. Another advantage is the homogeneous user interface to the data which is not specialized for our application.

7 Conclusions

The basic idea of the Intelligent Dental Care System project is the integration of restoration shape design, articulation simulation, database facilities, and user interface in an easy-to-use system. Since computer-aided dental systems are a relatively new idea, it is unreasonable to expect deep knowledge of computer techniques from the dentist. Therefore we have proposed the virtual reality user interface, referring to tools and techniques used in traditional dentistry which in our system are emulated mainly by software means.

Robust design of occlusal surface of restorations requires simulation of jaw articulation, which involves heavy geometric calculations. We have proposed an efficient cumulative distance maps technique, which takes advantage of graphics hardware for collision detection and calculation of the load on teeth. Our techniques realtime response makes possible interaction of the dentist during design of the occlusal surface of restorations. Our approach might be generalized for the design of human rigid parts which are under stress in motion, e.g., the design of joints.

At present we are using lower jaw motion data acquired by individual measurements. Because the measurement device is expensive, we are working on simulation of "sliding" of the lower jaw over the surface of the upper jaw, taking into account constraints imposed by the temporomandibular joint. This is another way of setting valid positions of the lower jaw which can be used for design of the occlusal surface of restorations.

Every step of the occlusal surface design is followed by interference checking for a set of representative lower jaw positions. This requires many sets of distance maps to collect final results into cumulative distance maps. The number of shots can be substantially reduced if, instead of opponent teeth, the so called functionally generated path (FGP) is used. In traditional dentistry, FGP is taken by cupus wax record, but we can calculate this surface, which is the movement envelope of the opponent teeth, using motion data and the shape of teeth.

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