Conferences on Orthodontics Advances in Science and Technology, Monterey, September 2002 (in press)

3D Visualization of the Craniofacial Patient: Volume Segmentation, Data Integration and Animation

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Keywords: 3D Visualization, volume rendering, CT, dentition models, jaw movement.

Acknowledgements:
We acknowledge grant support from the School of Dentistry at USC, the Integrated Media Systems Center, (a National Science Foundation Engineering Research Center, Cooperative Agreement No. EEC-9529152) at USC, Sun Microsystems and the American Association of Orthodontists Foundation.

Abstract:

The objective of our research is to develop computer methods to accurately visualize patients in 3-dimensions using advanced imaging and data acquisition devices such as cone-beam CT (Computerized Tomography) and mandibular motion capture. Data from these devices were integrated for 3D patient-specific visualization, modeling and animation. We are developing generic methods that can be used with common CT image format (DICOM), mesh format (STL) and motion data (3D position over time).

In this paper we present our preliminary descriptive studies on 1) segmentation of the lower and upper jaw with two types of CT data (traditional whole head GE HiSpeed RP CT scanner and the new dental CT Newtom 9000); 2) manual integration of accurate 3D tooth crowns with the segmented lower jaw 3D model; 3) realistic patient-specific 3D animation of the lower jaw.

Introduction:

Dental crown morphology on CT images is lacking detail due to limitations of the technology and interferences from metal and other materials. Yet this information is highly desirable for certain types of clinical procedures, such as dental implants, cleft palate or orthognathic surgery. An approach to resolve this situation is to integrate accurate 3-D dental crowns with the CT images, however this involves the process of registration of the two very different datasets. There is very limited work in this area, with a previous method described using spherical markers placed on the skeleton and dentition prior to CT imaging and production of the dental models [1], [2]. The spherical markers are located in both datasets and manually registered resulting in 2mm and 2 degrees mean error with maximum errors of 4.2 mm and 4 degrees.

Recent advances have allowed for production of very accurate 3-D dental models by destructive scanning (OrthoCad), laser scanning (e-Models from GeoDigm) or direct imaging of the teeth (OraMetrix). However they only feature the tooth crowns without the roots or skeletal information. In this paper we present computer methods to integrate the high-resolution 3-D dental models with the CT volume.

Accurate simulation of mandibular movement is fundamental in diagnosis and treatment simulations such as planning for orthognathic surgery involving autorotation of the mandible, wherein this movement must be accurately predicted. However, movement of the mandible is very complex and not easily recorded. For these reasons, its movement has historically been simplified to rotation about a single axis. However, this approach can lead to severe mal-positioning of the jaws, because the simulated axis of rotation is not related to the true path of mandibular motion [3]; [4].

More recently light and ultrasonic-based systems have been developed to record mandibular position and movement. Opticoelectric systems using CCD cameras to track light-emitting diodes on a headframe and face bow [5] have been developed [6]. The mean measurement error of this system is 150±10 µm [6]. However, this approach is time-intensive, requires attachment of intrusive hardware on the patient and involves a complex arrangement of cameras. Since, a newer approach utilizing ultrasonic sensors attached to a headframe and emitters firmly attached to the mandibular dentition has been developed and is commercially available (Zebris GmbH). The advantages of this system is the ease-of-use, significantly less hardware and an accuracy of ~100 µm. Both systems provide 3-D mandibular motion capture and report on the changes of coordinates positions with motion.

The second goal of this paper is to describe developed methods for simulation of mandibular motion on a 3-dimensional model of the craniofacial skeletal complex. This method applies the 3D ASCII motion data from the ultrasonic jaw motion tracker to the mandible of a craniofacial model created from a CT image.

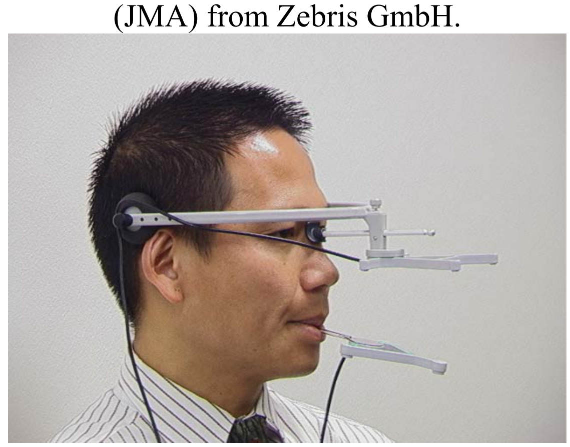
Materials:

CT: The data consisted on two kinds of CT image sequences: a) GE HiSpeed RP and b) the dental CT NewTom 9000. The GE CT sequence imaged the whole head with slices taken at 1mm, containing in total 129 slices (12 bits) in DICOM format. The Newtom CT sequence imaged only 13cm and was reconstructed to provide 285 slices of 0.33mm thickness (8 bits) in BMP format.

Digital dentition models: To obtain high accuracy digital tooth crowns modes, an impression of the patient imaged with the Newtom CT was sent to OrthoCad. Digital models of the lower and upper crowns were returned in STL format. Accurate 3-D models of the dentition can be obtained from several sources (OrthoCad, eModels, OraMetrix).

Jaw motion: Mandibular motion was recorded using the Jaw Motion Analyzer (JMA) from Zebris, (GmbH) and the software provided (WinJaw). JMA is an ultrasonic motion capture device depicted in Figure 1. The ultrasound emitter array is bonded to the labial surfaces of the mandibular teeth using a jig customized with cold cure acrylic. The sensors are located on a head frame secured to the patient's head. The spatial coordinates of

Figure 1: Ultrasonic Jaw Motion Analyzer (JMA) from Zebris GmbH.



the three emitters during motion are saved in an ASCII file.

Software: Whenever it was possible we used pre-existing software methods and programs. When necessary we wrote our own software in C. In this project we utilized the following software tools: a) DICOM2 from S. Barre (http://www.barre.nom.fr/medical/dicom2/) to convert DICOM 12-bit images to BMP 8-bit image format; b) Amira version 2.3 from TGS for 3D visualization, segmentation and modeling of the lower jaw; c) IrfanView 3.70 for contrast enhancement; d) 3D Studio MAX® R3 for animation of the lower jaw and creation of videos; e) Adobe Photoshop routines: Median Filter for removing the image noise.

Methods:

Visualization

Recent advances in volume rendering technology and graphic cards have provided a myriad of software to visualize CT data in three-dimensions. To cite some of them, Amira 2.3 from TGS, but also Volview from Kitware and VolumePro from Real Time Visualization (TeraRecon) allow the user to interactively change the scalar opacity function assigning to each gray value an opacity value between 0 and 1. The direct volume rendering process creates an image according to that opacity function (Figure 2b). The software named above also allows the user to create an isosurface at certain gray value (Figure 2a). The result is high flexibility: the user can display soft tissue or bone tissue in real-time for visualization, diagnosis or treatment planning in full three dimensions.

Segmentation and modeling of the jaws

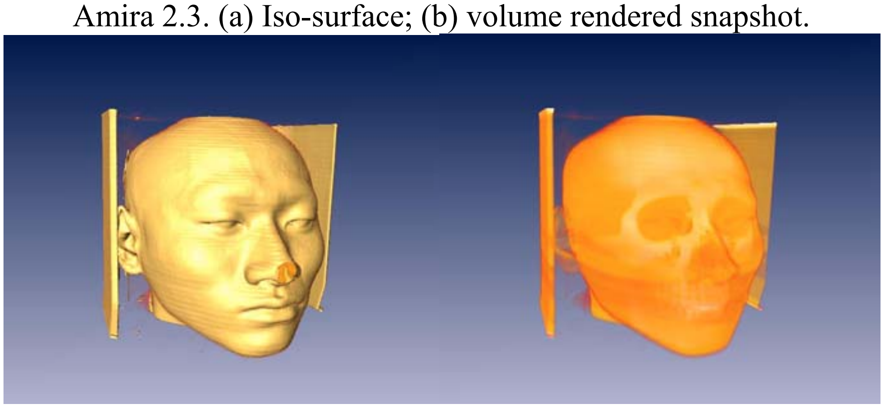
The creation of a separate 3D polygonal mesh for the lower jaw is needed for animation and integration of the crowns.

First, the soft tissue is removed from the images. The process is different for the two scanners because of different number of bits per pixel and different contrast.

- In the case of the GE CT images the segmentation of the bone tissue is achieved in two stages, sharpening (value 12) and enhancing the contrast (value 120) with Irfanview software.
- For the NewTom image slices, the images are binarized by thresholding at gray level 200.

Second, the lower jaw is manually segmented. While Amira 2.3 can automatically segment

Figure 2: Direct volume rendering: 3D visualization of the GE CT data with Amira 2.3. (a) Iso-surface; (b) volume rendered snapshot.



(a) (b)

or label every slice in the volume after manually segmenting the first, the software cannot distinguish between lower and upper jaw or lower and upper teeth (in particular, in the area close to the occlusal plane).

Third, the skull and upper jaw segmented images are obtained by subtraction of the lower jaw segmented slices from the processed images. To eliminate the outlier elements in the image obtained as a result of subtraction, the segmented image slices representing the lower jaw are passed through a Median filter (Photoshop) with a radius value of 3-4 pixels.

Using Amira 2.3 a 3D polygonal mesh (STL model) was created with the Generalized Marching Cubes Algorithm and decimated for later use (see Figure 3a and 3b for the results).

Integrating the digital teeth models

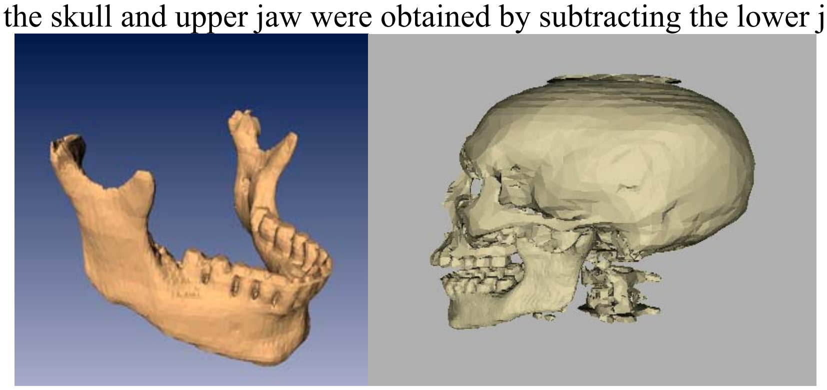
While the volume rendered image of the CT (Figure 4a) shows high detailed root information, the 3D model of the crowns in the reconstructed lower jaw (Figure 4b) is not as detailed as the digital teeth models from OrthoCad (see Figure 4c). Following are the steps carried out for fitting the 3D model of the teeth crown onto the 3D models of the jaw obtained from the CT:

The upper and lower 3D crown models are the same units as the patient's teeth, but the reconstructed 3D jaw models are not (Amira 2.3 scales the object). First, we compute the homogeneous scaling to fit the two together.

- The crown models are rotated in 3D such that the vector representing the frontal patient perspective gets aligned with one of the coordinate axes.
- Three corresponding points on the lower jaw and the crowns are manually selected, and the scaling factor is computed as the ratio between the X and Y distances along the axes. In the Newtom data, the two ratios are the same.

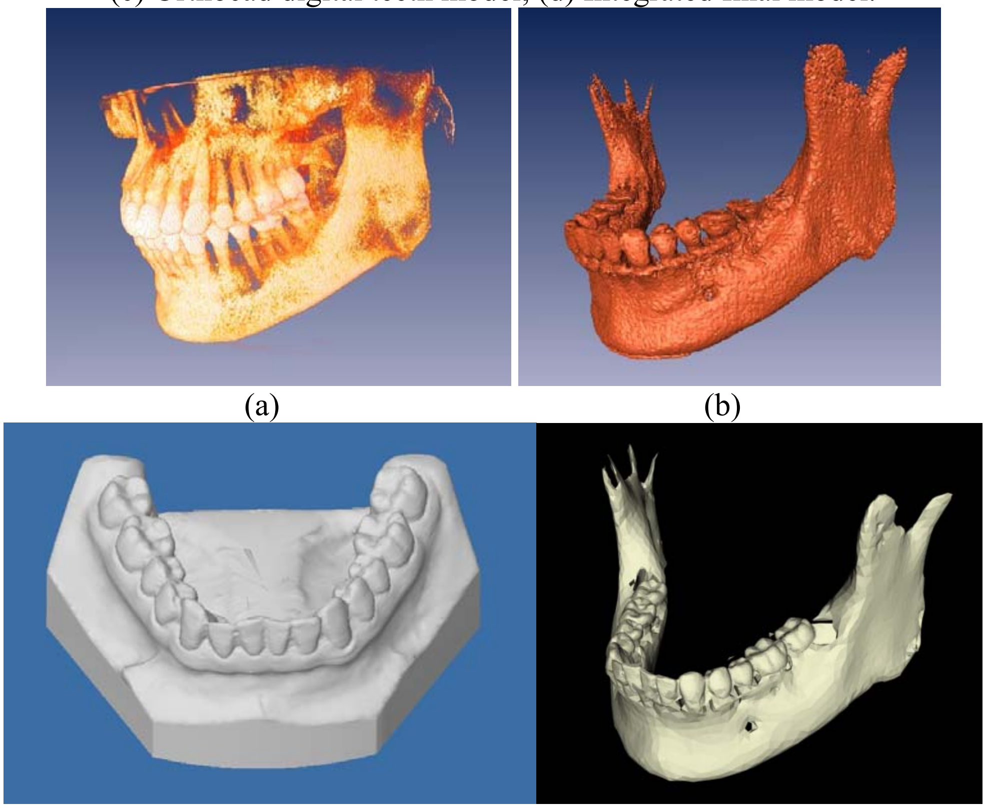
The 3D Jaw models are then scaled accordingly. The crude teeth from the 3D model of the jaw are removed in Amira 2.3 and replaced with the 3D crown models, which are manually aligned (Figure4d).

Figure 3: Polygonal 3D mesh reconstruction of (a) the lower jaw and (b) full skull (GE CT data) using Amira 2.3. First, the lower jaw was manually segmented and then the skull and upper jaw were obtained by subtracting the lower jaw areas.



(a) (b)

Figure 4: Integrating the crowns with the CT segmented 3D lower jaw:
(a) CT volume rendered; (b) Manually segmented lower jaw 3D mesh;
(c) Orthocad digital teeth model; (d) Integrated final model.



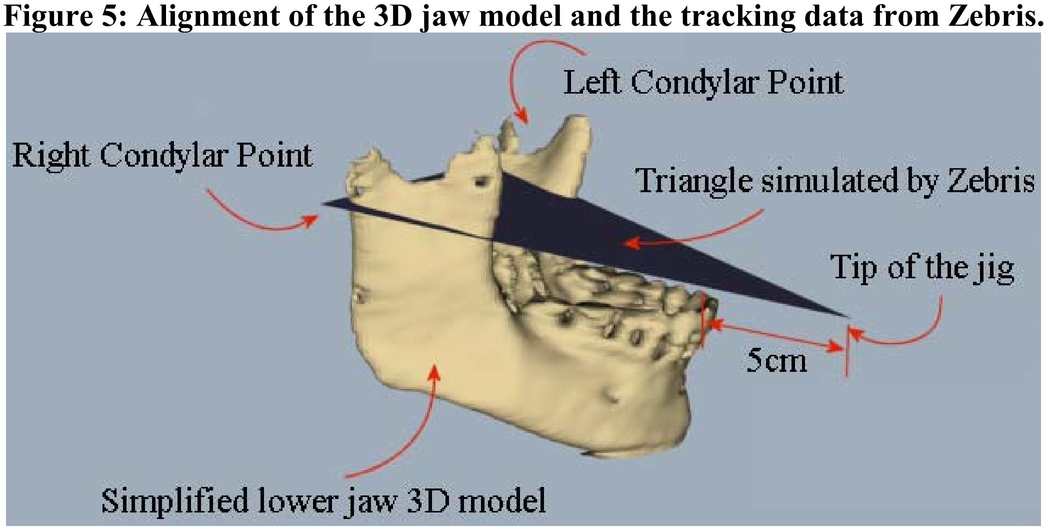
(a) (b)

(c) (d)

Animation

The Jaw Motion Analyzer tracks the position in space of three points defining a triangle shown in Figure 5: left and right condylar points (selected on the patient with a JMA T-pointer) and the tip of the JMA short pointer attached to the jig. The 3D lower jaw model is then aligned in space as shown in Figure 5 such that the condylar points coincide with the corresponding points on the triangle and the tip of the short pointer is at a distance of 5cm from the center of the two incisors.

Figure 5: Alignment of the 3D jaw model and the tracking data from Zebris.



The 3D positions of the tracked points are stored sequentially with respect to time in a file. A transformation matrix is computed for every successive position of the triangle so formed by the three points in space. This transformation matrix is recursively applied to all the points on the lower jaw. In fact, the lower jaw 3D model is treated as a single object in 3D Studio Max and the transformation matrix computed is applied to this object as a whole (see Figure 6 for some results).

Results and Discussion:

The overall goal of our research is to utilize multi-media imaging of the skeleton, dentition and motion to construct a Virtual Craniofacial Patient model. This patient-specific model serves as the basis for applications such as diagnosis and treatment simulation as well as advanced functions such as biomechanical testing and tissue engineering. Towards this goal, we have begun to utilize and integrate CT data with 3D dental crown information as well as animating mandibular motion. The presented modeling and animation results are descriptive studies and are ongoing research efforts in the process of further development and validation.

Segmentation of the Mandible

The GE CT data was processed to provide the resultant polygonal 3D mesh reconstruction of the lower jaw and the full skull (Figure 3). To automatically separate the lower jaw from the upper jaw, an “a priori” 3D model of the lower jaw must be known. Additionally, the teeth should be apart with no overlap during imaging such that the upper and lower teeth are not in the same slice, thereby facilitating segmentation. Our ongoing research efforts include automated image processing of the DICOM image slices for contrast enhancement and automated segmentation once the region of interest has been defined by the operator.

Integration of 3D Dental Crowns with the CT Volume

The NewTom CT volume (Figure 4a) was processed and segmented to provide the polygonal 3D mesh of the lower jaw (Figure 4b). The 3D model of the lower crowns from OrthoCad (Figure 4c) was fitted to the lower jaw (Figure 4d). In this process the key issues are registration and consideration of distortions related to the imaging modality. Registration relies upon common features present in both datasets. To overcome this problem metallic [7] and ceramic markers [1] placed on the dental arches for CT imaging and the dental impression have been used. This approach holds promise for future research on validation of the integration methods.

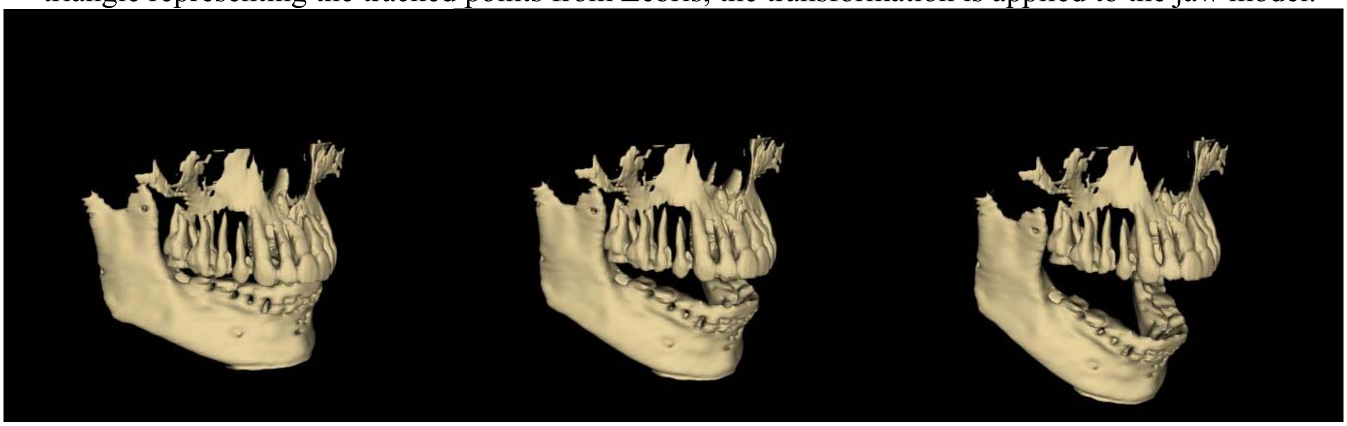
Animation of the Mandible

The segmented lower jaw was animated with the JMA motion data (Figure 6). The JMA device tracks three points over time and the transformation relating the position of the triangle over time is computed. After aligning the jaw models with the triangle representing the tracked points from JMA (see Figure 5), the transformation is applied to the jaw model. Our ongoing research is to automatically transfer the jaw models to the animation space. We will utilize ceramic markers as registration points that are tracked with the JMA and used for aligning the two coordinate systems.

The goal of constructing a Virtual Craniofacial Patient model is an ambitious interdisciplinary collaborative effort requiring both clinical and computer science knowledge. This goal will be accomplished in small steps such as those described above and with further development and advances the goal will be achieved. Realistic patient-specific models can greatly benefit patient care, education and research.

Figure 6: 3D jaw animation in 3D Studio Max

Some views of the animation video. Zebris device tracks three points over time. The transformation relating the positions of the triangle over time is computed. After aligning the jaw models with the triangle representing the tracked points from Zebris, the transformation is applied to the jaw model.



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