The Virtual Craniofacial Patient: 3D Jaw Modeling and Animation

Reyes ENCISO*°, Ahmed MEMON*, Douglas A. FIDALEO°,
Ulrich NEUMANN° and James MAH*

*Craniofacial Virtual Reality Lab, DEN 312
°Integrated Media Systems Center, EEB 131
University of Southern California, Los Angeles, CA 90089, USA

Abstract. In this paper, we present new developments in the area of 3D human jaw modeling and animation. CT (Computed Tomography) scans have traditionally been used to evaluate patients with dental implants, assess tumors, cysts, fractures and surgical procedures [1]. More recently this data has been utilized to generate models.

Researchers have reported semi-automatic techniques to segment and model the human jaw from CT images [6] and manually segment the jaw from MRI images [9]. Recently opto-electronic [2;15] and ultrasonic-based systems (JMA from Zebris) have been developed to record mandibular position and movement. In this research project we introduce: (1) automatic patient-specific three-dimensional jaw modeling from CT data and (2) three-dimensional jaw motion simulation using jaw tracking data from the JMA system (Zebris).

1. Introduction

1.1 Human Jaw Segmentation and Modeling

Recent developments in technology and software are providing better data and methods to facilitate research in biomedical modeling and simulation. In the area of segmentation, original methods involved the time-consuming task of manually tracing structures from slice to slice. This process is now possible with significantly less interaction from the user. Programs such as 3D Slicer [6], Mimics (Materialise N.V., Heverlee, Belgium) and Amira 2.3 (TGS) provide semi-automatic image-processing-based segmentation and modeling from CT images. These programs use the Generalized Marching Cubes algorithm to create a polygonal wireframe mesh of the segmented area and export a model in STL or other formats.

In this paper we present automatic segmentation of the mandible from CT images using the Amira 2.3 program. Previous reports have utilized manual methods to segment the mandible from MRI [9] and CT images [8]. Segmentation of the mandible contains common problems with this process in areas where anatomic structures contact and/or overlap and in areas that have indistinct borders. In the mandible, contact and/or overlap of the maxillary and mandibular teeth pose problems for segmentation. The other regions of difficulty are the condylar heads that rest in the radiographically dense temporal fossa resulting in borders that are often indistinct. As a result, many of the published reports present mandibles that lack parts of the dentition and the mandibular condyles.

1.2 Mandibular Motion

Accurate simulation of mandibular movement is fundamental in diagnosis and treatment simulations such as planning for orthognathic surgery [3;6;7;14] 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, recent research shows that during open-close movements in the human TMJ a pure rotation does not occur around the intercondylar hinge axis [5]. Also, simulation of a pure rotation around the center of the condyle 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 [12;13].

More recently light and ultrasonic-based systems have been developed to record mandibular position and movement. Opto-electric systems using CCD cameras to track light-emitting diodes on a head-frame and face bow [11] have been developed [15]. The mean measurement error of these systems have positional errors reported at 150±10 μm [15] and 0.11-1.33% [9] and maximum errors in angle computation of 0.7 degrees [9]. The opto-electric systems are fairly time-intensive to use, require attachment of intrusive hardware on the patient and involves a complex arrangement of multiple cameras.

Recently a simpler approach utilizing ultrasonic sensors attached to a head-frame and emitters firmly attached to the mandibular dentition has been developed (JMA from Zebris GmbH). The advantages of this system are the ease-of-use, significantly less hardware and a positional accuracy of ~100 μm. This tracking system provides 3-D motion capture in real-time and reports on changes of coordinate positions with motion.

In this paper we will describe new methods for simulation of mandibular motion on a 3-dimensional model of the cranio-facial skeletal complex. This method applies the 3D ASCII motion data from the ultrasonic jaw motion tracker to the segmented mandible of a craniofacial model created from a CT sequence.

2. Materials

2.1 CT

The data consisted of an image sequence from GE HiSpeed RP helical CT scanner. The CT sequence contained 129 slices taken at 1mm thickness at 12 bits in ACR-NEMA2 format.

2.2 Jaw Motion

Mandibular motion was recorded using the Jaw Motion Analyzer (JMA) from Zebris, (GmbH) and the software provided (WinJaw). The JMA is an ultrasonic motion capture device (Figure 1) that is comprised of an ultrasound emitter array that is bonded to the labial surfaces of the mandibular teeth using a jig customized with cold cure acrylic and a sensor array located on a head frame secured to the patient's head. The spatial coordinates of the two condylar points and an infraorbital point are pre-selected by the user to define a plane. Movements of at

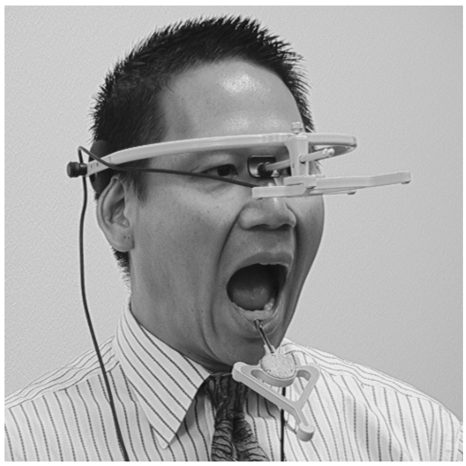


Figure 1: Ultrasonic Jaw Motion Analyzer (JMA) from Zebris GmbH.

least three points relative to this plane during jaw motions are saved in an ASCII file. The three points are the two condylar points and the base center of the T-attachment pointer attached to the jig.

2.3 Software

Whenever it was possible we used pre-existing software methods and programs to facilitate the reproduction of our methods. In this project we utilized the following software tools: a) DICOM2pgm from Grevera (http://www.rad.upenn.edu/~grevera/images/dicom2pgm.html) to convert ACR-NEMA2 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) 3D Studio MAX® R3 and the MAX Script for animation of the lower jaw and creation of videos.

3. Methods

3.1 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 2). The result is high flexibility- the user can display soft tissue or bone tissue in real-time for visualization, diagnosis or treatment planning in three dimensions.

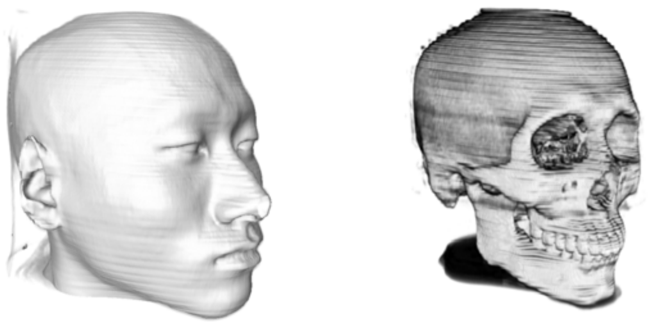


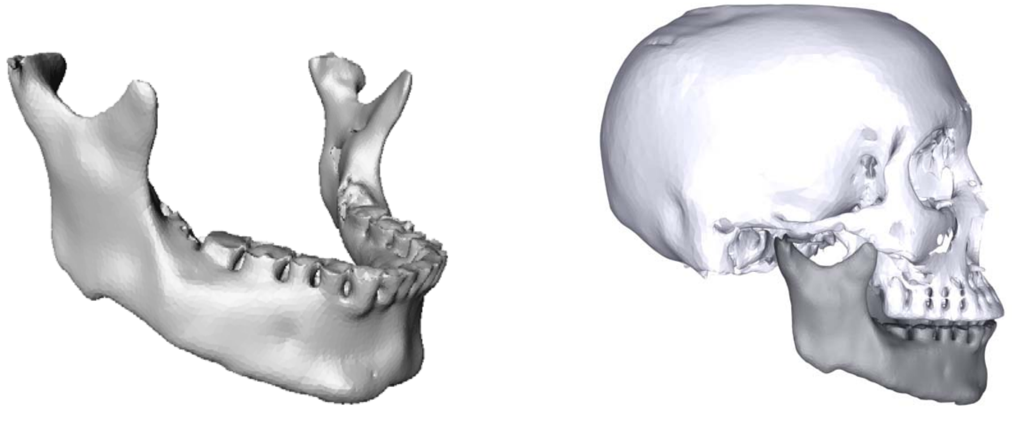
Figure 2: Direct volume rendering: 3D visualization of the GE CT data with Amira 2.3. The user interactively changes the opacity function to visualize soft or bone tissue

3.2 Segmentation and Modeling of the Jaws

Creation of a separate 3D polygonal mesh for the lower jaw is needed for animation. Therefore the mandible must be segmented from the CT volume. While the Amira 2.3 program provides computer tools for segmentation and jaw modeling, the software cannot distinguish between the maxilla and mandible or upper and lower teeth (in particular, in the area where teeth contact and overlap). To overcome this problem, two “phantom” slices were inserted in the image stack to facilitate separation: (a) one to separate the upper part of the mandible from the temporal bone and; (b) one to separate the upper from the lower teeth. The phantom slices were created by manually adjusting the greyscale value of the anatomic region of interest on a terminal slice to be sufficiently different than the remaining slices. This difference in greyscale was sufficient to terminate the segmentation routine. The interocclusal slice could be avoided if the patient was imaged with the teeth apart or if a radiolucent interocclusal splint was used to separate the teeth.

After the two phantom slices have been inserted in the stack of CT images, the user selects a point on any region in any slice containing the mandible and the software will automatically segment or label every slice in the volume. The same procedure can be applied to the maxilla.

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



(a) (b)

Figure 3: Polygonal 3D STL mesh reconstruction of (a) the mandible and (b) skull using Amira 2.3 software.

3.3 Animation

The Jaw Motion Analyzer tracks the position in space of three points defining a triangular plane (Figure 4). Left and right condylar points are selected on the patient with a pointer

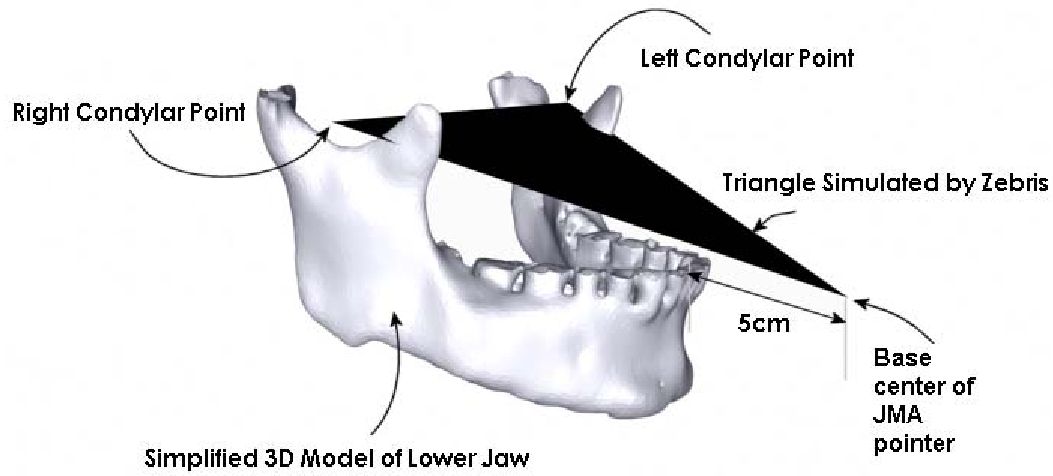


Figure 4: Alignment of the 3D jaw model and the jaw motion tracking data.

that is attached to the ultrasonic emitter array. The 3D mandibular model is then aligned in space as shown in Figure 4 such that the condylar points coincide with the corresponding points on the triangle and the base center of the JMA T-attachment is at a distance of 5cm from the jig.

The 3D positions of the simulated triangle are stored sequentially with respect to time in a file. Assuming *n* frames, the rigid transformation matrices $\mathbf{T_{01}}$, $\mathbf{T_{12}}$, ... $\mathbf{T_{(n-1)n}}$ are computed for every successive position of the triangle (Figure 5). For instance, for frames 0 and 1, if S is termed the source triangle and D the destination triangle, and O the triangle with A aligned with the origin and the vector AB aligned with axis Z, then it follows: $\mathbf{T_{01} = T_{SO} \cdot T_{DO}^{-1}}$.

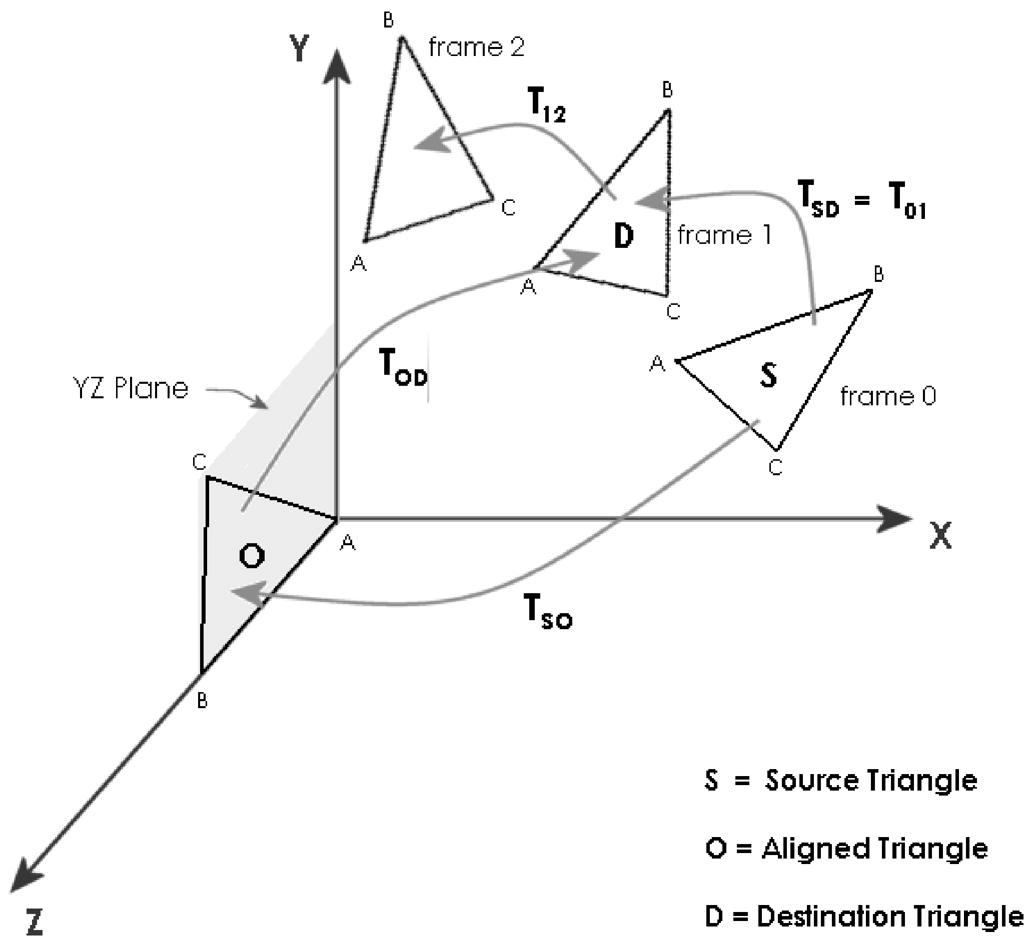


Figure 5: Each triangle represents the three tracked points at different frames or positions on time. To compute the transformation $\mathbf{T_{01}}$ from frame 0 (Source) to frame 1 (Destination), we compute first $\mathbf{T_{SO}}$ and $\mathbf{T_{DO}}$ for each frame, and then, $\mathbf{T_{01} = T_{SO} \cdot T_{DO}^{-1}}$

The transformation matrices $\mathbf{T_{01}}$, $\mathbf{T_{12}}$, ... $\mathbf{T_{(n-1)n}}$ were recursively applied to the model of the mandible which is treated as a single object in 3D Studio Max.

4. Results

This new technique combines CT data and current technology (ultrasonic real-time motion recorder) with computer graphics techniques to provide 3-dimensional visualization and animation of the jaw motion. The resultant animations could be of use to clinical researchers or practitioners interested in the three-dimensional motion of the jaw, for TMJ diagnosis [10] and treatment simulations.

4.1 Segmentation of the Mandible

The GE CT data was automatically processed to provide the resultant polygonal 3D mesh reconstruction of the mandible and the entire skull (Figure 3). To automatically separate the mandible from the remainder of the skull, two phantom slices were added to the original image sequence. If possible, 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.

4.2 Animation of the Mandible

After aligning the jaw models with the triangle representing the tracked points from JMA (Figure 4), the transformations (Figure 5) were applied to the lower jaw model. The segmented lower jaw was animated with the JMA motion data (Figure 6).

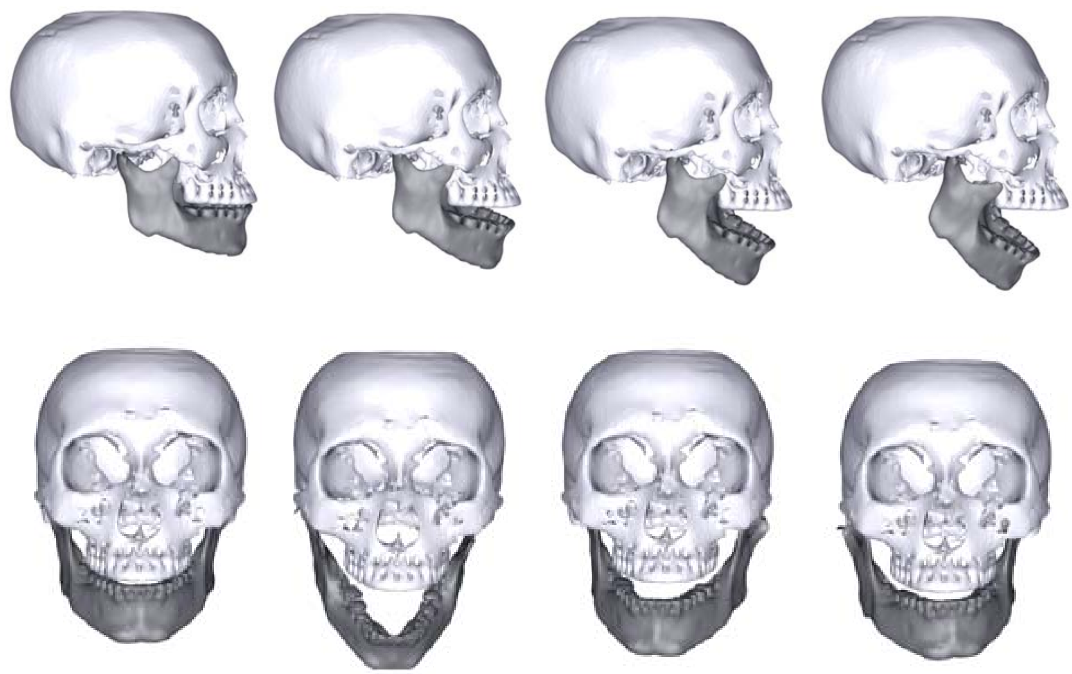


Figure 6: 3D jaw animation in 3D Studio Max.
Lateral and frontal views of selected frames of the animation. JMA device tracks three points over time. The transformation relating the positions of the triangle over time is computed. After aligning the jaw models with the triangle representing the tracked points, the transformation is applied to the lower jaw model.

5. Novelty/Discussion

Herein, we synthesize modeling of the jaw (from CT image sequences) and 3-D real-time motion information to provide patient specific 3D modeling and animation of the jaw. Previous reports of segmentation of the mandible from volumetric data involve manual techniques of tracing anatomic structures slice by slice [8] [9]. The segmentation method reported here is automated and made possible by inserting two "phantom" slices into the volume in the appropriate locations. Animation of the segmented mandible was achieved by registering and applying the relative motion coordinates obtained from an ultrasonic jaw motion analyzer. Further developments in these approaches will lead to more efficient methods to construct patient-specific models and to accurate simulation of motion.

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