

## Craniofacial Surgery Simulation Using Volumetric Object Representations

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### Abstract

Computer Assisted Surgery (CAS) systems facilitate surgical planning and analysis by aligning various datasets with information on morphology (MRI, CT, MR angiographies), cortical function (fMRI) or metabolic activity (PET, SPECT). These systems are categorized into performing one or more of the functions such as data analysis, surgical planning and surgical guidance, etc. The surgical planning systems present surgeons with data gathered prior to surgery and facilitate in plotting an approach trajectory that avoids critical structures such as blood vessels etc. Computer tomography (CT) has been widely used for surgical planners as craniofacial anomalies and fine anatomic details of facial traumatic injuries are well studied with CT. This research focuses on development of a system for simulation of craniofacial reconstruction surgery based on CT and laser scan data. The surfaces of soft tissue and hard tissue have been extracted from CT data using Marching Cubes algorithm and are rendered with surface based methods. Cutting of soft/hard tissue has been performed using cutting surface. Various rendering modes (surface, wireframe, point cloud) for soft/hard tissue have been implemented for better diagnostic visualization. This paper reports various components of the system and the current state of the integrated system.

**Keywords:** CAS, CT, surgery planner, soft tissue, hard tissue, tissue cutting.

### 1. Introduction

The key method to present data for the purpose of exploration in use today is visualization as the human visual sensory system is capable of understanding complex shaped rendered images with relative ease [1]. When visualization is applied to the representation of scientific data – it is called scientific visualization. Scientific visualization may be

described as “the integration of computer graphics, image processing and vision, computer-aided design, signal processing, and user interface studies” [2]. As such, scientific visualization would not only entail the visual representation of scientific data but also image synthesis using computer graphics techniques, data analysis, engineering and human perception.

The basic objective of scientific visualization is to create a mapping of data structures to geometric primitives that can be rendered using computer graphics techniques. Visualization is an important aspect in human understanding of objects and structures [1]. In medical imaging, the visualization of internal physiological structures is the fundamental objective. The visual observations in multi-dimensional medical imaging are often augmented by quantitative measurements and analysis for better understanding. Often the features extracted from analysis of medical images are incorporated in the visualization methods. For example, boundaries of a brain tumor can be superimposed on a two-dimensional brain image for better visualization of its local position and geometrical structure.

The system is the result of collaboration between a university, an industrial research organization and a research hospital. In this collaboration, we are developing a computer-based surgical simulator that uses surface-based volumetric object models generated from Computed Tomography (CT) data. In the next section, we present the work done in the related area. Section 3 elaborates system architecture. Results have been presented in section 4. Finally, section 5 presents the discussion.

### 2. Previous Work

First concepts of 3-D planning in craniomaxillofacial surgery, including soft tissue prediction, can be found in [3]. Active research started approximately 16 years ago. In [4], a finite element model of skin deformation has been stated. This work was followed by a PhD thesis [5] work, where an analysis of plastic surgery by means of the finite element

method has been presented. In 1991, another research work efforts were summed up to provide a system for computer-aided plastic surgery [6]. He focused on plastic surgery and therefore concentrated on cutting and stretching of skin and epidermis rather than on repositioning bones. Further, his model lacked the resolution [7] required for a reliable simulation of very subtle changes in the appearance of a face and did not provide a  $C^1$ -continuous surface.

In [8] a promising approach to facial animation has been presented, where a layered tissue model based on masses and springs connected to form prism-shaped elements has been introduced. In [9] a method has been proposed which provides a  $C^1$ -continuous finite element surface connected to the skull by springs. This model is generated directly from individual facial data sets and has successfully been tested for surgery simulation and emotion editing [9] on the Visible Human Data Set. Although providing very promising results the model lacks true volumetric physics.

In [10], researchers presented a system for surgery planning based on CT data. The 3D geometry of the head and the color of the skin surface are measured using a 3D laser scanner. For simulating craniofacial surgery, the bony skull is acquired by segmentation of CT data. For the visualization of volume data, surface based methods are used. Dissection of bone has been simulated using a "cutting plane".

In [11], a versatile framework for the finite element simulation of soft tissue using tetrahedral Bernstein-Bézier elements has been proposed. In this work higher order interpolation as well as incompressible and nonlinear material behavior has been incorporated, but again the work has been restricted themselves to  $C^0$ -continuous interpolation across element boundaries. In [7] surgical procedures such as the bone cuts and bone movements have been simulated with the help of a craniofacial surgeon using the Alias<sup>TM</sup> modeling system.

In [12] a system for three-dimensional visualization of the facial skeleton, selection of landmarks, measurement of angles and distances, simulation of osteotomies, repositioning of bones, collisions detection and superimposition of scans has been reported. For the surface-model generation, "3D Slicer" [13], a visualization software for medical images, was used to semi-automatically segment the bone. Once the segmentation is obtained, the 3D Slicer generates triangulated surface models of the skeleton and skin using the marching cubes method [14] and triangular surface decimation [15].

### 3. System Architecture

The craniofacial objects can be rendered by either one of the two methods: namely surface based method [14] [16] [17] where only the surface of an object is rendered and volume based method [18] where both surface and interior of an object is rendered. When an object is rendered using

surface based rendering techniques; the object is modeled with surface description such as points, lines, triangles, polygons, or 2D and 3D splines and the interior of the object is not described. In contrast, some applications require visualizing data that is inherently volumetric. The purpose of volume rendering is to effectively convey information within volumetric data and this technique allow us to see the inhomogeneity inside the objects. Information on the internal structures of the bone is irrelevant [10] in craniofacial reconstruction. Therefore, in this research we have used surface based rendering method for visualization of craniofacial objects.

Patient-specific 3D CT images are processed to generate surface-based volumetric object models. The surfaces of soft tissue and hard tissue have been extracted from CT data using Marching Cubes algorithm [14]. Human soft tissue also has been captured using 3D laser scanner. The CT data and laser scan data is registered with using a robust registration process. The integration of soft tissue data captured by Close Range photogrammetry with the model is next focus of the research. Object models are presented visually via rendering on the computer monitor. Visual parameters such as viewpoint, color and opacity transfer functions, and lighting effects can be interactively controlled and object models can be manipulated to change relative object positions, and to simulate surgical procedures such as cutting etc. Figure 1 shows the layout for the proposed system.

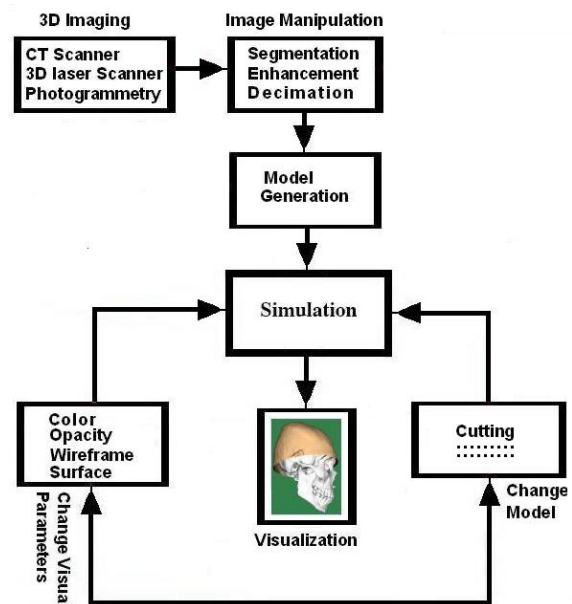


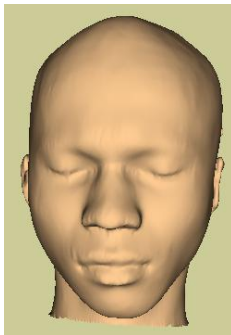
Figure. 1. Surgery planner system components

The objects can be rendered in one of the three modes, such as surface, wireframe and point cloud. The color and opacity of the objects can be changed, and hence two objects can be compared using different value of opacity and color.

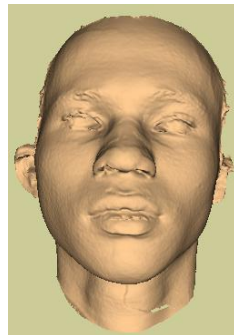
These visual parameters (render mode, color and opacity) can be modified interactively and the resulting models can be visualized immediately. Such type of human- computer interaction provides a better understanding for diagnostic visualization and planning surgery procedures.

The important technologies required by each component in the simulator are listed in Figure 1. These include: acquisition of patient-specific data by CT scan, 3D laser scan and Close Range photogrammetry; and segmentation of patient-specific 3D models, model enhancement by removing artifacts, reduction in the data of models by preserving anatomical details to enhance the rendering process; incorporation of the data into efficient and effective data structures; enhancement of the object models with measured material properties, visual maps, and other data; visual feedback through interactive rendering; image manipulations allowing adjustment of visual parameters such as color and opacity for simultaneous visualization overlapped objects and for comparison of two objects; and model manipulations allowing interactive manipulation of object models such as cutting objects for pre-operative surgery planning.

#### 4. Results

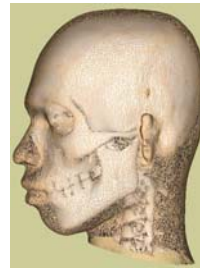


**Figure 2.** Soft tissue reconstructed from CT data



**Figure 3.** Soft tissue from laser scan data

This research is focused on development of a surgical planner for diagnostic visualization, planning surgical procedures and planning approach trajectory in craniofacial reconstruction surgery. Prior to the surgery, pre-operative data sets (CT data and Laser Scanner data) are fused with a robust registration process. Then this merged data is visualized in an interactive 3-D graphics environment. Figure 2 and Figure 3 display soft tissue reconstructed from CT scan and laser scan data of the same patient. The soft tissue has been rendered using surface based method. Figure 4 shows the result of soft tissue superimposed on hard tissue. The soft tissue has been rendered as wireframe to expose the underlying surface of hard tissue. In Figure 5, cutting of soft tissue has been demonstrated. Vertically left half of the soft tissue surface has been cut using cutting plane.

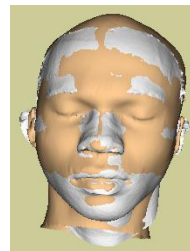


**Figure 4.** Soft tissue (wireframe) superimposed on hard tissue

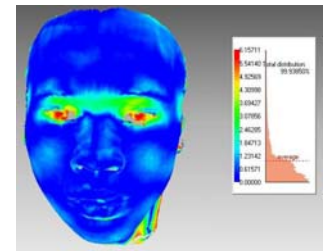


**Figure 5.** Cutting of the soft tissue

In Figure 6, laser scan soft tissue (white color) has been superimposed on CT scan soft tissue. The difference in these two surfaces is shown in Figure 7 as color distance map. Average difference in distance of the two surfaces is 0.99582mm and standard deviation is 1.13229.



**Figure 6.** Laser scan soft tissue (white) superimposed on CT soft tissue



**Figure 7.** Soft tissue surface difference between CT data and laser data.

#### 5. Discussion

The surface based visualization of human soft tissue (Figure 2 and 3) and hard tissue (Figure 4) has been demonstrated. The visualization of soft tissue superimposed on hard tissue has also been demonstrated. Any one or, both of soft tissue and hard tissue can be rendered as surface, or wireframe, or point cloud. In Figure 4, soft tissue superimposed on hard tissue, has been rendered as wireframe to provide better view of underlying hard tissue surface for diagnostic examination.

In Figure 7, a large surface distance of 6.23041 has been observed in the eye's region. The reason may include that the patient's eyes are kept closed during CT scan for safety while in laser scan the eyes may be kept open as the range of lasers used is safe for human eyes. The other difference area observed includes the cheeks region, the difference is in the range of 1.5mm. One of the main includes that the laser scan was taken after almost one month of the CT scan, and during this time there were changes in the soft tissues of this region.

The images obtained by surface based method are very fast and approach to interactive rate. Realistic cutting of tissue, as shown in Figure 5, is possible on low cost PCs using surface based techniques. The operations like rotation and zooming of these craniofacial objects are also fast and look realistic.

Surface rendering has several important advantages and have made possible to simulate surgery procedures on low cost PCs. Because they reduce the original data volume down to a compact surface model, surface-rendering algorithms can operate very rapidly on modern computers. The realistic lighting models used in many surface rendering algorithms can provide the most three-dimensionally intuitive images. Finally, the distinct surfaces in surface reconstructions facilitate clinical measurements.

Computer-Assisted surgery systems have many applications in education and training, surgical planning, and intra-operative assistance. Surgical simulation has important use in medical education and training to reduce costs, to provide experience with a greater variety of pathologies and complications, and to make it possible to repeat or replay training procedures. A surgery planner enables rehearsal of difficult procedures and can enhance communication among medical professionals or between doctor and patient.

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