Interactive Segmentation and Three-Dimension Reconstruction for Cone-Beam Computed-Tomography Images

Siriwan Suebnukarn, DDS, PhD  
Faculty of Dentistry, Thammasat University  
Klongluang, Pathumthani, Thailand, 12121  
Peter Haddawy, PhD  
Matthew Dailey, PhD  
Dinh Ngo Cao, MEng  
School of Engineering and Technology, Asian Institute of Technology  
Klongluang, Pathumthani, Thailand, 12120

ABSTRACT
We develop a novel interactive segmentation and 3-D visualization system for cone-beam computed-tomography (CBCT) data in a personal computer environment. Its design includes both a new user interface to ease the interactive manual segmentation of the volume rendered and artifact-suppressing algorithms to improve the quality of CBCT images. Four pipelines of noise removal were carried out by applying threshold filter algorithm only and with additional smoothing algorithms (Gaussian filter, Median filter, Dilation and Erosion filter). The interactive intensity plot was implemented to allow user to manually identify each anatomic structure and view the instant feedback. The visual feedback necessary during 3-D segmentation was provided by a ray casting algorithm. Both orthodontic and non-orthodontic patients demonstrated that the system was able to minimize the artifacts caused by CBCT and metal appliances. Based on the feedback obtained from the dental experts, the interactive segmentation and 3-D reconstruction functions are found to be very helpful.

KEY WORDS Cone-beam computed-tomography, 3-D Reconstruction, Segmentation, Noise reduction

บทคัดย่อ
คณะผู้วิจัยได้พัฒนาระบบแยกส่วนอวัยวะและการแสดงภาพสามมิติของข้อมูลจากเครื่อง cone-beam computed-tomography ที่สามารถให้ตอบสนองผู้ใช้งานเครื่องคอมพิวเตอร์ส่วนบุคคลได้ โดยมีการออกแบบด้วยขั้นตอนที่มีให้ใช้งานตอบสนองได้สะดวกในการแยกส่วนอวัยวะ ประกอบกับการใช้กรองสัญญาณสร้างภาพสามมิติ threshold filter, Gaussian filter, Median filter และ Dilation and Erosion filter เพื่อให้คุณภาพของภาพสามมิติที่สามารถแยกส่วนอวัยวะได้ชัดเจน ผู้ใช้สามารถเลือกและกำหนดขอบเขตของอวัยวะได้ด้วยตนเอง จากการแยกส่วนความเข้มของข้อมูล ระบบแสดงภาพสามมิติเรียกว่า ray casting แสดงการเคลื่อนไหวของสิ่งแวดล้อมรอบข้อมูล และผู้ใช้ที่ไม่ใช่เครื่องมือจัดฟัน พบว่าสามารถแยกส่วนอวัยวะชัดเจนจากเครื่อง cone-beam computed-tomography และโค้งรูปริด จากเครื่องมือจัดฟันได้ ทันตแพทย์ผู้เชี่ยวชาญพบว่าการแยกส่วนอวัยวะที่สามารถตอบสนองได้กับระบบและการแสดงภาพสามมิติประโยชน์มาก

คำสำคัญ Cone-beam computed-tomography, การสร้างภาพสามมิติ, การแยกส่วนภาพ, การก๊าจัดสัญญาณระบบภาพ
1. Introduction

The goal of medical visualization is to produce clear and informative pictures of the important structures in a dataset. Volume visualization is currently in use as a tool to help in diagnosis, surgery, radiological treatment planning, and anatomical education. Recently, computed tomographic (CT) scans are widely used to evaluate craniofacial anomalies, and three-dimensional (3-D) CT images constructed from 2-D images have become popular. These images can be used to visualize and assess craniofacial anomalies and are extremely useful for computer simulation using virtual reality techniques.

There are a number of processing steps involved in 3-D visualization. Among them, segmentation, which refers to the extraction of structural information of particular interest from surrounding images, is important because it delineates the anatomy to be visualized or characterized [1]. There are several different approaches in segmentation, including a semi-automated computational algorithm using supervised and unsupervised statistical methods [2] as well as manual segmentation [3]. An automatic segmentation can never be perfect for the specific task the user wants to perform, so interactive visualization and refinement are still important. These methods, nonetheless, may require a certain degree of user-computer interactivity, and an instant 3-D visualization is often desirable even during the segmentation processes.

Unlike conventional CT scanners, which are large and expensive to purchase and maintain, cone-beam computed tomographic (CBCT) is suited for use in clinical dental practice where cost and dose considerations are important, space is often at a premium and scanning requirements are limited to the head. Disadvantages of CBCT are, for instance, the scattered radiation [4], the limited dynamic range of the x-ray area detectors, the truncated view artifact [5], and artifacts caused by beam hardening [6]. These drawbacks need to be considered as they may influence image quality and tissue segmentation accuracy.

Accordingly, this study was aimed to develop an interactive segmentation and three-dimension reconstruction system for cone-beam CT images. The paper was organized as follows. In the next sections, we described the development of our system using the image data exported from the CBCT under DICOM file format. Threshold filter algorithms were used to eliminate the noise from the raw input data. The topologic relationship of anatomy was extracted from the images through interactive segmentation processes. Image-order volume rendering and filter algorithms were applied for 3D image reconstruction and display. The experimental results of human subjects and the usability evaluation of the system were provided to demonstrate the performance of this system. We then gave a discussion on this system and a conclusion was drawn.

2. Material and methods

2.1. CBCT Data acquisition

Two healthy volunteers (23-year-old male and 25-year-old female) who underwent orthodontic treatment participated, and gave written consent in accordance with the institutional review board prior to the study. The data was obtained from an i-CAT CBCT (Imaging Sciences International, PA, USA) covering the whole maxilla and mandible.

2.2. The software

The software was programmed to perform two major operations: interactive volume segmentation and the 3-D visualization of the segmented structures for real-time display and user guidance.

2.2.1. Segmentation

A segmentation tool, which uses interactive segmentation interface developed by our group with the ray casting algorithm [7] for 3-dimensional visualization, was developed in the C++ language for computing algorithms and programming the user-interface. VTK and ITK libraries [8] were used for developing the application. Four pipelines of noise removal were carried out by applying threshold filter algorithm only and with additional smoothing algorithms (Gaussian filter, Median filter, Dilation and Erosion filter).

2.2.2. Volume rendering

The process of visualizing an object or a set of objects using a computer is called rendering. Volume rendering describes methods to visualize three-dimensional scalar fields. In this section we discuss the ray casting approach that we used in rendering a three-dimensional anatomical model from CBCT images.

Ray casting, often referred to as image-order volume rendering, is a flexible technique that can be used to render any structured point data set, and can produce a variety of images by adjusting the richness in the content of the volume data [9]. The basic idea of ray casting is that the value of each pixel in the visualization is determined by sending a ray through the object into the scene. If the ray retains all the information on its path as it passes through the volume data, true volume rendering with transparency (i.e. alpha value) information could be realized. However, this requires more rigorous computation thus more processing time and memory. To reduce the processing time, only the distance along the ray at which the ray first
encounters the threshold or segmented pixel values for visualization is computed. A Z-buffer algorithm \[10\] allowed the shortest data on the model-surface from the viewer's eye to be displayed as solid texture while an adequate shading gives the depth information \(z\)-value). The effects included variations in shading and coloring to provide a realistic 3-D visualization. This simplified ray casting algorithm, which eventually gives a surface representation of volume, was chosen as the visualization method because it provides fast and effective 3-D representation of objects with relatively simple programming.

We integrated the ray casting algorithm into the segmentation program. The segmented data is labeled with a single value, and passed to the geometrical transformation for aspect ratio, translation and rotation. The geometrical transformation was done by multiplying the data coordinate with an appropriate Affine transformation matrix defined by the user. Then the volume information was projected onto the 2-D field-of-view where the user can define the projection resolution matrix (i.e. number of 2-D array of rays projected to the objects). Any changes in the user-defined parameters refresh the 3-D visualization routine. It allowed the user to decide between image quality and computation time by adjusting projection resolution, providing an interactive environment during the proposed volume segmentation \[7\].
2.2.3. Noise reduction

The purpose of noise reduction is to optimally suppress unwanted artifacts of the imaging process while preserving the details of the structures being measured. We experimented with three basic filters for removing noise from CBCT images prior to rendering: the Gaussian filter, the median filter, and morphological opening [11]. The Gaussian filter is a linear 3D convolution operator that blurs the image, reducing both noise and image detail. The median filter replaces each pixel with the median value of the pixels in a 3D neighborhood around that pixel. Morphological opening first erodes the dense regions of the image then dilates them. Whereas morphological opening tends to eliminate spurious dense voxels while preserving contours, the median filter both eliminates spurious dense voxels and fills in small holes with less density than the surrounding neighborhood.

2.2.4. User interface

The segmentation and 3D reconstruction tool consists of windows for following functions; (1) 3-D Display (Fig. 1, upper left window), (3) 2-D Multi-Orientation View (Fig. 1, lower left windows), (4) Data Operations including ‘Load Data’, ‘Intensity Plot’, ‘Segmentation’, ‘Render’ and ‘Export Segmented Data’ (Fig. 1, right menu).

In ‘Load data’ operation, DICOM files are read. In order to classify different layers of an anatomic structure, an intensity plot was created using a spline as an interpolation function to probe intensity values of volumetric data along that spline. The probing data was plotted to provide user with a visual view (Fig. 2). First, the user sets the maximum and minimum intensity-scale thresholds from the intensity plot, making a window of allowable signal intensities. A binary mask is then generated over the original images where all voxels inside the threshold window are labeled. In ‘Segmentation’ operation, the user applies a labeling operation for a connected-component to separate isolated sets of morphologically connected voxels (connectivity analysis). After the operation, the voxels are each marked with a different color and intensity value (Fig. 3). The user is also able to select only the components belonging to the desired target object disregarding everything else.

An example of the 3-D viewing window and three orthogonal-plane display (axial, coronal and sagittal) is shown in Figure 1 for maxillary arch. In the ‘3-D Display’ operation, 3-D information on segmented structure and pre-labeled data are updated by the ray casting algorithm. The ‘2-D Multi-Orientation View/Control’ window provides three orthogonal views of a 2-D image of volume data with adjustable cutting plane. A plane can be positioned in any planar-data, and the corresponding location in 3-D is automatically updated.

Figure 2. An intensity plot of maxillary right canine. The user sets the maximum and minimum intensity threshold of enamel, dentine and pulp.

Figure 3. The user can view the preliminary result of the segmented tissues while adjusting the intensity threshold.

3. Results

3.1. Patient Studies

Two clinical cases are shown in Figures 4 and 5 for non-orthodontic and orthodontic patients respectively. In non-orthodontic case, the artifacts were almost completely removed by the threshold filter algorithm while preserving the original structure in the nearby region. It is also interesting to observe that the subtle ring artifact caused by imperfect CBCT detector calibration in this version of the CBCT software was also removed.
Metal appliances are another example of the source of severe metal artifacts in CT images, which can cause major difficulties in the visualization of anatomy. In Figure 5, we demonstrated the application of the threshold filter algorithm for the patient who had undergone fixed orthodontic treatment. Although the overall performance is not as ideal as the example in Figure 4, we can still see the improvement in tissue visibility.

We also tested the image quality resulting from additional filtering algorithms. The quality of the rendering increases by using Gaussian filter and Median filter. The quality of the 3-D image did not improved significantly by using dilation and erosion filter (Fig. 6). The average performance speed (CPU speed of 700 MHz) during the fourth trial by experts was $1.3\pm0.04$ min, $3.2\pm0.06$ min and $3.4\pm0.05$ min respectively. The results of user-identified segmentation in both cases are shown in Figure 7.

3.2. User Evaluation

To test the usability of the software, eight dental experts are asked to test the software and fill an evaluation form. These experts are affiliated with Thammasat University Dental Faculty and Advanced Dental Technology Center, where a complete digital radiology system environment (i.e. Radiology Information System (RIS), Picture Archiving and Communicating System (PACS), diagnostic/clinical workstations, and web viewers) has been in use for several years. 3D visualization programs are routinely in use for diagnosis and treatment planning in implantology and orthodontics. It is determined that the experts joining this study are using 3D visualization with a frequency of 5–12 times a month. Twelve questions are asked under four headings and grading was from 1 to 5 where 1 is the best.
Figure 6. Comparative results using Gaussian filter (a, d), Median filter (b, e), dilation and erosion filter (c, f) in non-orthodontic patient (a, b, c) and orthodontic (d, e, f) patient.
The views of the experts and the average evaluation value (AVV) for each heading are as follows:

1. **Graphic User Interface (GUI) and ease of use**: The experts find the GUI elements easy to use and understand (AVV2).

2. **Software panel and specification properties**: The menu options are found to be sufficient. However, it is pointed out by the experts that there is a strong need for an information panel which interactively shows the intensity values of the tissues on the intensity plot. An example of this information panel may be a “mouse listener” which shows the intensity value of a pixel that the mouse cursor points on the image. Such information is indicated to be necessary to give a coarse idea to the user on where to locate the tissue of interest (AVV2).

3. **The visual feedback**: The visual feedback and manipulation properties of the software such as the ‘Segment’ view in the intensity plot and the automatic updated of the intensity value are found to be helpful. The 3-D display and 2-D multi-orientation view are found to be acceptable (AVV1).

4. **The Browser and the file system**: The usability of the Browser, import/export file format are found out to be acceptable. Nevertheless, although the segmented file format is found to be very effective, the experts prefer a system that generates STL file for further development of the virtual reality system (AVV2).

These evaluation forms show that the initial results are very promising and optimistic for our software. Feedbacks from dental experts show that the software is very useful for interaction with visualizations and for producing 3-D models for CBCT images. It is pointed by the experts that it is efficient to use the software after a segmentation process which eliminates artifacts from the data, especially in orthodontic cases with metal appliances. We plan to add the function in the software that users can remove remaining artifacts by themselves.

### 4. Conclusion

We develop the interactive segmentation system that allows user to manually identify each anatomic structure using the interactive intensity plot and view an instant 3-D reconstruction feedback. The interface makes it easy for the user to choose noise reduction algorithm appropriate for the task at hand. Both orthodontic and non-orthodontic patients demonstrated that the system was able to minimize the artifacts caused by CBCT and metal appliances. Based on the feedback obtained from the dental experts, the interactive segmentation and 3-D reconstruction functions are found to be very helpful.

### Acknowledgment

We would like to thank National Electronics and Computer Technology Center for funding this project (Grant No. NT-B-22-MS-14-50-04).

### Reference


