Automated filtering and polygonal reconstruction of virtual skull model based on computed tomography

M G Grif, A M Grif
Automated Control Systems Department, Novosibirsk State Technical University, Novosibirsk, Russia
E-mail: grifmg@mail.ru

Abstract. A method of automated filtering and polygonal reconstruction of the skull virtual model using the methods of "Marching cubes" and "Connected component labeling" is considered. An algorithm for effective software implementation is described. A computational experiment on computed tomography data consisting of 244 DICOM images is presented. The experimental results confirm the correctness and computational efficiency of the algorithm.

1. Introduction
According to statistics, about 30% of people with traumatic brain injury have a trepanation defect [1]. In modern medical practice, the method of 3D printed implants, which are designed for each patient individually by using a virtual skull model, is recognized as an advanced solution [2]. In the vast majority of cases, the results of computed tomography (CT) examination conducted in a medical institution are used to obtain this model. Moreover, these results are used to create skull models both voxel-based and polygonal which are user-friendly [3].

However, the created polygonal model of the skull may require significant improvement, because it may contain many small three-dimensional objects the so-called artifacts, that do not correspond to the patient's skull. The fact is that the CT scans may show an imaginary intensity of x-ray radiation that does not correspond to the tissue parameters of the study area, which occurs due to physiological (for example the presence of dental crowns), systemic or hardware nature.

This paper is devoted to the description of the artifacts filtering method at the stage of the polygonal model reconstruction.

2. Theory
3D polygonal model of the patient's skull. The virtual model of the patient's skull is reconstructed from a set of CT scans taken in a medical institution. Most modern x-ray equipment, including computed tomography (CT) and magnetic resonance imaging (MRI), supports a single standard for storing, transmitting and visualizing medical data. An example of such international standard is DICOM [4], developed by the International Organization for Standardization (ISO).

A quantitative evaluation of the density of the study structures is the scale of the x-rays attenuation the so-called Hounsfield unit scale (HU). To create a 3D voxel-based human body model, the linear interpolation of pixel values of neighboring images is used. According to this model and the correspondence between the HU scale and human organs and tissues (Figure 1), it is possible to segment the study structures. In this case, the area of the skull bone tissue corresponds to the value of +700 HU.
The voxel-based model is transformed into a polygonal one, and the most effective way to obtain such triangulation of a surface is the "Marching Cubes" algorithm [5]. The substance of this algorithm is to create triangular isosurfaces of a scalar 3D field by evaluating the values of the voxel function. Figure 2 shows an example of using this algorithm [6, 7] to construct a volumetric digital model of the patient's skull.

Artifacts filtering of topical diagnosis. In DICOM images, the imaginary signal intensity may not correspond to the tissue parameters of the study area the so-called artifacts. Artifacts can be physiological, system or hardware in nature. For example, several metal dental crowns which are adjacent can light up the image due to the non-falling of the metal parameter in the coverage area of the HU scale. For such cases, it is advisable to use image filtering. Figure 3 shows an example of the image reconstruction with artifacts in the research area.
Figure 3. The skull model with the artifacts.

Modern soft and algorithmic filtering tools are mainly represented by "manual" functional. The application allows you to "cut off" the necessary study area with the help of a 3D parallelepiped. This process is simple, but it requires a large number of similar actions to select a new artifact object and its cutting. For example, for the model considered earlier in Fig. 3, it is necessary to make about 20 such manipulations.

The natural idea of an automatic filtering is to remove objects that are not related to the skull from the research area. It requires the knowledge of the morphology of the study image, i.e. segmenting it into related three-dimensional objects with their identification and subsequent removal of those objects that are not included in the structure of the patient's skull. 3D segmentation of the image can be performed using the "Connected Component Labeling" algorithm [8], which is one of the most effective ways of matrix selection of related components. However, preliminary studies have shown that the "direct" application of a segmentation model of about 5 million polygons (Figure 3) is a computationally expensive task even with the use of preliminary indexing of polygons by an octree.

A method of image filtering combining the process of image reconstruction and filtering is proposed. Its essence is as follows:

At the first stage, a three-dimensional graph of the model described by the function is constructed

\[ \chi(i, j, k) = \begin{cases} 1, & \text{if voxel } (i, j, k) \text{ contains polygons}, \\ 0, & \text{else}, \end{cases} \]

moreover, the correspondence of polygons to a given voxel fabric is determined by the "Marching Cubes" algorithm, and for all values of the function \( \chi(i, j, k) \) equal to one. Polygons for this voxel are stored in a separate hash table.

At the second stage, the values of the function \( \chi(i, j, k) \) are equated so that a certain value \( c = 1...n \) corresponds to a set of numbers \( \{(i, j, k)\} \) that describe a geometrically related component. To do this, the "Connected Component Labeling" algorithm is used.

At the third stage there is such a number \( \xi \in \{1...n\} \) that the power (number) of connected voxels of the formed \( \xi \) component is the maximum among the whole set of components. It is natural to assume that many voxels will correspond to the geometry of the skull.

At the fourth and final stage, only those polygons that correspond to the voxels found at the third stage are extracted from the hash table built at the first stage.
3. Experimental results

We can consider the application of the proposed approach by using the example: patient's MRI data with a traumatic brain injury obtained in Novosibirsk Research Institute of Traumatology and Orthopedics of Ya.L.Tsivyan.

Tomographic data is represented by a set of 244 DICOM files. Figure 4 shows the 10th, 80th, 140th and 180th images of the series.

![Figure 4. A series of research images are 10 (a), 80 (b), 140 (c) and 180 (d).](image)

The digital three-dimensional skull model is reconstructed from a series of images. Figure 5 shows the obtained model.

It can be seen that in the skull there are many artifacts. Moreover, some of them are formed due to the semicircular design of the tomographic table (it can be seen at the bottom of all the images in Fig. 4), and some reflect the presence of the dental crowns.

Moving to the simultaneous reconstruction and filtering of the practice model. Figure 6 shows the obtained model.
Figure 5. Skull model with the artifacts: front view (a) and side view (b).

Figure 6. Skull model after filtration: front view (a) and side view (b).

It is seen that the proposed algorithm automatically filters the image in a proper way. It is worth noting that the reconstruction and filtering of this model using an Intel Core i7-2820QM processor and a frequency of 2.30 GHz takes less than three minutes.

4. Conclusions
The method and algorithm of automated filtering and polygonal reconstruction of the virtual skull model are considered.

The results of the reconstruction and simultaneous filtering of tomographic data, presented by Novosibirsk Research Institute of Traumatology and Orthopedics of Ya.L.Tsivyan, confirmed the effectiveness of the proposed method. The software implementation of the algorithm does not require preliminary indexing of model's polygons and uses a small amount of memory as well as it is computationally low-cost.

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