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3-D Brain CT Image Display for Planning of Craniofacial Operation

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We have been developing a 3D brain CT image display system for planning of craniofacial operations. This system helps doctors plan craniofacial operations on a graphic display (GD) terminal by rendering 3D images reconstructed from a set of slices. We will present in this paper how the system generates 3D shapes of organs from given CT images and how it modifies or transforms the obtained shapes according to the user's request. The system functions now available are extraction and display of the skull and the skin, measurement of the distance between two points on the skull given through the GD terminal, and generating and eliminating a polygonal region arbitrarily given on the skull as an operative region.

1. INTRODUCTION

Various kind of CT machines, such as x-ray CT, magnetic resonance CT, and positron CT, have come into wide use in recent years. Clinical use of the CT machines, especially x-ray CT, has become popular and remarkably contributes to diagnosis of brain diseases such as tumor or hematoma. Because such facilities only provide 2D cross sections of a human body in various directions, doctors had to imagine 3D shapes of organs from a sequence of CT images with their anatomical knowledge and imagination. By computer, on the other hand, it will be possible to construct and display 3D images of organs, since all slices are produced as digitized pictorial data. From this point of view, several experiments for 3D display of CT images using Computer Graphics (CG) techniques have been performed, as were surveyed in Ref. [7] and [10].

We have developed a 3D CT display system which gives us some idea on shapes and positions of disease lesions or organs by generating 3D images of them. We use both cross section images and 3D surface images of bone, soft tissues and diseased part for rendering 3D anatomical structure. The cross section is displayed as a half tone image with grey values proportional to the CT numbers. The surface is constructed by borders extracted from slices automatically. Both of these images are helpful for detecting abnormalities and diagnosing them.

In craniofacial operations, surgeons have to understand 3D complex skull deformities, based on a sequence of 2D images. Therefore, it is difficult to plan the operation precisely. Recently, we have been developing a 3D CT display system for planning craniofacial surgery. This system generates 3D images of bone or skin surface on GD terminal. Doctors then can try the pre-operative simulation which removes or connects some part of the bone, according to the plan of the actual surgery.

Functions now available in our system are as follows;

(1)Automatic extraction and display of the skull and the skin surface.

(2)Measurement of the shortest distance between two points on the skull or the skin surface.

(3)Interactive determination of a cut-off region on the skull.

(4)3D display of the skull with the cut-off region removed.

Applications of 3D CT display to craniofacial surgery were reported and some of them have already been used in clinical stage. Their aim is mainly generation of 3D images to help doctors understanding abnormalities, and not the pre-operative simulation like our system [3,5,8].

2. SYSTEM FUNCTIONS

2.1 AUTOMATIC EXTRACTION AND DISPLAY OF THE SKULL AND THE SKIN SURFACE

2.1.1 EXTRACTION OF THE SKULL BORDER

Our system should be required to show the details of bone structure so that it may be effectively utilized for craniofacial surgery. Therefore, all bone borders on each slice should be extracted. Since as far as x-ray CT is concerned, the CT number of the bone is much higher than that of any other soft tissue, it is possible to extract the skull border automatically by computer, employing simple thresholding and border following procedures. The minimum CT value in bone is found from the histogram of CT numbers on a sequence of CT slices. We use this minimum value as the threshold in each slice to generate a binary image representing bone area. The skull contour is extracted by tracking borders on this binary image, and is represented as a sequence of pixels connecting each other in the sense of 8-connectivity.

2.1.2 DISPLAY OF THE SKULL

We have already developed a method to render the skull surface, which constructs triangular tiles from contour points represented by the cylindrical coordinate system (CCS) [11]. This method is not suitable for representing complex bone shape in this system, although useful for describing simple shape such as the upper part of the skull.

Christiansen and Sederberg proposed another methods to construct triangular tiles as 3D surfaces from a sequence of contours [1]. However their method is not also applicable to the case which a cross section of the organ is multiply connected or some of cross sections consist of more than two parts separate each other.

We have developed a rather simple method called Border Sweeping Method (BSM) to display this kind of complex skull [9]. Let us assume that the original slices are arranged horizontally (Fig.1). Then borders extracted from each slice are shifted both upward and downward by half of the interval between slices. Thus each border making a closed curve produces a board with the thickness equal to the interval between slices. The 3D shape is reconstructed simply as a stack of all such boards.

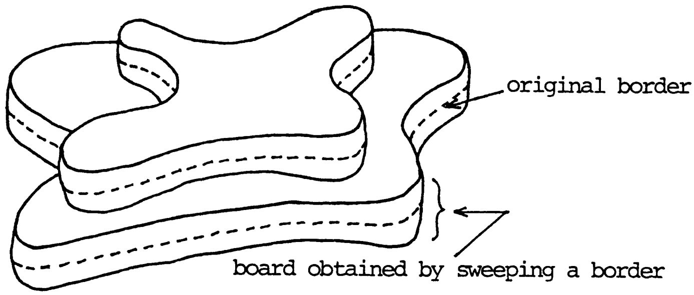

Fig.1 Border sweeping method

The grey value of the board surface is determined according to the Lambert's cosine law, that is the scalor product of the surface normal vector and the direction vector of the light source. Unfortunately, the result displayed by this method has stair-like shape due to the disconnection of each board. Therefore, for the grey value calculation we use the depth coding which is frequently used in other organizations [2-5,8]. The grey value is decided only basing upon the distance between the board and the viewing point. This method can produce rather smooth images and suitable for understanding macroscopic structure , though fine structures of the surface are not expressed well.

2.1.3 EXTRACTION OF THE SKIN SURFACE

Since the shape of the skin surface is relatively simple, the contour can be described by CCS on each slice (Fig.2). First we binarize each slice to obtain a figure containing only soft tissues, and then extract the contour by tracing the outmost border of the resultant figure. All contours extracted are transformed into CCS expressions.

2.1.4 DISPLAY OF THE SKIN SURFACE

The 3D skin surface is constructed by triangular tiles and rendered by using the Lambert's law to decide grey values of tiles and smooth shading method to realize feeling of a 3D curved surface.The skin surface can be rendered transparently using the method of Newell et al., if necessary [6]. Then the skull shape is observed and studied through the transparent skin surface displayed simultanously.

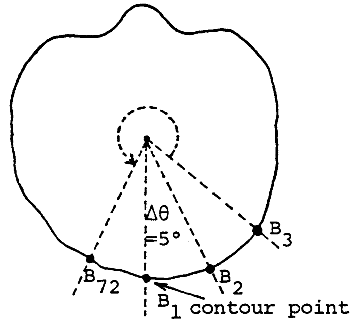

Fig.2 Extraction and expression of the skin surface by CCS

2.2 MEASUREMENT OF THE SHORTEST DISTANCE BETWEEN TWO POINTS ON THE SKULL OR THE FACE

Geometrical information is necessary in order to give doctors some idea of the degree of deformation in the shape of the skull. The function now available is to measure the shortest distance between two points specified on a GD terminal by a doctor. Two extremal points P1 and P2 are specified on the screen by an input device like a hair cursor after displaying the whole 3D image of the skull (Fig.3). We can get x and y coordinates of those points in the Projection Coordinate System (PCS) immediately, since the row and the column on the screen correspond to the x and y axis in the PCS respectively.

In order to obtain z coordinate in the PCS, the z-buffer table is helpful. Since the z-buffer always indicates the z coordinate of the point which is nearest from the viewing point, the z coordinate of the specified point is readily found as the form Zij=f(Xi,Yj) from the z-buffer table (Fig.4). In this way, we determine 3D coordinates of the two specified points in the PCS. The system calculate the shortest distance between these points in the World Coordinate System (WCS) after transforming the coordinates in the PCS to the WCS.

2.3 INTERACTIVE DETERMINATION OF THE CUT-OFF REGION ON THE SKULL

An important problem, faced in the surgical planning stage, is to decide the appropriate shape and size of the region to be removed (cut-off region or removal region) during the operation. In our system, we approximate the region by a polygon which is defined by vertices specified in the same manner as 2.2. Assuming, for example, points V1 - V4 are the specified vertices, the system generates a sequence of contour points on the line segment which connects a pair of vertices, and stores both input points and the generated point sequence denoting the contour of the cut-off region as WCS (Fig.5).

The contour of the removal region is superimposed on the 3D skull image by projecting all stored points on the screen. There might be some disconnection on the displayed contour when we observe it from the view point which is quite different from the position where we input the vertices. In such case, the system interpolates necessary points in order to keep continuity of the contour (Fig.6).

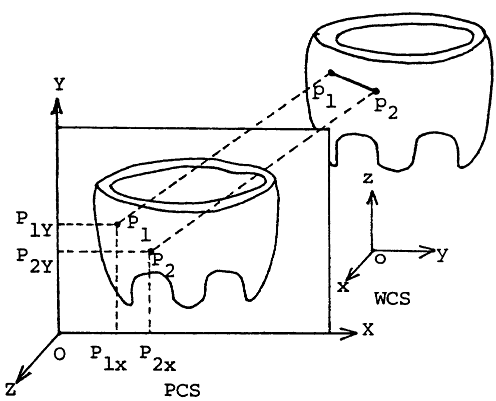

Fig.3 Shortest distance between two points on the skull

Y\X	X_1	X_2	-----------	X_i	--------
Y_1	Z_{11}	Z_{21}		⋮	
Y_2	Z_{12}	Z_{22}		⋮	
⋮				⋮	
Y_j	---	---	------- ----	Z_{ij}	-------
⋮				⋮	

Fig.4 Z-buffer table

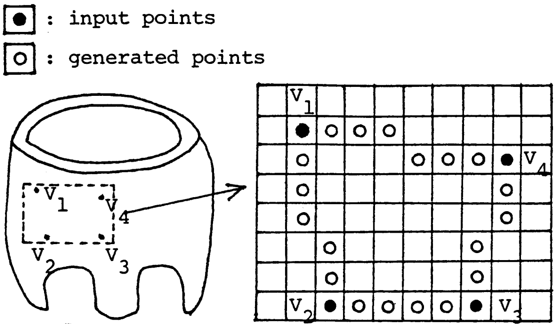

Fig.5 Input and generated points

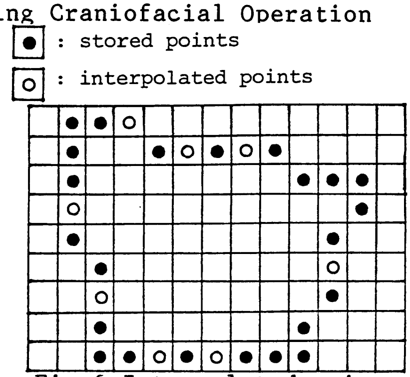

Fig.6 Interpolated points

2.4 3D DISPLAY OF THE SKULL WITH THE CUT-OFF REGION REMOVED

The function for 3D display of the skull from which the cut-off region is removed is available after deciding the removal region described in 2.3. In order to use the BSM for rendering the skull image, the following process is applied to each original CT slice. For an original slice, we find the pair of the contour points, such that the line connecting them intersects the slice, and determine the intersection point between the slice and the line.

Denoting a sequence of the contour points by C1,C2,---,Cm, z coordinates of these points by zc1,zc2,---,zcm, and the z coordinate of the slice by zs , we find the pair of the contour points Ci and Cj which satisfies the intersection condition as follows (Fig.7):

for an arbitrary i (1<i<m),

$$(z_{ci} - z_s)(z_{cj} - z_s) < 0$$

where $j=i+1$, if $i=m$
$j=1$, otherwise

The x and y coordinates xk and yk of the contour point K on the slice (z = zs) are calculated by the interpolation of the x and y coordinates of Ci and Cj, namely

$$x_k = \frac{x_{ci}|z_{cj} - z_s| + x_{cj}|z_{ci} - z_s|}{|z_{cj} - z_{ci}|}$$

$$y_k = \frac{y_{ci}|z_{cj} - z_s| + y_{cj}|z_{ci} - z_s|}{|z_{cj} - z_{ci}|}$$

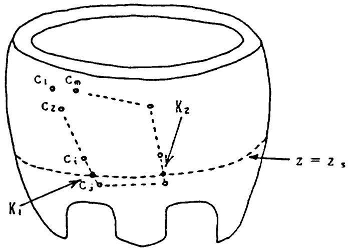

Fig.7 Determination of contour points K on the slice (z = zs).

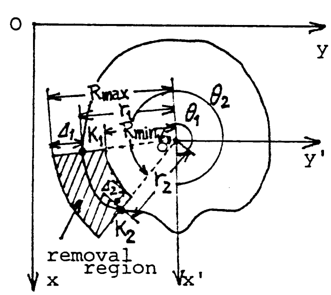

Fig.8 Removal region.

This process is applied to all stored contour points in order to find all intersections on the slice.

Assuming the intersections K1 and K2 are found as shown in Fig.7, the removal process is carried out as follows (Fig.8). First,we calculate the angles θ1,θ2 and the distances r1,r2 from the center of the slice to the points K1 and K2. Second, the maximum and the minimum radii Rmax, Rmin of the cut-off area are determined by

$$R_{max} = \max(r_1, r_2) + \Delta_1 \ , \quad R_{min} = \min(r_1, r_2) + \Delta_2$$

where Δ_1 and Δ_2 are the constants given beforehand.

Third, the CT value at the pixel P(rp,θp) which satisfies the following condition is replaced by the value lower than the CT number of bone,

$$\text{Condition:} \quad \theta_1 < \theta_p < \theta_2 \quad \text{and} \quad R_{min} < r_p < R_{max}$$

after transforming all pixels to the r-θ coordinate system from the x-y coordinate system.

By applying this process to all slices, pixels belonging to the removal region are eliminated when the 3D image of the skull is displayed.

More advanced functions such as transformation or rotation of the skull with a cut-off region removed are required for simulation of the actual craniofacial operation. Above functions now available are the first step to a higher level of system satisfying these requirements.

3. RESULTS

Several examples of displayed 3D images are shown in Fig.9 - 12. Input data are children's x-ray CT images provided by Saitama Children's Medical Center. Their size is 256*256 pixels and the slice interval is 4 mm.

Fig.9 shows the skin surface rendered by the smooth shading method. Inside of the skull and other bones can be seen in Fig.10. In this figure, a sequence of 52 slices generated by interpolating original 26 slices were used with the depth coding to calculate the intensity.

After the removal region was decided as a polygon (Fig.11a), we can observe and examine the region from different view points (Fig.11b). Since the BSM is employed, edges of the polygon include irregular fluctuation in Fig.11b. Fig.12 shows the skull image from which the cut-off region is removed. The system was implemented on FACOM M-382. Computation time to generate figures shown above was from 20 seconds (Fig.9) to 1 minute 20 seconds (Fig.12). The GD terminal used here is GRAPHICA M-508, whose resolution is 512*512 dots and the color information of each dot is stored in the corresponding 24 bits memory of which 8 bits are assigned to R,G and B components respectively.

(Figs. 9, 10, 11, 12 are printed on Plate II at the opening of this volume)

4. CONCLUSION

We have developed a new 3D brain CT image display system in order to use in craniofacial surgery. The purpose of this system is to help doctors plan craniofacial operations more precisely. Functions presented below have already been developed as the first step :

(1) Automatic extraction and display of the skull and the skin surface.
(2) Measurement of the shortest distance between two points on the skull or the skin surface.
(3) Interactive determination of the cut-off region on the skull.
(4) 3D display of the skull from which the cut-off region is removed.

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