3D BIOMEDICAL MODELLING OF HUMAN VERTEBRAE AND ITS DEFORMATION

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ABSTRACT: Three dimensional models have their principal part of application in the medical domain. In the medical field, a three dimensional model gives a more accurate and visually viable version of the internal organs, bone structures, blood vessels and tissue structures. Hence various algorithms and software have been developed in the recent years for accurate analysis of a medical data in the three dimensional form. Here we obtain a three dimensional model of the human vertebrae using CT scan slices. The algorithms used for obtaining the three dimensional models are marching cubes algorithm and constrained Delaunay tetrahedralization. A comparison of these two algorithms is performed. Later this model is used as a standard model which is deformed using the specifications of subject specific stereo-radiographic images, hence obtaining a personalized vertebrae model. The deformation method used is known as dual kriging. These vertebrae on stacking produces a personalized model of deformed human spine. This model can be used for effective diagnosis of the spinal deformities.

KEYWORDS: marching cubes, constrained Delaunay tetrahedralization, dual kriging.

INTRODUCTION

Spinal deformations are three dimensional irregularities in which the normally straight vertical line of the spine has lateral deviation, with abnormal deformations between and within vertebrae as well as rotation in transverse plane. The three main types of spinal curvature disorders are: Scoliosis, Lordosis and Kyphosis [1]. Deformations to the spinal column curvature can also occur after accidents or injury. The treatment for such spinal curvature disorders includes observation, bracing and surgery. The deformations being three dimensional in nature necessitate the need for a 3D model for observation and diagnosis. A 3D model also provides the necessary information for surgeons to plan the way to surgery in advance [2].

Basically, the 3D models in medical field are obtained using the data from two dimensional stereo radiography, Magnetic Resonance Imaging and Computed Tomography [3]. The CT and MRI methods cannot be immensely relied on (considering the case of spinal deformities), since the image acquisition is performed with the patient in a horizontal position making the diagnosis difficult in case of CT and MRI. Hence for spinal deformity analysis, a stereo radiographic method is more reliable, since it requires the patient to be in a standing position [4]. Also a person undergoing treatment for spinal deformities will have to undergo scanning several times to determine effect of treatment. This increases the patient exposure to radiation in case of CT or MRI scan. But the stereo radiographic method is able to reduce patient’s exposure to radiation.

Although the CT scans have their drawbacks, a 3D CT model obtained is considered a closest approximation of the actual anatomical geometry. Hence the 3D model obtained from CT scans can be used as a standard model for the validation of other three dimensional models. The standard model is constructed from CT scan slices of a cadaveric vertebra. This standard CT model of the vertebra is then given to deforming algorithm with specifications of a particular subject. The specifications of the subject are retrieved in the form of six control points on the subject's vertebra using stereo-radiography. The three dimensional reconstruction of a subject using stereo-radiography is as shown in Fig. 1(a), whereas the actual spine looks like Fig. 1(b). To improve the visibility of stereo-radiographic reconstruction, morpho-realistic spine model is developed using marching cubes and constrained Delaunay tetrahedralization.

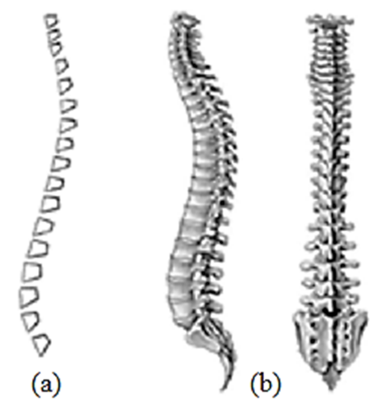

Figure 1. (a) Spine reconstruction using 3D stereo radiography (b) Actual 3D view of the spine

3D surface construction problem has several approaches. The technique mentioned in [5] is one of the earliest and deals with the contours of the surface. In this algorithm, triangles are used to link adjacent contours. When a slice has more number of contours, ambiguities arise. These errors can be overcome by user interaction which is a disadvantage in the clinical environment. Octree representation [6] and ray cast methods [7] [8] can be used to find the 3D surface. The Mayo Clinic uses a method [9] which instead of displaying the surface, it will give the volume density. Each of these methods mentioned, discards useful information in the original data, which is a major shortcoming. Hence marching cubes and Delaunay tetrahedralization are used for modelling. This model is deformed using free form deformation technique known as dual kriging to get personalized spine model.

METHODOLOGY

The method for 3D reconstruction and its deformation to obtain a personalized model is shown as a flow chart in Fig. 2. The procedure involves 3 major parts: Image processing, Computer Graphics and Deformation. These sections are discussed in detail in the subsequent sections. The CT scan slices in DICOM format is the input to the algorithm. It is preprocessed using image processing techniques and modelled using computer graphics. Deformation is then applied to the obtained model for personalization.

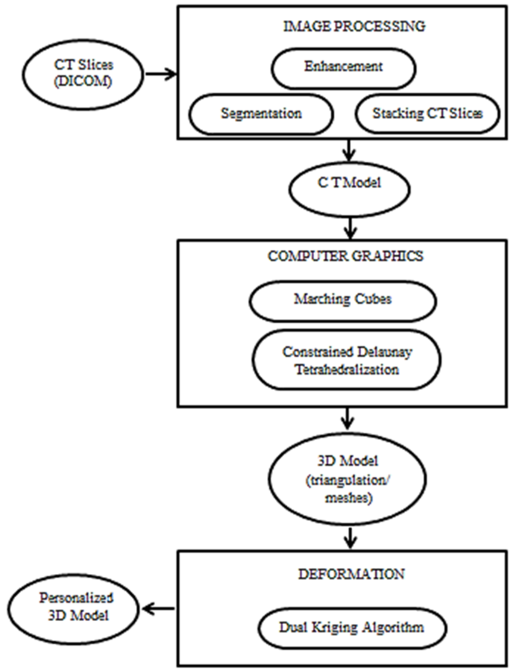

Figure 2. Block diagram

Image processing

The CT scan device is used to obtain slices of size 512 x 512 and 12 bits per pixel. The CT slices in DICOM (.dcm) format is enhanced using multilevel thresholding method. The enhancement process is followed by segmentation to remove unwanted components and noise from each slice. The 3D reconstruction is then started by superimposing each slice on the next one. Polyhedron elements are constructed locally by joining pixels of slice n to corresponding pixels on adjacent slice n + 1.

The main aim of multilevel threshold is to increase the separability of the classes in a gray scale image. Multilevel threshold of gray level is an important tool to extract the objects from its background. When histogram has two peaks, one for the background and the other for object, in an ideal case there is a significant separation between the two peaks. The separation is sharp and very deep so the threshold is taken from the bottom of this separation. But practically this threshold can be difficult to obtain as the space that separates the two peaks may be flat and broad. It is also difficult to take the threshold if both the peaks have different height or corrupted with unwanted noise. Hence in this method the image is segmented based on pixel intensities based on the number of levels provided. This method is known as the Otsu's Method [10]. The between class variance will be maximized in this method, thereby making it an optimum one.

Computer graphics

In computer graphics, the three dimensional rendering techniques are either "surface rendering" or "volume rendering". A surface rendered model will not give the interior structure of the model, only outer surface is viewed. The volume rendering on the other hand allows the display of not only the surfaces that meet a threshold density, but also a better representation of the volume of 3D model. A volume may be viewed by extracting the isosurface from a volume data and modelling as polygonal meshes. In 3D CT scans isosurface represent regions of particular density. A common technique to extract isosurface from volume data is the connecting cubes algorithm or marching cubes algorithm.

Marching cubes algorithm
The algorithm is used here to create an inter slice connectivity using a predefined set of triangulated cubes [11]. A logical cube is created from two adjacent slices, as shown in Fig. 3 (a) to locate the surface.

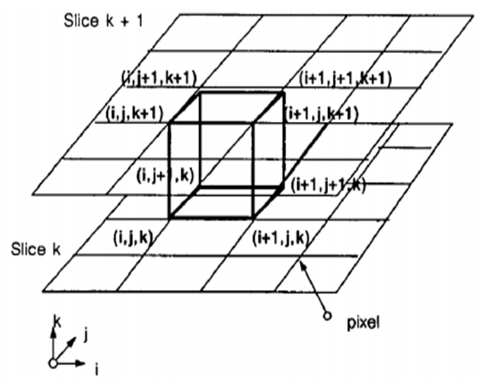

Figure 3. Logical cube [11]

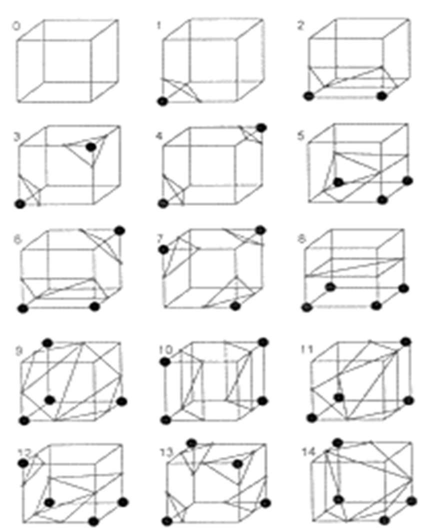

Figure 4. Triangulated cubes for marching cubes algorithm [11]

How each surface intersects this cube is determined by assigning the cube vertices with value 'one' the value of the surface being modeled. The value 'zero' is given for vertices outside the surface. Each cube has eight vertices with one state as inside and the other one as outside. Hence, there are $2^8 = 256$ways the cube intersects a surface. Considering different symmetries of the cube, the look up table is created for 14 patterns instead of 256 cases. These look up tables are shown in Fig 4. Based on the vertex numbering shown in Fig. 3, an index is created for each case. The index determines the edge where the surface overlaps. These overlapping surfaces are used to linearly interpolate along the edge.

Constrained Delaunay tetrahedralization

The initial step of constructing a CDT is to construct a Delaunay triangulation as the surface mesh [12]. The surface of an object to be modeled is shown as point clouds. For triangulation with Delaunay method, there is a need to generate the point clouds. The contoured slices are processed in order to obtain the coordinate of each point in the cloud. For this purpose, the metadata in each slice is extracted. The pixel coordinate is obtained with respect to an origin point in each slice. This point is also termed as the reference point. Hence, in this manner the point cloud is formed using the three dimensional vertices coordinates. Coordinates are found using the following equations,

$$X_{new} = x(k,l) \times pixelspace + refx \tag{1}$$

$$Y_{new} = y(k,l) \times pixelspace + refy \tag{2}$$

$$Z_k = z_{k-1} - gap \tag{3}$$

$$Z_1 = refz \tag{4}$$

Where,

$refx$ - Reference point or origin in the x direction

$refy$ - Reference point or origin in the y direction

$refz$ - Reference point or origin in the z direction

gap - Space between subsequent slices

k, l - Coordinates in x, y direction

The point cloud in each CT slice is then connected by a triangulation in three dimensional spaces. Delaunay triangulation for a set of points P in the plane is a triangulation such that no point in P is inside the circumcircle of any triangle. Let C be the circumcircle of the triangle abc. A test is designed such that,

inCircle (a, b, c, d) = 0 if d ε C (5)

inCircle (a, b, c, d) > 0 if d is outside C (6)

inCircle (a, b, c, d) < 0 if d is outside C (7)

If abcd is a quadrilateral, having ab as its diagonal. Then if we draw a circumcircle for abd, then c is either within or outside the circumcircle. Similarly. If we draw a circumcircle for abc, it can be found that the point d will be positioned either inside or outside this circumcircle. The case where the points lie inside are illegal Delaunay triangulations as depicted in Fig. 5.

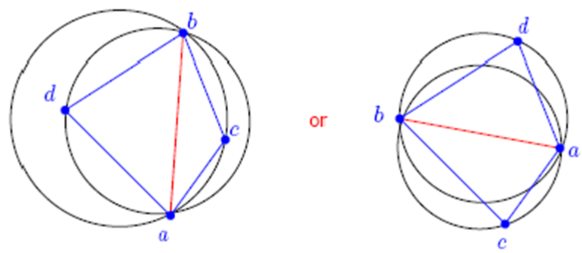

Figure 5. Illegal Delaunay Triangulation abc and abd [12]

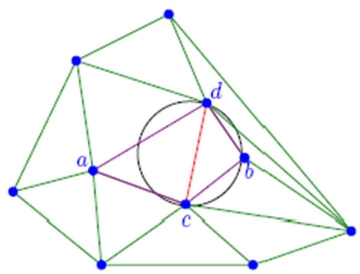

Figure 6. Edge flipping leading to triangles *abc* and *bcd* that are legal Delaunay triangles [12]

The edge ab is considered illegal if the point d lies within the circumcircle of abc. The sign of equation (5)-(6) helps to determine if the edge ab is locally Delaunay or not. In Fig. 5 illegal Delaunay triangles are formed by the edge ab. Hence edge flipping is performed. Edge flipping is nothing but replacing the edge ab with cd, which forms the legal Delaunay triangulation shown if Fig. 6.

Deformation using dual kriging algorithm

Consider a physical phenomenon for which a sequence of measurements v_j are obtained at locations x_j where $1 \le j \le N$. An approximate function $v(x)$ is formulated using kriging [13].

$$v(x_j) = v_j, 1 \le j \le N \quad (8)$$

v(x) can be written as

$$v(x) = c(x) + d(x) \quad (9)$$

Where, $d(x)$ is the fluctuation or error term. $c(x)$ is the average behavior of $v(x)$ or drift. A drift is either a linear polynomial or constant i.e. $c(x) = c_1(const.)$ or $c(x) = c_1 + c_2 x + c_3 y + c_4 z$. Drift can belong to a linear sub space S which is spanned by M basis functions q_l, $1 \le l \le M$.

Therefore,

$$c(x) = \sum_{l=1}^{M} c_l q_l(x) \quad (10)$$

The drift is randomly chosen. The three drift patters are: constant, linear or quadratic. The drift pattern of a physical phenomenon gives its average behaviour. Ordinary kriging is a commonly used kriging procedure when S has a set of constant functions. Another commonly used method is universal kriging, when S is subspace Q_k with a degree of polynomial equal to or less than k (where k is an integer greater than or equal to 0). For example, a two dimensional kriging system for $k = 1$ is as given below,

$$\begin{bmatrix} & K(\left|x_j - x_i\right|) & & & 1 & x_1 & y_1 \\ & & & & 1 & x_2 & y_2 \\ & & & & : & : & : \\ & & & & 1 & x_N & y_N \\ 1 & 1 & \ldots & 1 & 0 & 0 & 0 \\ x_1 & x_2 & \ldots & x_N & 0 & 0 & 0 \\ y_1 & y_2 & \ldots & y_N & 0 & 0 & 0 \end{bmatrix} . \begin{Bmatrix} d_1 \\ d_2 \\ : \\ d_N \\ c_1 \\ c_2 \\ c_3 \end{Bmatrix} = \begin{Bmatrix} v_1 \\ v_2 \\ : \\ v_3 \\ 0 \\ 0 \\ 0 \end{Bmatrix} \tag{11}$$

Hence,

$$v(x, y) = c_1 + c_2 x + c_3 y + \sum_{i=1}^{N} d_i K(h_i) \tag{12}$$

where, h_i is Euclidean distance between control points (x, y) and (x_i, y_i),

$$h_i = \sqrt{(x - x_i)^2 + (y - y_i)^2} \tag{13}$$

An equivalent three dimensional kriging matrix will be similar except a column or a row is inserted for z-coordinate. An additional c_4 term also appears and hence the equation becomes,

$$v(x, y) = c_1 + c_2 x + c_3 y + c_4 z + \sum d_i K(h_i) \tag{14}$$

where, h_i is the three dimensional Euclidean distance.

$$h_i = \sqrt{(x - x_i)^2 + (y - y_i)^2 + (z - z_i)^2} \tag{15}$$

Using the above equations, parameters c_i and d_i are computed from known points. This will provide the amount of deformations to be applied for remaining points in the model. Thus deformation is achieved.

RESULTS

Segmentation Results

Slice 20 of the lumbar vertebrae – L3 is used to demonstrate the segmentation results. Fig. 7(a) is the original CT slice image. The binary thresholding yields the result in Fig. 7(b). The multilevel thresholding with five levels of thresholding is obtained in Fig. 7(c). Dice coefficient of an image gives the similarity between two images. The dice coefficient for Fig. 7(b) and Fig. 8(c) is 0.9535. Another mode to measure the difference between the two images is by finding its area. The area extracted by binary segmentation is only 7058 pixels, whereas the area extracted by multilevel thresholding is 7747. Hence it is observed that with multilevel thresholding the image pixels are enhanced and segmented better.

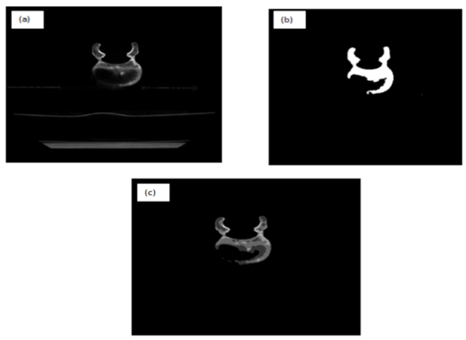

Figure 7. Slice 20 of L3 vertebra (a) Original CT Image (b) Binary Segmented Image (c) Image Segmented using five threshold levels

3D Standard models

The three dimensional models of vertebrae obtained by Marching Cubes algorithm is shown here. The 47 slices of C1 vertebrae. 62 slices of C7 and 95 slices of L3 are used to construct the 3D model. Fig. 8 shows the 3D model of L3 vertebra using Marching cubes Algorithm.

Figure 8. 3D model of L3 vertebra using Marching cubes algorithm

Now using the constrained Delaunay tetrahedralization, L3 vertebrae model is given in Fig. 9, where the inner packed tetrahedrons are rendered. Table 1 gives a comparison of the two algorithms based on number of faces and vertices and time taken for reconstruction.

Deformation Results

CT data scans of actual cadaveric vertebrae are used (T2, T5, T10, L2). As discussed earlier, since constrained Delaunay tetrahedralization are found to be simpler and easier to work with, this algorithm is used for three dimensional modeling of the cadaveric vertebrae. Initially, the mesh reduction is carried out to reduce the number of vertices from around 40000's to a few hundreds for deformation purpose.

Six control points per vertebra are obtained from the mesh reduced three dimensional models of L1 and L2 vertebrae as initial points. Final points are obtained from stereo-radiographic

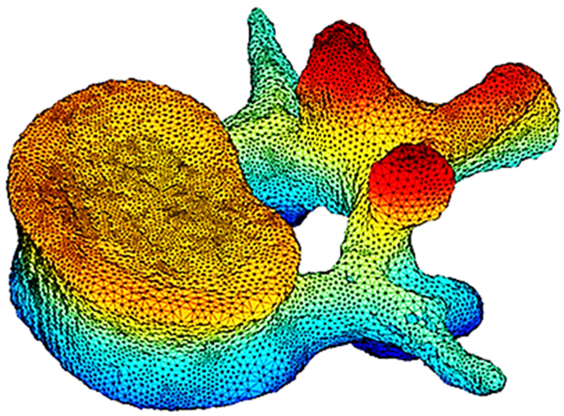

Figure 9. 3D model of L3 vertebra using Constrained Delaunay tetrahedralization

Table 1. Comparison of Marching cubes algorithm and Constrained Delaunay tetrahedralization

Vertebra	Slice	Marching Cubes			Constrained Delaunay		
		Faces	Vertice	Time (sec)	Faces	Vertice	Time (sec)
C1	47	465474	165282	5.18	81902	45316	52.95
C7	62	521040	184000	8.47	82524	46118	66.33
L3	95	1033402	356425	11.7	83072	47179	71.55

reconstruction. This data is used to deform the mesh and obtain personalized model. Table II and Table III lists these points from two different subjects. Using these points in the dual kriging algorithm, we get the deformed models of L1 and L2 vertebrae as in Fig. 10 and Fig. 11 respectively.

Table 2. Initial and final control points for deformation of subject 1vertebra

Location of points	Initial control points			Final control points		
	x-axis	y-axis	z-axis	x-axis	y-axis	z-axis
Front of end plate center	61.5	100.3	9.773	67.65	110.33	10.75
Back of end plate center	124.5	114.9	8.936	133.2	122.94	9.561
Front of left pedicle	60.47	143.5	30.46	57.44	136.32	28.93
Back of left pedicle	100.8	152.1	34.5	107.9	162.74	36.91
Front of right pedicle	67.5	73.76	32.81	62.77	68.596	30.51
Back of right pedicle	107.5	73.27	33.49	112.9	76.933	35.16

Table 3. Initial and final control points for deformation of Subject 2 vertebra

Location of points	Initial control points			Final control points		
	x-axis	y-axis	z-axis	x-axis	y-axis	z-axis
Front of end plate center	61.5	100.3	9.773	55.2	105.52	10.7
Back of end plate center	124.5	114.9	8.936	120	100.58	10.4
Front of left pedicle	60.47	143.5	30.46	65.2	180.54	25.4
Back of left pedicle	100.8	152.1	34.5	120	140.32	30.9
Front of right pedicle	67.5	73.76	32.81	70.2	65.25	30.4
Back of right pedicle	107.5	73.27	33.49	100	80.47	35.5

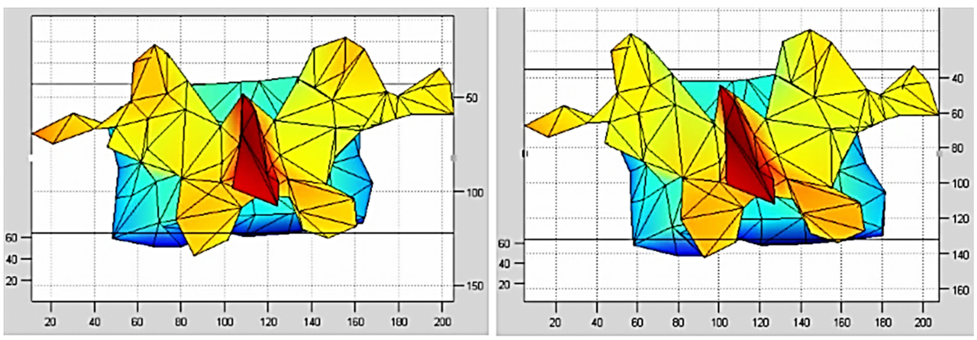

Figure 10. L2 vertebra before & after deformation for subject 1

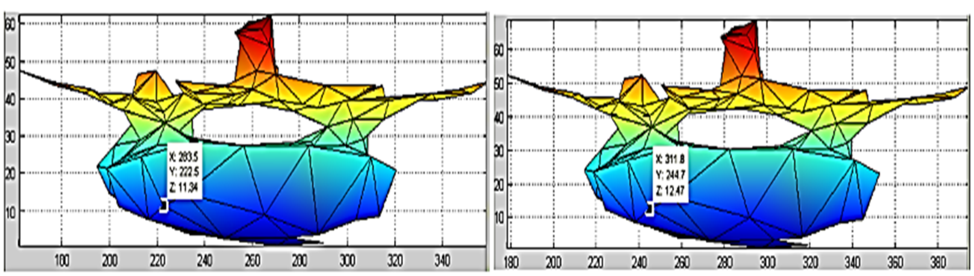

Figure 11. L1 vertebra before & after deformation for subject 2

CONCLUSIONS

The CT scan slices were initially segmented and enhanced before stacking. Binary and Multilevel enhanced images were compared. The multilevel thresholding was observed to extract more information. The dice coefficient and the area extracted were calculated to draw this conclusion.

A three dimensional standard model of the lumbar (L1) and Cervical (C1 and C7) are generated using Constrained Delaunay tetrahedralization and the Marching cubes algorithm. After obtaining the results it is observed that the model from constrained Delaunay tetrahedralization was faster and simpler to work with. The constrained Delaunay tetrahedralization gives a much visually better model compared to Marching cubes algorithm. Hence the three dimensional model obtained from constrained Delaunay was used further for the deformation purposes. The volume meshing is also completed.

Now this algorithm was used to model three dimensional cadaveric vertebrae. Samples of cadaveric vertebrae taken for trial were T2, T5, T10 and L2. These are the standard models. Mesh reduction was done on these standard vertebrae model so that 40000 nodes were reduced to an order of few hundreds. The six initial control points are manually obtained from the standard mesh reduced model and final control points are obtained from two different subjects using stereo-radiographic reconstruction. After dual kriging algorithm, the personalized models for subject 1 and subject 2 were obtained. Hence, a deformed model of cadaveric vertebrae were obtained. In future these vertebrae can be stacked to form a 3-D model of human spine. This in turn increases the diagnostic accuracy of various spinal deformities.

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