

Anatomical Modeling and Rapid Prototyping Assisted Surgical Reconstruction

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Abstract

A CAD-based approach to generate three-dimensional anatomical modeling and its application in analysis and rapid prototyping for surgical reconstruction is presented. The process of modeling technique, starting from processing computed tomography segmentation profiles, reverse engineering to reconstruct 3D anatomical model, and rapid prototyping to fabricate physical models are described. Methods of applying the least-square fitting criteria to simplify CT or MRI anatomical data, to generate NURBS based curves, surfaces, and solids, and to develop a CAD-based anatomical modeling for femur are introduced. Feasibility of using finite element method for femur structural analysis and using rapid prototyping to reproduce tactical medical model for surgical reconstruction is also discussed.

1. Introduction

Computed tomography (CT) and magnetic resonance imaging (MRI) technology has been successfully used to provide true three-dimensional anatomical views for internal structures of the human body [1-4]. The application of this technology has now moved forward with the utilization of CAD/CAM and rapid prototyping technology (RP) to allow a rapid fabrication of the physical tissue models or custom-made prostheses from CT or MRI data [5-8]. RP produces extremely detailed models that serve as excellent templates for the creation of custom implants, offers the surgeon a three-dimensional tactile imaging modality, and display local regions of interest, such as surgeon to draw round a tumor on the CT image and have it built into the model for disease diagnosis in the prototyping anatomic model. Both computer anatomical model and RP physical mode have been utilized as an accurate planning tool for reconstructive surgeons of many specialties, covering from oral surgery, plastic and reconstructive surgery, neurological surgery, orthopaedic surgery, and craniomaxillofacial surgery [9-12].

Commonly used anatomical modeling reconstructions are usually based on the voxel representation. The anatomical images are developed through either contour generation, or surface extraction, or volumetric representation. Contour-based method generates 3D-like displays from sliced CT or MRI outlined segmentation profiles of tissue interested [13,14]. 3D surface extraction uses the full three-dimensional nature of the tomography data to directly produce a geometric surface description [15]. 3D volumetric representation directly produces the appearance of 3D surfaces without to explicitly define their geometries. Although those models are capable of describing the anatomical morphology and are used to rapid prototyping through a converted STL format, due to the voxel-based nature, those models may not suitable for customized design and anatomical structural analysis. For example, the contour generation represents only surfaces without the internal details, 3D surface extraction requires either a large amount of computational power or extreme sophistication in data organization and processing, and 3D volumetric model, while produce a realistic 3D anatomical appearance, does not contains geometry and topological relations in the database of the model [16, 17].

The objective of this paper is to present our study on developing a computer-aided modeling technique for anatomic tissue reconstruction, and its application in modeling analysis and rapid prototyping for reconstructive surgical planning. Activities involving in our modeling approach, starting

from processing computed tomography imaging and CT or MRI 2D segmentation profiles, using reverse engineering to reconstruct 3D anatomical model, and using rapid prototyping to fabricate physical model will be presented. Details of the modeling algorithm to convert CT or MRI anatomical data into a CAD-based solid model, and to use the model for analysis and simulation will be described. Application in rapid prototyping to reconstruct tactical medical model for surgical reconstruction is also discussed.

2. Framework of developing a CAD-based three-dimensional anatomical modeling

The CAD-based three-dimensional anatomical modeling is developed based on using the commercial available medical imaging processing software (MIMICS), a computer-aided design software (Pro/Engineer), and the B-rep CAD technique for generating NURBS based curves, surfaces and solids.

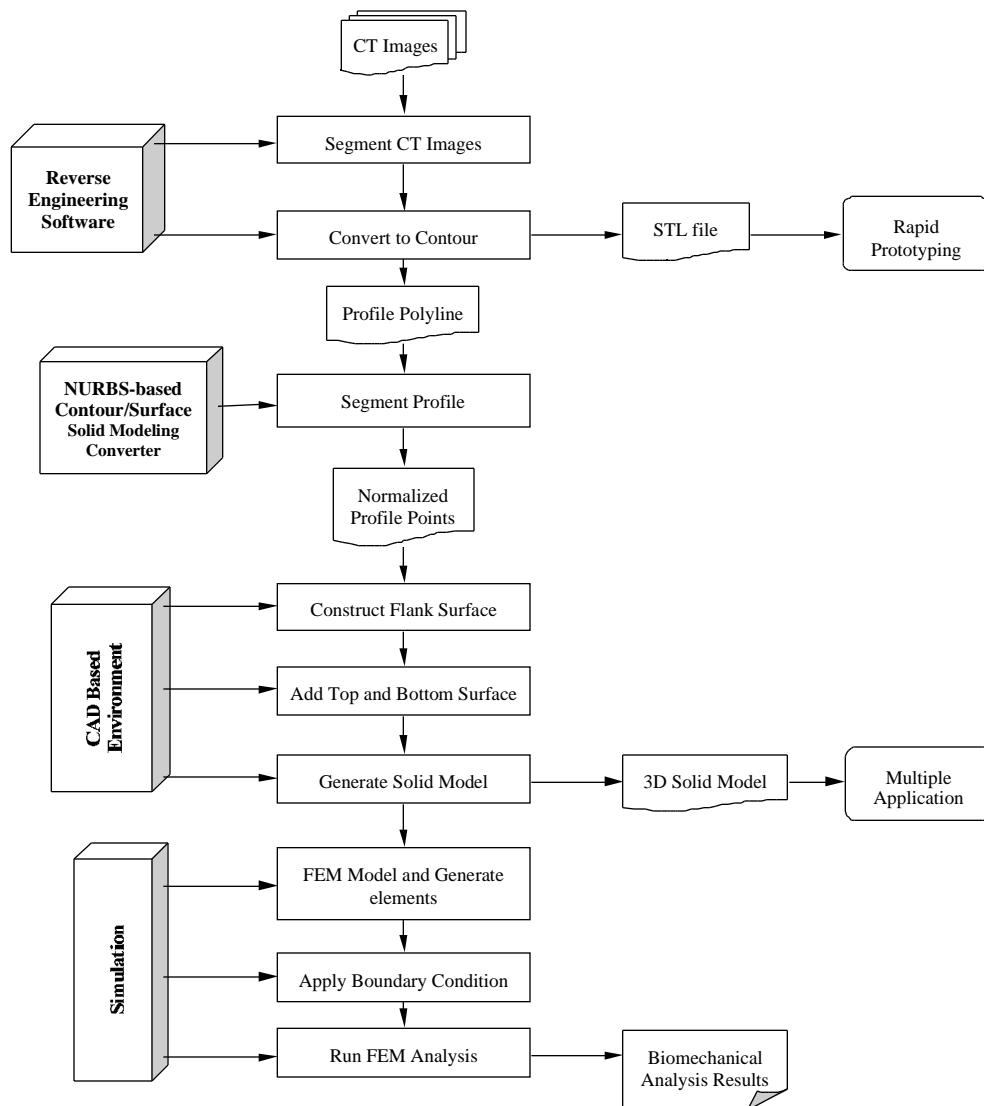


Figure 1: Framework for developing CAD-based anatomical modeling

The framework for developing the CAD-based anatomical modeling is outlined in Figure 1. By creating a computer-generated contour following a single CT or MR image intensity threshold value of the interested anatomy, we start to generate NURBS curves based on the cloud point data exported from

MIMICS' sliced CT or MRI segmentation profiles. A series of ordered NURBS curves are generated from the 2D segmentation profiles and those curves are collected to generate NURBS surfaces and solid in a CAD (Pro/Engineer) environment. Thus generated surface or solid contains the built-in geometry and topological relations in the modeling database. Particular attention is paid to generate interface for anatomic structures with bifurcated protrudes.

3. Approach to construct CAD based anatomic modeling

3.1 3D segmentation to contour polygons

The interface from CT or MRI scanner to rapid prototyping has already been well developed. For example, Figure 2 shows a bony image of femur represented by the 3D STL data generated from MIMICS. However, this "solid" image doesn't contain the real geometry and topologic relationship for the represented solid. In general, most medical image processing software are not capable to introduce the CAD-based data structure into the model database because of their voxel-based nature. Some software may provide interface between the medical modeling and CAD modeling, however, they are difficult to be used in modeling complicated anatomical structure, particularly for anatomic structures with bifurcated protrudes, such as a femur model shown in Figure 2.

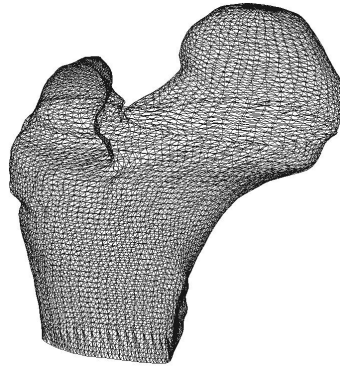
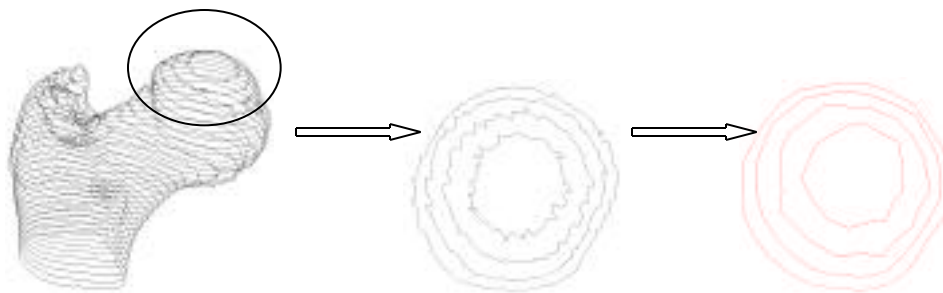


Figure 2: Femur anatomic structure (3D STL representation)

To develop a CAD-based model for femur structure shown in Figure 2, we start with obtaining the polygons exported from MIMICS at each segmentation layers (Figure 3a). Those polygons are constructed as geometrical contours formed by the points on the segmentation profiles (Figure 3b). Those polygons are then fitted through the least square criteria to reduce the number of the points interpolated in the NURBS curves (Figure 3c). Closed surfaces from the NURBS curves are then generated and a B-rep solid model can be created from these surfaces.



(a) femur by contour representation (b) polygons from MIMICS (c) fitted polygons

Figure 3: Contour polygons

3.2 Polygon approximation by the least square fitting method

The curves shown in Figure 3b are zigzagged because there are too many cloud points on the profiles. It is not necessary to take all the vertices as interpolation points to generate NURBS curves. So the least square fitting method is used to reduce the number vertices on the polygons before the NURBS curve generation. The closed polygon (profile) is divided into segments before the fitting. There are two alternatives in this curve segmentation:

- 1) Dividing the polygon according to the number of points, for example, given a particular number of points as one fitted segment. This approach is easy to be implemented, but it is not adaptive to handle complicated geometry.
- 2) Dividing the polygon according to the distance. The algorithm for this approach is as following: First, we calculate the total distance of the closed contour, *dist*, which is the summation of the distance of each segment. Second, we select a segmenting number *num* according to precision required. The larger of the number *num* is, the more accurate of the fitting. Each fitted segment is determined by: *dist/num*. This approach is adaptive to the shape of the closed contour so it is used in this model reconstruction.

The least square criteria can be represented as:

$$f(\alpha) = [D_i^2(\alpha_i - \alpha)^2] \quad (1)$$

where, α is the angle between the fitting line and X axis, α_i is the angle between each segment and X axis, $f(\alpha)$ is a function of α , D_i is the length of each segment, and D is length of the goal segment which can be calculated by *dist/num*. Schematic view of these parameters is shown in Figure 4.

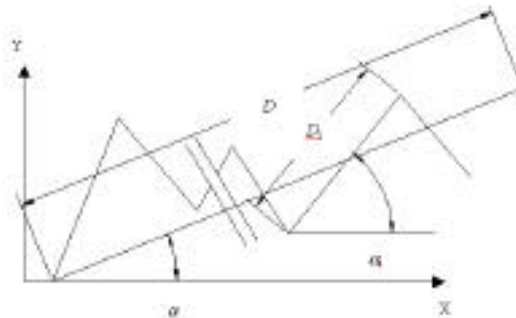


Figure 4: Polyline fitted by least square criteria

The angle α can be determined from solving following derivation equation:

$$f'(\alpha) / f\alpha = 0 \quad (2)$$

The fitting algorithm is written in LISP program. The fitted polygons are shown in Figure 3c.

3.3 Generating NURBS curves

In order to generate a NURBS surface, the contour NURBS curves need to be generated first. The sequence of control points will have an influence on the shape of the generated NURBS surface. As shown in Figure 5, two sets of closed curves have the same control points, but the sequences of control points are different, so the generated surfaces from those curves are different. The first surface is generated by sorted curves (Figure 5a), the second one is generated from the original sequence of points with unsorted end points and the direction. So it creates a twisty surface (Figure 5b). In order to generate a useful surface, the sequence of the interpolating knots must be sorted first.

After given a set of points $\{Q_k\}$, $k = 0, \dots, n$, on each segmentation layer, a p th-degree NURBS curve can be constructed by the $(n+1) \times (n+1)$ system of linear equations:

$$Q_k = C(\bar{u}_k) = \sum_{i=0}^n N_{i,p}(\bar{u}_k) P_i \quad (3)$$

where C is the NURBS curve, \bar{u}_k are parameter values, P_i are the $n+1$ unknown control points, and $N_{i,p}(\bar{u}_k)$ are the p th-degree NURBS basis function defined on the non-periodic knot vector:

$$U = \{u_0, \dots, u_p, u_{p+1}, \dots, u_{m-p-1}, u_{m-p}, \dots, u_m\} \quad (4)$$

m is the dimension of knot vector. The choice of \bar{u}_k and U will affect the shape and parameterization of the curve. Using averaging technique to define the parameter U yields:

$$\begin{aligned} u_0 &= \dots = u_p = 0 \\ u_{m-p} &= \dots = u_m = 1 \\ u_{j+p} &= \frac{1}{p} \sum_{i=j}^{j+p+1} \bar{u}_i \quad j = 1, \dots, n-p \end{aligned} \quad (5)$$



(a) through sorted curves



(b) through unsorted curves

Figure 5: Different surfaces generated through different sequences of control points

With this method, the knots reflect the distribution of the \bar{u}_k . Using Equation (5) to compute the \bar{u}_k leads to a totally positive system represented by Equation (3) and banded with a semibandwidth less than p , $N_{i,p}(\bar{u}_k) = 0$ if $|i - k| > p$. Hence, it can be solved by Gaussian elimination without pivoting. Thus generated NURBS curves for the femur structure are shown in Figure 6.

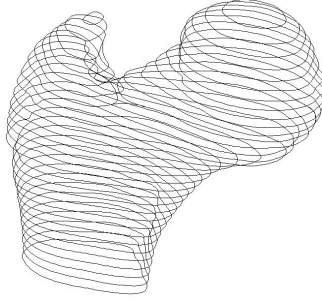


Figure 6: Femur model represented by NURBS curves

3.4 Generating NURBS surface and solid modeling

The global interpolation of the surface can be constructed based on a set of $(n+1) \times (m+1)$ data points $\{Q_{k,l}\}$, $k = 0, \dots, n$ and $m = 0, \dots, m$

$$Q_{k,l} = S(\bar{u}_k, \bar{v}_l) = \sum_{i=0}^n N_{i,p}(\bar{u}_k) \sum_{j=0}^m N_{j,q}(\bar{v}_l) P_{i,j} \quad (6)$$

in which, \bar{v}_l are parameters, and $P_{i,j}$ are the unknown control points. Since the contour curves are already generated, $P_{i,j}$ can be computed more efficiently through the sequence of curve interpolations.

For a fixed l Equation (6) can be expressed as:

$$Q_{k,l} = \sum_{i=0}^n N_{i,p}(\bar{u}_k) \left(\sum_{j=0}^m N_{j,q}(\bar{v}_l) P_{i,j} \right) = \sum_{i=0}^n N_{i,p}(\bar{u}_k) R_{i,l} \quad (7)$$

$$R_{i,l} = \sum_{j=0}^m N_{j,q}(\bar{v}_l) P_{i,j} \quad (8)$$

Equation (7) represents the curve interpolation through the points $Q_{k,l}, k = 0, \dots, n$. $R_{i,l}$ are the control points of the isoparametric curve on $S(u, v)$ at fixed $v = \bar{v}_l$. If we fix i and let l vary, Equation (8) will represent the curve interpolation through the points $R_{i,0}, \dots, R_{i,m}$, with $P_{i,0}, \dots, P_{i,m}$ as the computed control points. Therefore, the control points can be obtained by using knot vector and parameters, and the curve interpolation can be performed through $Q_{k,l}, k = 0, \dots, n$ and $R_{i,0}, \dots, R_{i,m}$. Figure 7 shows three 4th-degree NURBS surfaces with a C^2 continuity surfaces generated by above curve interpolation.

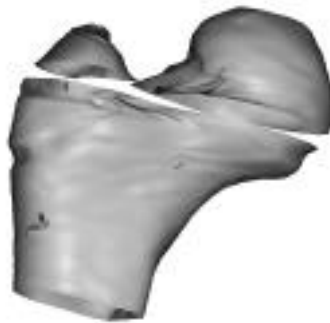


Figure 7: Generated three NURBS surfaces

It should be noted that the femur structure has bifurcated protrudes. Most modeling software are unable to generate the single surface for bifurcated structure because there are two closed contours in each scanning layer beyond the bifurcated section. Therefore, an interface layer is generated in order to connect the bottom diaphysis and top two bifurcated protrudes. This interface layer is shown in Figure 8.

An important property of NURBS curve is the local approximation, as explained by Les Piegl [18]. That is, if the control Point P_i is moved, or the weight W_i is changed, the curve is only affected at the portion on the interval $u \in [u_i, u_{i+p+1}]$. Based on this property, we divide the control points on the original curve into two intermediary curves. By adding new control points, we generate two 4th-degree NURBS curves, curve 1 and curve 2, as shown in Figure 8. These two new curves are geometric identical to the bifurcated section curve. With these two intermediary curves, two new bifurcated surfaces can be generated and added to the top two protrudes to form the closed surfaces. With the interface layer as the surface for diaphysis, three solid models can be generated and then merged to form a single solid model as shown in Figure 9.

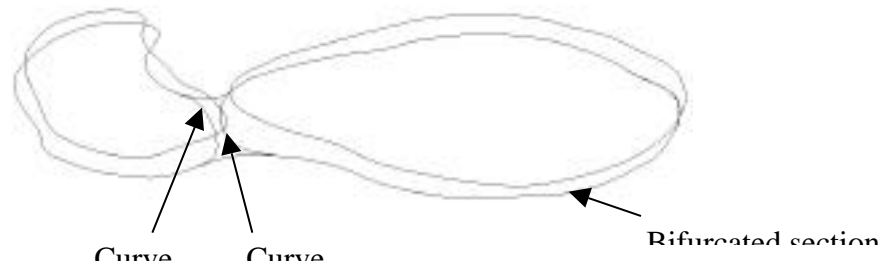


Figure 8: Intermediary NURBS curves for bifurcated section



Figure 9: A single solid model for femur

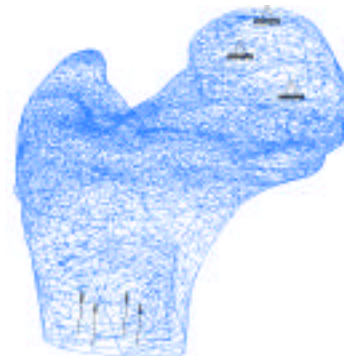


Figure 10: Mesh and BC of bone FEA model

4. Application in finite element analysis and rapid prototyping

4.1 Integrated CAD and finite element analysis

The CAD-based femur model is applied for finite element analysis. Three-dimensional mesh of the bony model is generated from Pro/MECHANICA. The modulus of elasticity of the bone is taken from the assumed relationship between bone elastic modulus and apparent density presented by Carter and

Heyes [19]. The mesh representation, loading and boundary condition is shown in Figure 10. Predicted stress and strain distribution is shown in Figure 11 and Figure 12, respectively.

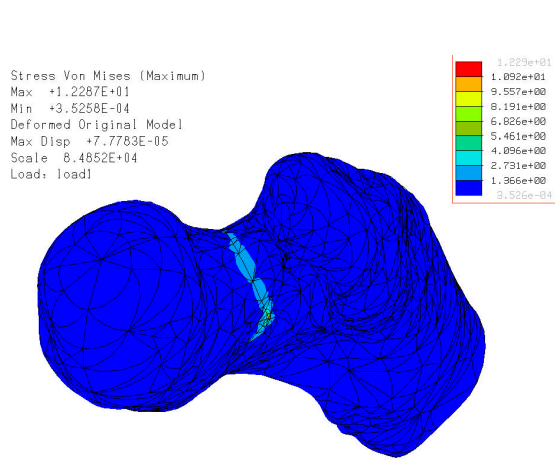


Figure 11: Von Mises stress distribution

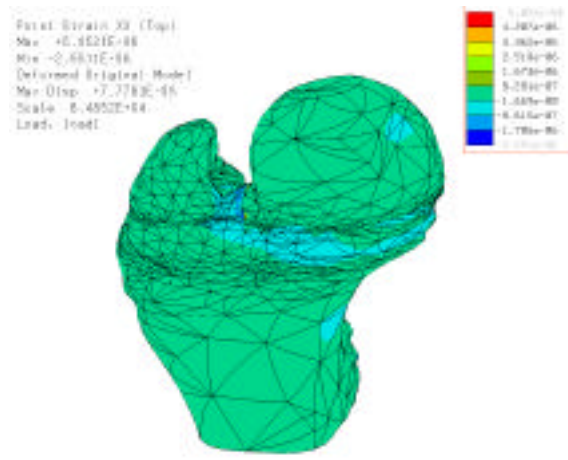


Figure 12: Strain distribution in the bone

It should be pointed out that the objective of current finite element analysis is to explore the feasibility of integrating the CAD-based model (Pro/Engineer) with CAE-based analysis (Pro/MECHANICA), and to test the model capability of automatic meshing generation, rather than to study the detail of biomechanical properties of the femur structure. Therefore, only preliminary FEA results are presented.

4.2 Application in rapid prototyping

Applications of using rapid prototyping to produce physical anatomic models are presented in Figure 13 and Figure 14. Figure 13 shows a prototyped hip anatomy prototyped by 3D Printing (Z-corp). The prototyped major bones included the upper portions of the left and right femur, the pelvic bones, and the lower end of the spine (sacrum and coccyx). The model includes the entire pelvic region with all of the bones connected and keeps the proper anatomic position between them.



Fig. 13: Prototyping model of hip anatomy

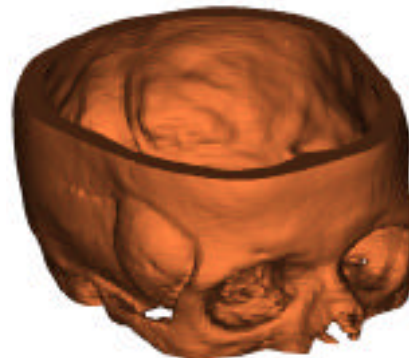


Fig. 14: Prototyping model of skull with tumor

Figure 14 shows a rapid prototyping model of a skull with a tumor. The growth of the tumor is visible and has created a large protrusion from the skull. In order to analysis the volume and anatomic position of tumor, the tumor identification is necessary. Both anatomic model and prototyping model of tumor and skull without tumor are constructed and the prototypes are shown in Figure 15.

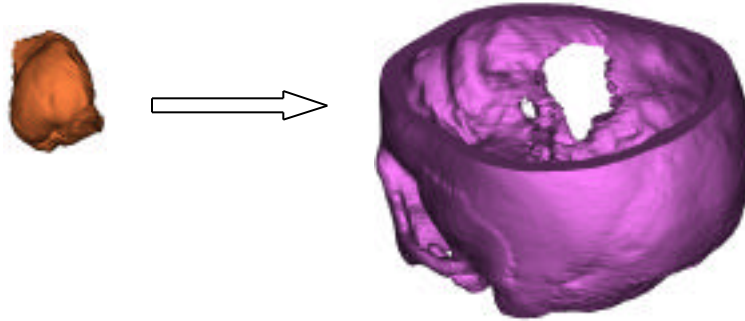


Figure 15: Rapid prototyping model with tumor identification

5. Conclusion

A CAD-based modeling approach to construct three-dimensional anatomical modeling is presented. Procedures of the modeling approach and applications of the model in structural analysis and rapid prototyping for surgical reconstruction are given. The presented computer modeling approach is useful to model bifurcated anatomic structure. Both anatomic modeling and rapid prototyping modeling can be used as useful tool for surgical planning and design and fabrication of customized prostheses.

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