Human tissue geometrical modelling

Přemysl Kršek
Department of Computer Graphics and Multimedia
Faculty of Information Technology
Brno University of Technology
Božetěchova 2
612 66 Brno, Czech Republic
email: krsek@fit.vutbr.cz

Petr Krupa
Radiology klinic, St. Anne's University Hospital Brno
Faculty of Medicine
Masaryk University Brno
Komenskeho nam. 2
662 43 Brno, Czech Republic
email: pkrupa@med.muni.cz

ABSTRACT
The article is dealing with novel and relatively complex computer system for automatic creation of human tissues geometrical models. Applications of the created models can be found in orthopedy, aesthetic surgery, dental surgery, etc.

On the input are discrete volume CT/MR data in DICOM 3.0 data format. The models creation process consist of several steps: tissue segmentation, volume data vectorization by Marching cubes method, triangular mesh smoothing and export into desired data representation, which depend on particular application. The geometrical models can be exported into CAD/CAM/FEM systems as polygonal, polysurfaces or tetrahedral meshes.

KEY WORDS
CT, MR, CAD, FEM, tissue, model

1 Introduction

1.1 The problem

Computer tomography (CT) and Magnetic resonance (MR) are modern diagnostic medical methods, that produce discrete volume data sets. The data sets provide good source of the patient's body physical properties, tissues geometry, and structure information.

Many medical applications are based on 3D geometrical models of human tissues. Examples of such applications can be found in orthopedy, aesthetic surgery, dental surgery, etc. The tissues models are usually used for physical and computational simulations, planning and testing surgeries, designing and making individual implants, etc.

For most of the real medical applications it is very important to use good quality 3D geometrical models of the tissues, that the models are created automatically (at least in most cases), and that thye are created quickly (within minutes). The main problem is, that the creation process of the models is not easy to perform fully automatically, fast enough for immediate, for clinical use (by doctors or lab. assistants) and open for research of specific, individual, and experimental applications.

1.2 Previous work

Traditionally, the most used method of the 3D geometrical tissue models creation is based on cross-section curves. The method consists of several steps:

- Tissue boundary tracing by planar cross-section curves, slice by slice on input CT/MR data.
- Boundary 3D surface (spline or polygonal) creation based on the cross-section curves.
- Customization of the created surfaces for applications requirements (smoothing, optimization, etc.) and export into CAD/CAM/FEM for applications.

The method requires significant amount of manual work and time. The results are depend on user experience and on the tissue geometry complexity. For tissues with very complex geometry (skull, pelvis, etc.), it is not possible to use the method at all.

Some modifications of the cross-section curves method for automatic connection on 3D polygonal surfaces do exist [1]; however, they are not geometrically general. The surfaces they create lack small details, they implementation is not easy, and they are not robust.

Another known tissue model creation method is "Direct Vectorization of Segmented Volume Data". Currently the most used direct vectorization method is "Marching cubes" method [2] (see 3.1). The method is executed in several steps:

- Tissue segmentation of input CT/MR data.
- Vectorization of segmented tissue volume model.
- Customization of the created surfaces for applications requirements (smoothing, optimization, etc.) and export into CAD/CAM/FEM for applications.

Several commercial computer systems, which implement 3D tissue geometrical models creation and data export for some medical applications exist. An example of such system is "Materialize/Mimics". These systems are mostly for general use and they are not specialized for any particular application; moreover, they are not open and do not allow application and research specific modifications.

1.3 Motivation

The article is focuses on the novel and relatively complex computer system for automatic creation of human tissues geometrical models. The system has been developed for real life medical applications and for research purposes. The description of main principles, algorithms, methods, and features of the system and also its possible application areas can be found in the following sections.

2 Input CT/MR data

The input of the system is the CT/MR data in DICOM 3.0 format. The DICOM (Digital Imaging And Communications In Medicine) [10] format is currently de facto data interchange standard in radiology. The discrete volume of the scanned body is saved as group of 2D slices. One DICOM file contains one of such slices.

Each data voxel's value is saved 16 bits unsigned format, but the actual information is only in 12 bits, so each voxel can have 4096 discrete levels of particular physical unit (e.g. x-ray density for CT).

For the purposes, it is necessary to perform input data volume segmentation in order to obtain regions filled with selected tissues (Fig. 1, 2). The result of the segmentation process are again discrete volume data containing indexes of segmented tissues. The segmented volume data sets are used as an input for the next step (see 3).

The segmentation process itself is not trivial. Fully automatic segmentation remains an open problem [3]. Currently, the semiautomatic segmentation with manual corrections is used in the system. Full 12 bits information is used during the segmentation. Automatic part of the process work directly on 3D data while the manual corrections are made in multi-planar views (XY, XZ and YZ planes). The segmentation algorithm consist of several steps:

- Optional data filtering for noise removal (median, low pass, smoothing, etc.).
- Automatic decomposition on regions by density (watershed, PCA, adaptive tresholding, etc.).
- Automatic connection of the adjacent regions with statistically close features.
- Regions filtering for noise removal (median, solitary voxel removing, etc).
- Manual corrections of resulted regions (shape, connections, removing, etc.).
- Manual regions creation, removing and modifying (flooding, contouring, etc).

Figure 1. CT slice of empty dry human skull (image has color inversion)

Figure 2. Bone segmentation of the slice

3 Tissue models creation

The input of the models creation process are the discrete segmented volume CT/MR data sets (see 2). The desired output are the tissue geometrical models. The geometrical models should be vector based polygonal or spline (NURBS) meshes, which mathematically describes boundaries of objects. The models creation process is basically a vectorization process.

The following subsections describe all steps of the creation process, which are implemented in our system.

3.1 Volume data vectorization

Vectorization of discrete segmented volume data is the main step of tissue models creation. "Marching Cubes" algorithm [2], which fully automatically produces closed and oriented boundary triangular meshes (isosurfaces) of selected tissues, has been used (see 1.2). The meshes produced by the algorithm consist of many small triangles (Tab. 1) and has a little bit layered and edgy character (Fig. 3).

3.2 Triangular mesh smoothing

Because meshes created by Marching cubes algorithm have features unsuitable for further use (Fig. 3), smoothing needs to be applied. Historically, the ”Direct Smoothing Method For Surface Meshes” algorithm [4], that uses ”Laplacian Smoothing” [4] has been used. Because of the shrinking problem [5] it has been replaced by the ”Geometric Signal Processing on Polygonal Meshes” method, which better preserves the models volume [5] (Fig. 4).

3.3 Triangular mesh decimation

Because meshes created by Marching cubes algorithm contains many small triangles (Tab. 1), decimation algorithms must be used to get the suitable size models. Algorithms that perform optimal triangles number reduction, with maximum geometry preservation are available. For our applications we have tested ”Decimation of triangle meshes” [6] and ”Surface simplification using quadric error metrics” [7]. The second algorithm is more satisfactory. In practice we have about 97% triangle number reduction (Fig. 5, 6) (Tab. 1).

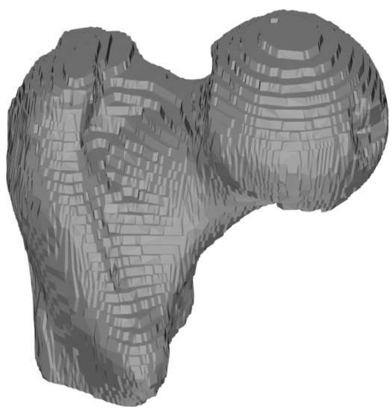

Figure 3. Hip-bone model after Marching cubes algorithm

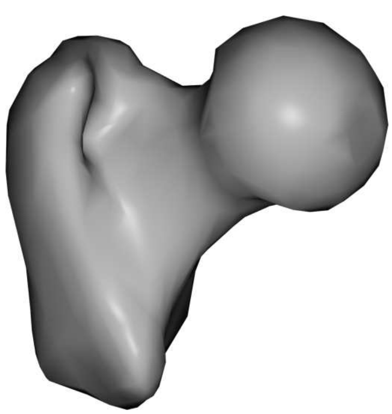

Figure 4. Smoothed hip-bone model

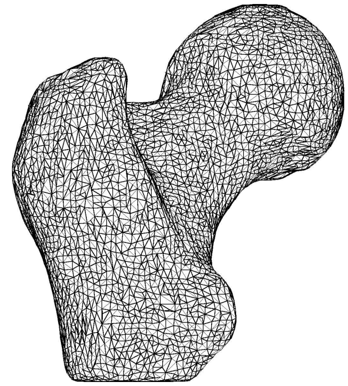

Figure 5. Hip-bone model before decimation

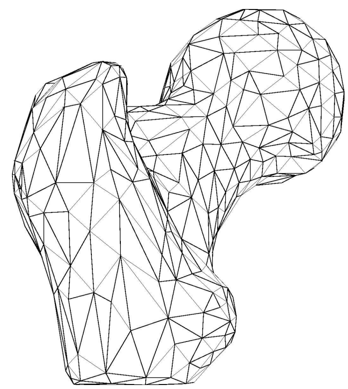

Figure 6. Decimated hip-bone model

4 Models export for applications

The geometrical models can be used in many different applications. The applications can use different data representations. The export models for particular applications depend on the data representations.

In the following subsections, three groups of data representations possible to use will be described.

4.1 Polygonal meshes

The real 3D polygonal meshes can consist of triangles or quads, but triangles are more general. Marching cubes algorithm produces triangular meshes; therefore, we are working with this mesh type only.

The meshes are possible to export in number of data formats: STL, VRML, DXF, etc. Most of the CAD/CAM systems can read the formats. The polygonal meshes are easy to visualize using standard technologies (OpenGL, DirecX) and several viewers (VrmlView, CosmoPlayer, etc.). Manipulations with the meshes (cutting, Boolean oper., etc.) are usually not included in CAD/CAM functions.

Therefore, the data representation is useful for visualization and as a geometrical template. Triangular meshes (as STL) are natural data type for rapid prototyping.

4.2 Spline surfaces

The modern 3D CAD/CAM systems use spline (NURBS) surfaces as basic representation for boundary geometrical object modeling. All modeling tools and functions of the systems are prepared for the spline surfaces. Our models are triangular polygonal meshes, because of Marching cubes algorithm. Therefore, we have to transform the models into the spline surfaces.

The CAD/CAM geometrical models consist of spline surfaces (patches) group. Spline patches have rectangular and structured topology. The available data is unstructured triangular meshes. Therefore the transformation task is to change triangles on quads and unstructured mesh on structured with maximum geometry saving. The three possible ways, how to perform the conversion, exist:

- Polysurface:
  It is simplest and geometrically general method. The main idea is to transform each triangle into a degenerated triangular spline patch. The final spline surface contain many patches, but fully usable in CAD/CAM systems. This is the currently used method.

- Striped polysurface:
  The method is small modification of previous method (Polysurface). First step is to transform the unstructured triangle mesh into triangle stripes [8]. Second step is to transform each stripe into a narrow spline patch. The method is currently under implementation.

- Regular spline patches:
  This is the most complex and still open method. It is not fully functional on free geometry. The method is based on clustering or remeshing of the triangle mesh into a quad structured mesh with rectangular patches. The rectangular patches is easy transform into the spline patches.

4.3 Tetrahedral meshes

In FEM (Finite Element Method) the computational modeling of tissues behaviors (stress, deformations, etc.) can be make (Biomechanics of Man). For the modeling the 3D FEM tissues models are available. The models consist of volume elements (tetrahedron, prism and their extensions) meshes. The task is to create a volume FEM model based on boundary triangular meshes. It is possible to do it fully automatically for tetrahedral meshes only.

Most used method for tetrahedral meshes creation is Delaunay triangulation [11]. We have used the method for tetrahedral mesh creating based on boundary triangular mesh vertices [9]. After optimization of tetrahedrals quality, it is possible to export created tetrahedral meshes into particular FEM system (ANSYS).

5 Implementation

The system is implemented in C++ for Win32 platform, but it is also portable to UNIX platform. The system consists of several computer programs:

- Graphics program for CT/MR data viewing and segmentation.
- Command line (CL) program for volume data vectorization that implements Marching cubes algorithm.
- CL filters for triangle mesh smoothing, decimation and quality optimization.
- CL filter for triangle mesh saving into STL, VRML, DXF and internal data formats.
- CL filter for polysurface creation based on tri. mesh.
- CL filter for Delaunay triangulation based on triangular boundary mesh.
- CL filter for tetrahedral mesh quality optimization.
- CL filter for tetrahedral mesh saving into internal or ANSYS data formats.
- Dialog front end for all programs executing.

It is possible create arbitrary configuration for volume data vectorization and tissue geometrical models processing, because of command line filter conception. The created geometrical tissue models are possible to import in the CAD/CAM/FEM systems for particular application.

6 Results and examples

Following subsections show three examples human tissues geometrical models. Each one of the models represents one of the export data representations (see 4).

All the models was created on PC computer, CPU Pentium 4 2.4 GHz, 512 MB RAM DDR 333 MHz, with WinXP. Programs was compiled with MS Visual C++ 6.0.

6.1 Skull FEM model

The skull FEM model was created from CT data set. The set has 160 slices, matrix size 512x512 and slice thickness 1.0 mm. Empty dry skull was scanned because of an experiment. The FEM model was used for the skull computational modal analysis (Fig. 7, 8, Tab. 1).

6.2 Hip-bone polysurface model

Because of hip-bone cancer has been necessary to design individual hip-join implant for some patient. Therefore, the patient was scanned on CT and hip-bone polysurface model was created. The polysurface model was imported into CAD system for implat design (Fig. 9, 10 , Tab. 2).

6.3 Maxilla and gingiva polygonal model

Teeth implants are very common at present. Good positioning of the implants in compact jaw bone is very important for successful dental surgery. Patient has been scanned on CT, his jaw and gingiva polygonal (or polysurface) models was created and imported into CAD system for surgery planning and navigation (Fig. 11, 12, Tab. 3).

7 Conclusion

The main advantages of the system is its openness that allows for modifications and application specific development. The system uses advanced algorithms, works mostly automatically and allows for fast models creation process.

Future work is focused on: advanced system integration for easy-to-use, better geometrical quality of created models, implementation of polygonal mesh transformation on regular spline surfaces, and better application support in CAD/CAM/FEM systems.

8 Acknowledgement

The work is supported by grant project GP 201/01/D141.

References

[1] Keppel E., Approximating Complex Surfaces by Triangulation of Contour Lines: IBM Journal of Research and Development, 19(1), 1975, 2-11

[2] Lorensen W., Cline H., Marching cubes, A high resolution 3D surface construction algorithm: Proceedings, Siggraph 87, USA, 1987, 163-169

[3] Nagy. I. Kršek P. Hustak. J., Voxel Model Creation of Human Tissues from CT and MRI Data for Biomechanical Applications: Proceedings, Euroconference Biosignal 2000, Brno, FE VUT Brno, 2000, 278-280, ISBN 80-214-1610-6

[4] Balendran B., A Direct Smoothing Method For Surface Meshes: Proceedings, 8th International Meshing Roundtable, South Lake Tahoe, USA, 1999, 189-193

[5] Taubin G., Geometric signal processing on polygonal meshes: Eurographics 2000 State of The Art Report(STAR), September 2000.

[6] Schroeder W. J., Zarge J. A., Lorensen W. E., Decimation of triangle meshes: Proceedings, Siggraph 92, USA, 1992, 65-70

[7] Garland M., Heckbert, P., Surface simplification using quadric error metrics: Proceedings, Siggraph 97, USA, 1997, 209-216

[8] Evans F., Skiena S. Varshney A., Optimizing Triangle Strips for Fast Rendering: IEEE Visualization '96, 1996, 319–326

[9] Kršek P., Automatic creating of tetrahedral fem models of human tissues from segmented CT/MR data: Processing EMBEC02, Viena, AT, 2002, 232-233

[10] David A. Clunie, DICOM Structured Reporting, 394 pages, 2001 by PixelMed Publishing, ISBN 0-9701369-0-0.

[11] George P. L., Borouchaki H., Delaunay triangulation and meshing: 1. vyd. Paris, Hermes 1998, 413 s., ISBN 2-86601-692-0.

Table 1. Skull FEM model creation parametrs

	Vertex #	Tri. #	Tetra. #	Time [s]
March. cubes	478 646	957 356	—	19
Smoothing	4 473	9 018	—	79
Decimation	4 473	9 018	—	286
Delaunay tri.	7 680	—	24 859	18
Optimization	10 911	—	38 983	26
All time				358

Table 2. Hip-bone polysurface model creation parametrs

	Vertex #	Tri. #	Time [s]
March. cubes	67 102	134 208	28
Smoothing	67 102	134 208	15
Decimation	2 997	5 998	27
All time			70

Table 3. Maxilla and Gingiva polygonal model creation parametrs

Maxilla	Vertex #	Tri. #	Time [s]
March. cubes	36 166	72 188	12
Smoothing	36 166	72 188	7
Decimation	2 571	4 998	13
All time			22
Gingiva	Vertex #	Tri. #	Time [s]
March. cubes	47 829	95 630	12
Smoothing	47 829	95 630	10
Decimation	2 513	4 998	17
All time			39

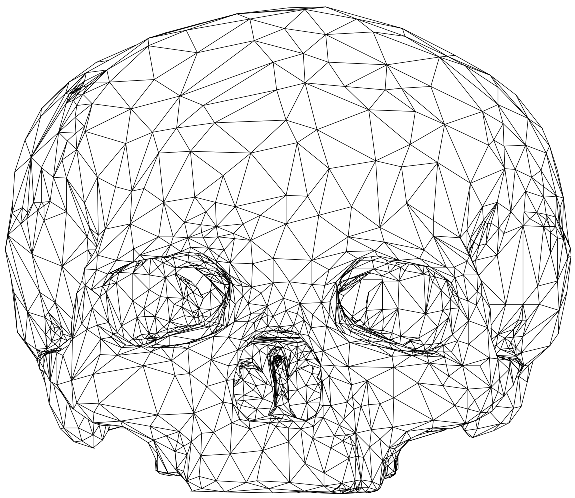

Figure 7. Skull FEM model, front view

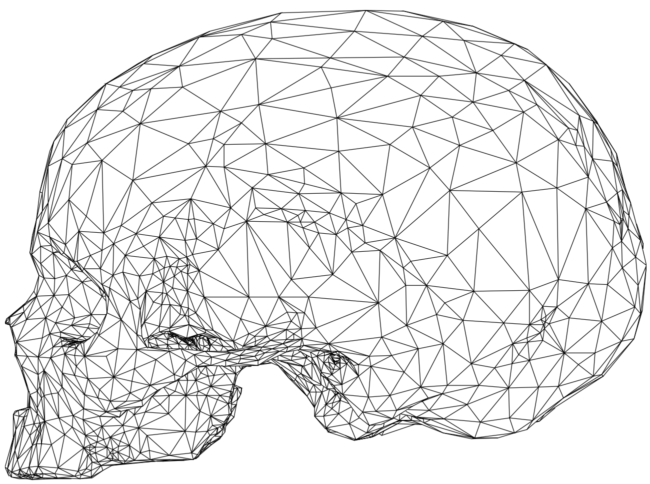

Figure 8. Skull FEM model, left view

Figure 9. Pathology hip-bone polysurface model

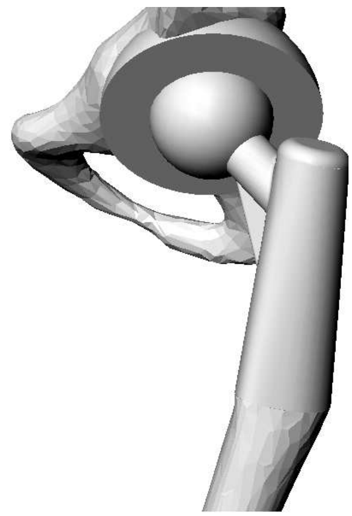

Figure 10. Resected hip-bone with raw implant design

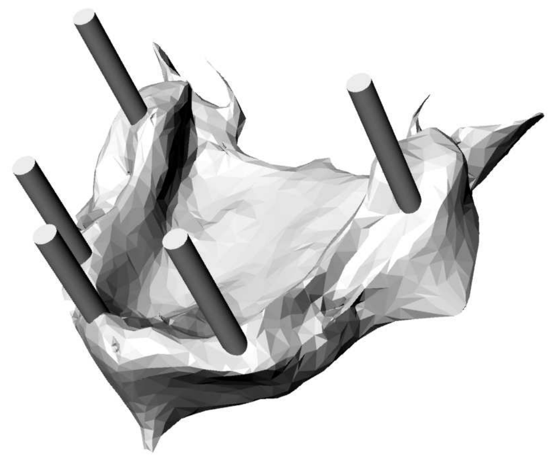

Figure 11. Maxilla polygonal model with implants positions

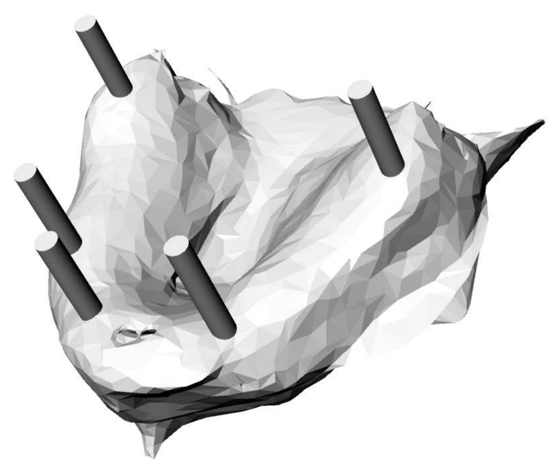

Figure 12. Maxilla and gingiva polygonal models with implants positions