Creation of Finite Element Models of Human Body based upon Tissue Classified Voxel Representations

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ABSTRACT

Introduction

Numerical methods like finite difference methods (FD), finite integration techniques (FIT), the boundary element method (BEM) or the finite element method (FE) have been proven to be powerful tools for the calculation of electric, magnetic, electromagnetic and thermal fields.

The FE method, the most widely used technique for engineering design and analysis, is distinguished from all others by different reasons:

- it can be applied to various boundary value problems

- approximations of solutions can be obtained by using a wide range of different shape functions

- a FE model is a geometrical flexible decomposition of object space

Finite element models have to be topological compatible, that means, elements do not intersect each other but they cover the full object space. Besides elements border each other at most on vertices or on complete edges or faces.

FE models usually are created by using automatic mesh generators. Automatic mesh generators require detailed information about the geometry of object structures during the course of model creation.

In the domain of CAD (computer aided design) objects are described by using CSG (constructive solid geometry), by representing their boundaries eg using NURBS (nonuniform rational B-splines) or other representational schemes.

These kinds of descriptions usually are not available for anatomical structures of human body. The fundamental sources of anatomical information are the various methods of medical imaging. By using segmentation and classification schemes tissue distributions in human body in high spatial resolution can be obtained. A tissue classified voxel representation can serve as an alternative description of geometrical structures.

Mesh generation

This paper presents an automatic FE mesh generator, which is able to create models of anatomical structures. To classify and to value model entities, characteristics of an underlying tissue classified voxel representation are determined.

For the automatic mesh generation in three dimensional space a Delaunay algorithm was chosen, which ensures topological compatibility as well as additional geometrical properties of the model. This algorithm links up a given set of knot points with tetrahedral elements. Appropriate knot points are found either before or in the course of mesh generation.

Classification and validation of mesh entities necessitate an extensive interaction between FE model and voxel representation. Using a three dimensional rasterization method the tissue class of a mesh element and the error volume - volume which do not consists of this element tissue class - can be determined. Based on these characteristics and additional rules an adaptive mesh refinement can be carried out.

Respectation of boundaries

A known problem of automatic mesh generation, especially when using Delaunay triangulation, is the respectation of object boundaries. Object boundaries which have to be maintained may be defined through topological compatible triangle meshes. These triangle meshes can be determined by employing several processes:

- marching cube algorithm

- intersection of tetrahedron meshes with object boundaries in voxel representations

- active contours

- free forms

Triangle meshes may be improved during the course of boundary preservation.

Results and applications

The presented automatic FE mesh generator enables the creation of anatomical models of human body. The grade of approximation and the number of DOF's (degrees of freedom) are scaleable in wide ranges. Mesh refinement may be done in interaction with a FE solver.

The resulting model can be used to calculate various problems like distribution of static electric, static magnetic fields or stationary current problems.

INTRODUCTION

The finite element method has been proven to be a powerful tool for the calculation of electrical, magnetical and thermal fields. This method, the most widely used technique for engineering, design and analysis, approximates the solution of various differential equations and boundary problems. To employ the finite element methode, the object space has to be segmented into finite elements.
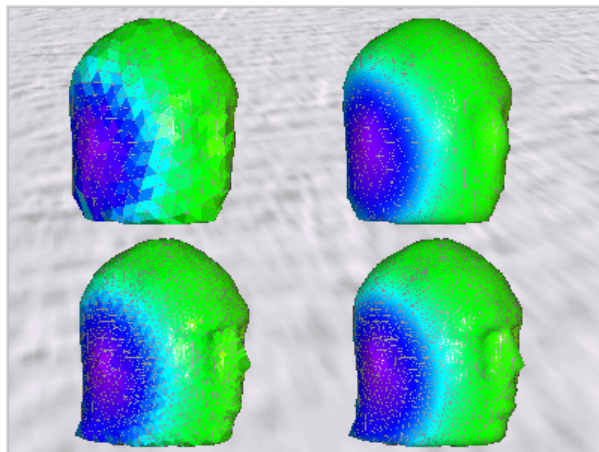

Figure 1.: The advantages of the finite element method are the mathematical flexibility, shown on this figure through different approximation functions within single elements (left/right), and the geometrical flexibility of the used model, shown through different resolutions (top/bottom).

Inside each element a set-up function has to be chosen, which course depends on this elements

degrees of freedom. The resulting shape functions span a function space which includes the approximation of the solution. The grade of shape functions, the shape, size and amount of used elements can variee widely which yields to a high flexibility.

MESH GENERATION

A finite element model has to keep some geometrical properties. To ensure continuity of the approximation, the model has to be topological compatible which implies that elements do not intersect each other but they cover the full object space. Besides elements border each other at most on vertices or on complete edges or faces. If the shape functions depend only of values on nodes, continuity of the approximation can be obtained. Further the numerical stability of the calculation process can be increased by avoiding obtuse and acute angles.
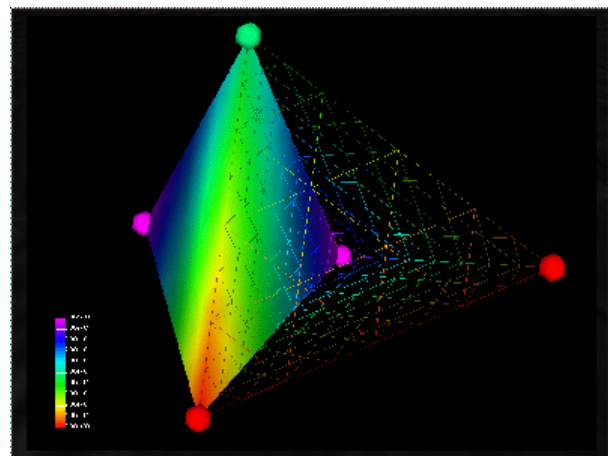

Figure 2.: One demand on Finite Element models is the topological compatibility. Two elements which border each other on a complete face share the same node points within this area. The same approximation functions and the same values on this points guarantee a continuous solution.

DELAUNAY TRIANGULATION

For the automatic mesh generation in three dimensional space a Delaunay algorithm was chosen [2] which ensures topological compatibility as well as additional geometrical properties of the model. A Delaunay triangulation is a decomposition of object space into tetrahedral elements which meet all demands on finite element models.
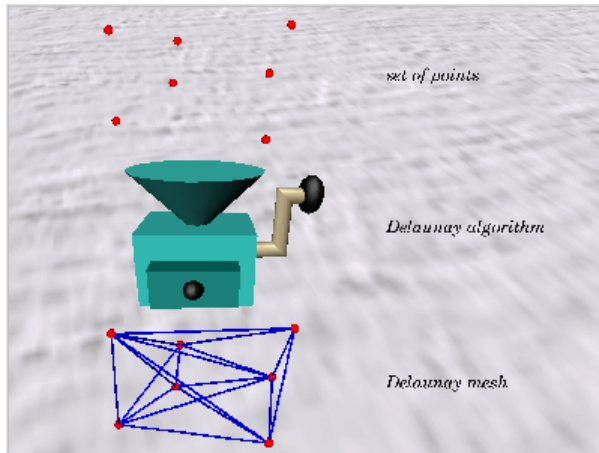
Figure 3.: A Delaunay algorithm can be seen as a black box which produces a mesh of tetrahedrons out of a set of given node points.

A Delaunay algorithm generates a mesh of tetrahedrons out of a set of node points. All of the resulting elements respect the Delaunay criterion. A Delaunay algorithm can be implemented as a successive process. Starting with a given Delaunay triangulation a new node point is inserted. The volume of elements which does'nt meet the Delaunay criterion any more has to be replaced by new tetrahedrons.
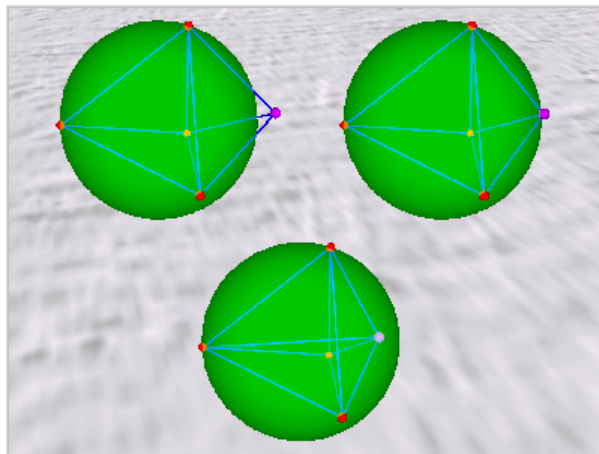
DELAUNAY CRITERION

If the circumsphere of a tetrahedron contains no node point, this element meets the Delaunay criterion. The figure 4 illustrates this aspect. The green transparency sphere is the circumsphere of the left tetrahedron. If the violett node point enters this sphere a new triangulation results in new elements, which again meet the Delaunay criterion.

ELEMENT ASSESSMENT

The element assessment can be considered as the connection between the finite element model and the underlying tissue classified voxel representation. A tissue classified voxel representation is a threedimensional grid of volume data. To each voxel a unique tissue class is assigned. The goal of element assessment is to assign a tissue class to each tetrahedron of the model too. To determine a histogram of the occurrence of tissue inside a tetrahedron, all voxels inside this element have to be counted. The tissue class which wins the simple majority can be chosen as the elements tissue class. The quality of this element can be measured with the volume of the opposition, here the error volume. Thereby the different tissue classes can be weighted by priority factors.

Figure 4.: A Delaunay triangulation is a triangluation in which each element meets the Delaunay criterion. Inside the circumsphere of each tetrahedron no node point is lying. The magenta node is moving from right to left. If it enters the circumsphere of the left tetrahedron, a new triangulation will been necessary.
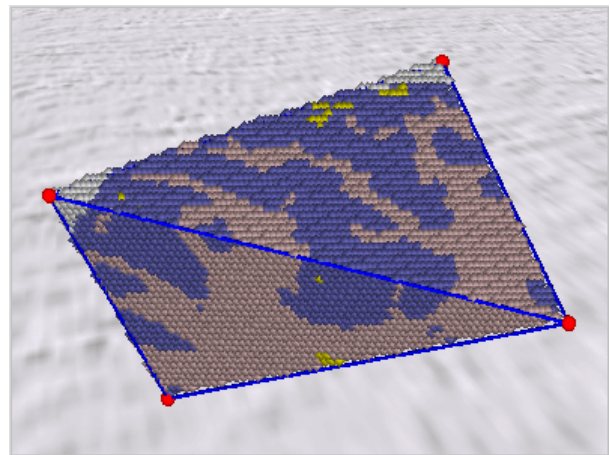

Figure 5.: The assessment of single elements is realized through a 3d rasterization. Thereby all voxels which are lying inside the tetrahedron are counted, the majority defines the tissue class of this element, the rest, the error volume, is a measure of its quality.

Using a quality function, which depends on the error volume and other geometrical motivated components like size or aspect ratio, a quality key can

be calculated by which the set of elements can be sorted. This point is illustrated by figure 5, an element which is filled up with its including voxels is shown.

MESH REFINEMENT

The strategie of mesh refinement is to place new node points inside the element with the worst quality. The exact position can be chosen by ignoring the tissue distribution within the element eg the center of the tetrahedron, the center of the innersphere or the middle of the longest edge. Using information about the tissue distribution can result in better positions for node points. This can be done by walking along a given line and detecting the first material change. Good rays are half edges starting at the middle of edges and walking to the vertices. Another possibility is to start at the center of an element and search on the lines connected with the vertices.

Figure 6 shows the course of the error volume and the quality key of the worst tetrahedron during the presented adaptive mesh generation. With the increasing number of node points, the error volume is decreasing and the quality key is increasing.
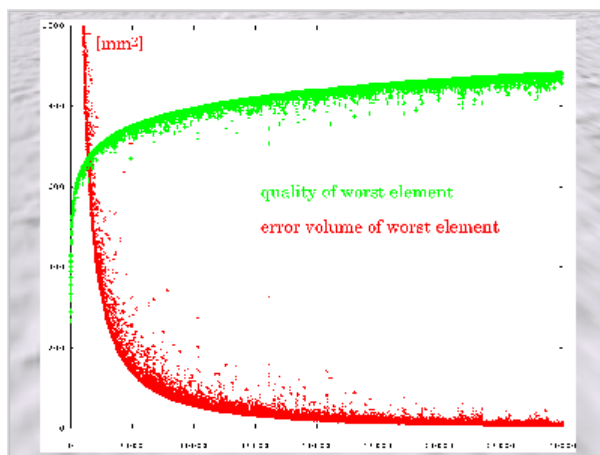

Figure 6.: With a growing number of node points, the quality of the worst element of a FE model, created with the discribed algorithm, is increasing, the error volume is decreasing.

RESPECTATION OF BOUNDARIES

Beside the presented method to get new node points, another possibility to meet the anatomical structures of the human body is to define tissue boundaries which have to be respected. These boundaries can be represented by triangle meshes. For this reason an active contour model has be-

en implemented. The three dimensional surface adapts its shape to a chosen tissue class by following internal and external forces which acts on the node points. Internal forces are resulting of the position and the deformation of the surface, external forces depends on the underlying volume data. With this active contour model the surface of different tissue classes can be obtained.
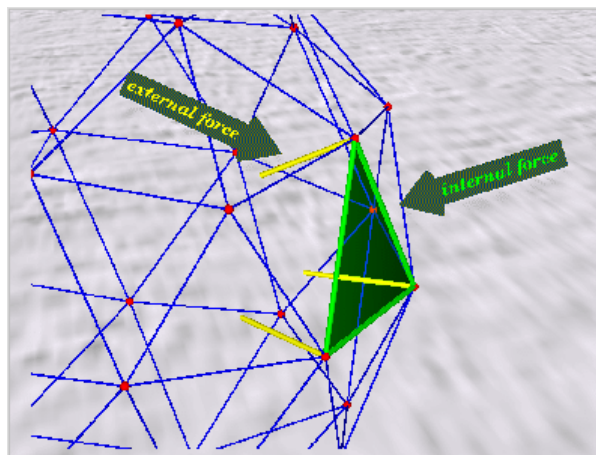

Figure 7.: Active contour model which is represented by a triangle mesh. The positions of the node points are determined through internal and external forces.

The triangle meshes in figure 8 were created with this active contour model. Starting with an initial mesh, the elements change their position depending on an underlying tissue classified voxel representation. The direction of the external forces can be derived out of the gray level gradient within the voxel representation. In this situation the voxel representations acts as a potential field, which can be manipulated using a wide range of different three dimensional filters.
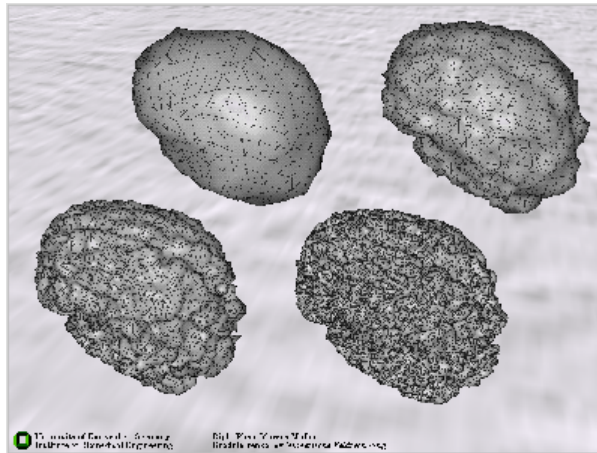
Figure 8.: Example of the adaption of an active contour. The number of element is increasing, the surface shows more details.

Figure 10.: A komplex sturcture like the skull yields to a high amount of triangles when using the Marching Cubes algorithm. The quality of the reconstruction depends on the resolution of the volume data.

Elements within the mesh can be subdivided or decimated, which results in an adapted resolution. This adaption can be controlled by the curvature of the surface or by the size of the individual triangles.

RESULTS AND APPLICATIONS

The presented automatic FE mesh generator enables the creation of anatomical models of human body. The grade of approximation and the number of DOF's (degrees of freedom) are scaleable in wide ranges. Mesh refinement may be done in interaction with a FE solver. Therefor the discribed quality function has to take into account the relative errors of a finite element solution in the different elements.

The resulting model can be used to calculate various problems like distribution of static electric, static magnetic fields or stationary current problems.

Figure 9.: Decimation of elements may depend on the curvature of the surface, which is visualized in this picture using false colors. On the left side you can see the upper part of the body, on the right side a head model is shown.

Another possibility to get surface discriptions represented by triangle meshes is to use the Marching Cubes algorithm. This algorithm produces a high amount of triangles to reconstruct detailed volume data. The resulting meshes normaly have to be decimated as discribed above.
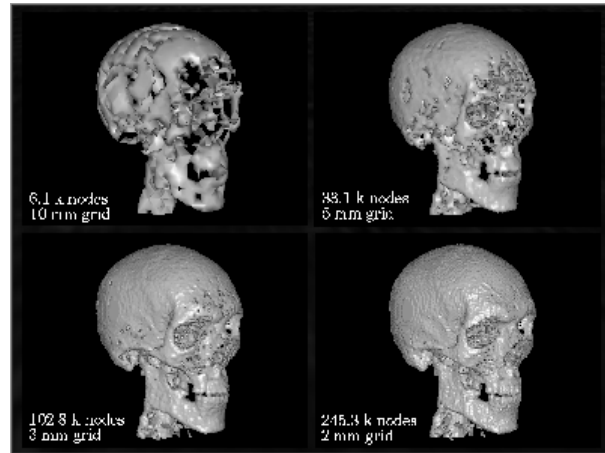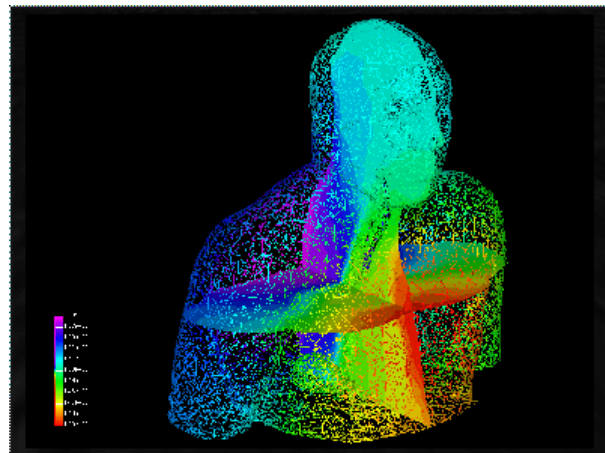

Figure 11.: An application of Finite Element models of human body is the numerical calculation of eletric or magnetic fields and potentials.

IMAGES

The following images represent models of the head and the upper part of the body which where created using the discribed adaptive finite element mesh generator. The used underlying voxel representation is the result of the tissue classification of the Visible Man Dataset of our group [6][7].
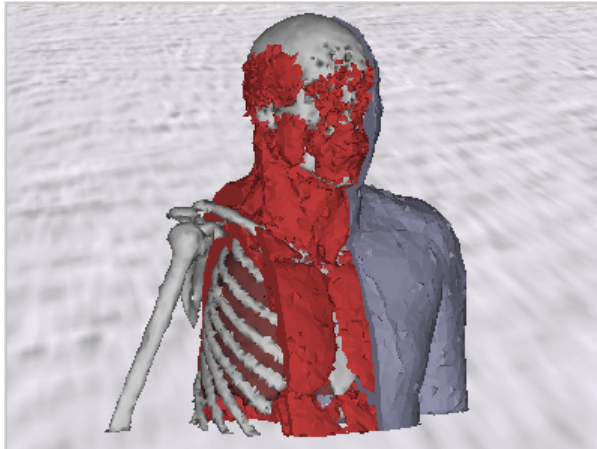

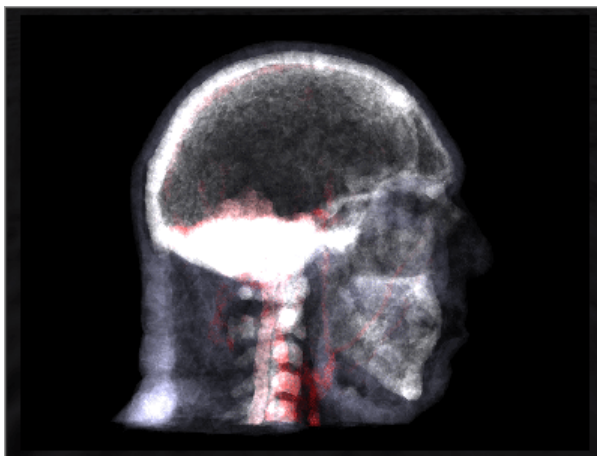*Figure 12.: Surface visualization of the upper part of the body.*

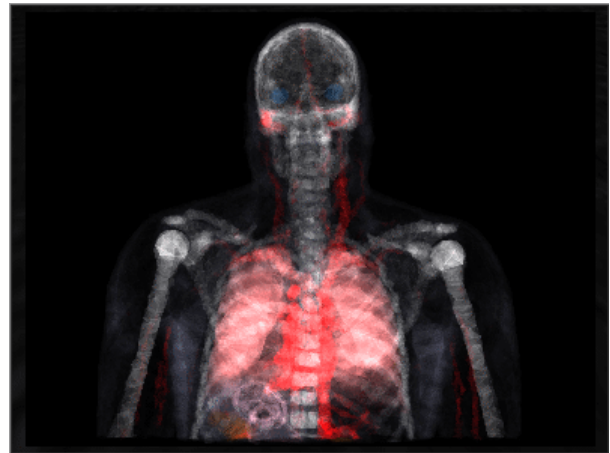*Figure 13.: Volume visualization of a head model.*

Figure 14.: Volume visualization of the upper part of the body.

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[7] SACHSE, F., WERNER, C., MUELLER, M., MEYER-WAARDEN, K. *Segmentation and Tissue-Classification of the Visible Man Dataset Using the Computertomographic Scans and the Thin-Section Photos* Proc. First Users Conference of the National Library of Medicine's Visible Human Project, 1996.