U.P.B. Sci. Bull., Series D, Vol. 73, Iss. 4, 2011 ISSN 1454-2358

CONTRIBUTIONS TO 3D VIRTUAL MODELING OF HUMAN FEMUR AND OSTEOSYNTHESIS ELEMENTS

Paul-Nicolae ANCUȚA[1], Constantin Anton MICU[2]

În lucrare sunt prezentați algoritmi şi metode numerice pentru modelarea tridimensională a osului femur, de tip suprafață şi de tip volum, precum şi modalități de vizualizare. Programele au fost realizate folosind biblioteca de programe VTK. De asemenea, sunt precizate etapele pentru realizarea unui ansamblu virtual tridimensional ,de tip volum, os-element de osteosinteză, precum şi rezultate ale deplasărilor folosind analiza cu element finit a ansamblului folosind programul CAD SolidWorks.

The paper presents algorithms and numerical methods for surface or volume-type three-dimensional modeling of the human femur bone as well as viewing software. The software has been designed using the VTK software library. The paper also outlines the steps required to obtain a virtual 3D assembly comprising of bone and osteosynthesis element as well as some displacement results obtained by using the finite element analysis module of SolidWorks software.

Key words: 3D modeling, CAD software

1. Introduction

The preoperative plan requires a precise geometric description of the anatomical structures on which the surgical act will be carried out. There are several sources of data, provided by X-ray computed tomography (CT) and Magnetic Resonance Imaging (MRI). Digital image processing includes viewing the area of interest of 2D images and obtaining three-dimensional representation. Algorithms and their implementation have been widely developed in the last three decades.

The methods for 3D reconstruction can be classified into two broad categories:

1. Reconstruction methods using planar sections of the object examined

This type of reconstruction falls within the field of medical imaging. Magnetic Resonance Imaging and Computed Tomography provide the surgeon with a series of two-dimensional images of the object. These sets of images must be used for a virtual three-dimensional image representation of the anatomy part. The images

[1] Engineer, The National Institute of Research and Development in Mechatronics and Measurement Technique ,Bucharest, ROMANIA, email: apaul@incdmtm.ro
[2] Professor, Faculty of Mechanical Engineering and Mechatronics, University POLITEHNICA of Bucharest, ROMANIA, email: micuanton@yahoo.com

are stored in compuer files having DICOM format (Digital Image and Communication in Medicine).

During a Computed Tomography procedure, X-rays pass through the subject's body. The residual radiation is captured by detectors and transmitted to a computer.

The Hounsfield unit (HU) scale is a linear transformation of the original linear attenuation coefficient and represents a method for defining the radiodensity of a body.

$$HU = \frac{\mu_x - \mu_{water}}{\mu_{water} - \mu_{air}} \text{x}1000 \quad (1)$$

Some values are presented in the following table

Table 1

Reference Hounsfield Values

Value	Object or Substance
-1000 HU	Pure air
-120 HU	Fat
0 HU	Pure water
0 to +40 HU	Various liquids
dozens of HU	Muscles
a few hundred HU	Compact bone
a few thousand HU	Metallic elements

2. Reconstruction methods using points sampled from the surface of the object to be analyzed ("reverse engineering").

The paper presents two surface modeling algorithms and their software implementation. The software interface has been developed by the authors. The paper also outlines two volume reconstruction methods used by the authors by means of SolidWorks features and modules.

2. Marching cubes algorithm and software implementation

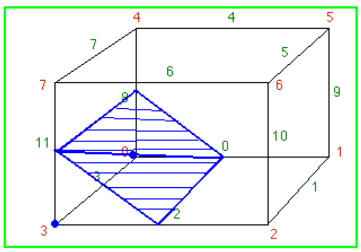
This algorithm [1] is used to represent isosurfaces from images contained in adjacent planes. The image results of the CT scan contain various shades of gray. The intensity of the image elements belonging to various areas (the gray value) is proportional to the HU value of the structures through which the radiation has passed . The principle of the Marching Cubes algorithm is the following:

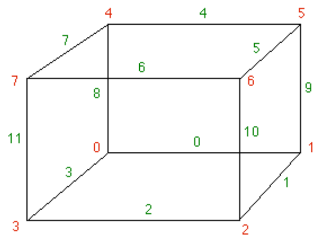
-in order to generate an isosurface, the volume is divided into an array of cubes.

-a voxel (a cube element) is defined through the values of its eight vertices. The vertices are positioned in two adjacent planes. Each vertex is assigned a numerical value proportional to the HU value of the 2D image at (X,Y) coordinate of vertex.

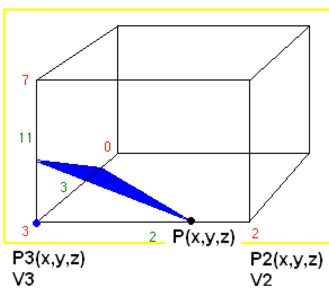
- if one or more vertices have lower or upper values than the isosurface value defined by the user,then the voxel defined by these vertices will contribute with certain surfaces in the final construction of the isosurface.

- the algorithm finds the edges of the voxel which are crossed by the isosurface. By using an index into two predefined tables, the edge list and the triangle list, the algorithm selects generic triangles that will be part of the isosurface. There are 256 possible situations. The triangles vertices are created by linear interpolation for determining their coordinations . Fig. 1 shows two cases of voxels which contribute with triangles to the isosurface.





0,1,2,3,4,5,6,7,8,9,10,11= **edge list**
0,1,2,3,4,5,6,7 = **vertex list**



Edge weigths

Vertex	7	6	5	4	3	2	1	0
	128	64	32	16	8	4	2	1

The sum of vertex 0 and vertex 3 is 9

LINEAR INTERPOLATION FOR (X,Y,Z) coordinates of point P is:

P=P3+(isovalue-V3)*(P2-P3)/(V2-V3)

	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S	T	U	V	W	X	Y	Z	AA	AB
1	Weight value		EDGE LIST											TRIANGLE EDGE LIST														
2		11	10	9	8	7	6	5	4	3	2	1	0	L1-a	L2-a	L3-a	L1-b	L2-b	L3-b	L1-c	L2-c	L3-c	L1-d	L2-d	L3-d	L1-e	L2-e	L3-e
3	0	0	0	0	0	0	0	0	0	0	0	0	0	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1
4	1	0	0	0	1	0	0	0	0	1	0	0	1	0	8	3	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1
5	2	0	0	1	0	0	0	0	0	0	0	1	1	0	1	9	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1
6	3	0	0	1	1	0	0	0	0	1	0	1	0	1	8	3	9	8	1	-1	-1	-1	-1	-1	-1	-1	-1	-1
7	4	0	1	0	0	0	0	0	0	0	1	1	0	1	2	10	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1
8	5	0	1	0	1	0	0	0	0	1	1	1	1	0	8	3	1	2	10	-1	-1	-1	-1	-1	-1	-1	-1	-1
9	6	0	1	1	0	0	0	0	0	0	0	1	1	9	2	10	0	2	9	-1	-1	-1	-1	-1	-1	-1	-1	-1
10	7	0	1	1	1	0	0	0	0	1	1	0	0	2	8	3	2	10	8	10	9	8	-1	-1	-1	-1	-1	-1
11	8	1	0	0	0	0	0	0	0	1	1	0	0	3	11	2	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1
12	9	1	1	0	1	0	0	0	0	0	1	0	1	0	11	2	8	11	0	-1	-1	-1	-1	-1	-1	-1	-1	-1
13	10	1	0	1	0	0	0	0	0	1	1	1	1	1	9	10	2	3	11	-1	-1	-1	-1	-1	-1	-1	-1	-1
14	11	1	0	1	1	0	0	0	0	0	1	1	0	1	11	2	1	9	11	9	8	11	-1	-1	-1	-1	-1	-1

Fig. 1. Voxels and triangles generation

The results depicted in Fig. 2 below have been obtained using set of images for Hounsfield values associated with bone tissue, respectively metal clamping elements.

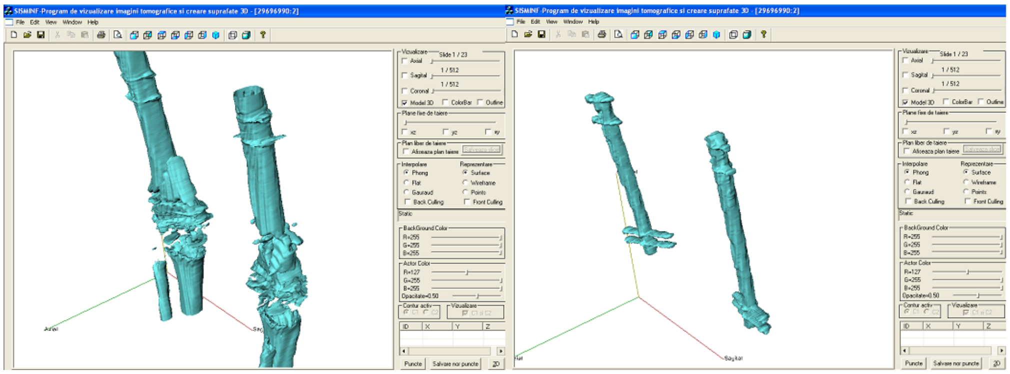


Fig. 2. 3D surface reconstruction of a bone fracture for H=500 units (left) and fixation elements H=2200 units (right)

The visualisation and reconstruction software has been developed using the open source VTK software library [3]. The VTK library is an open-source software system for 3D computer graphics, image processing and visualization.

The original software developed by the author performs several tasks which are either not provided by the VTK library or needed improvement. The most relevant are as follows:

- an easy-to-use Graphical User Interface using Microsoft Visual C++ compiler version v6.0 , Visual Studio 2005 and Microsoft Foundation Class
- monitoring the timing of calculation stages
- obtaining the set of points from the isosurface for further use.

3. Hoppe algorithm and software implementation

This algorithm [4] is used to create surfaces by using sets of points. The Hoppe algorithm works globally on any surface that does not intersect itself.
The steps of the algorithm are the following:

1. Initial surface estimate**:** from a set of points X, an initial dense triangle mesh is obtained. The aim of this step is to determine the surface topology as well as to estimate the surface.
2. Mesh optimization: the initial mesh created in step 1 is optimized by reducing the number of facets and better matching the mesh nodes with the points selected from the surface.
3. Optimization of the surface continuity**.**

The algorithm makes an initial estimate of the surface using points from the X set.

For a point x_i which belongs to the set *X,* a tangent plane $Tp(x_i)$ is defined in a neighborhood of x_i by the pair made up of point o_i (centroid of the points in the neighborhood) and n_i , the unit vector normal to the plane. "Consistency of orientation" of the two planes which are adjacent is obtained if the product $n_i.n_j$ is approximately equal to 1 (the two normal vectors have the same direction). Value $W_{ij}=1- n_i \cdot n_j$ is a criterion. Going through all the planes in such a way that the value of W_{ij} numbers is minimal ensures "consistent orientation" of the normal vectors (Fig. 3).

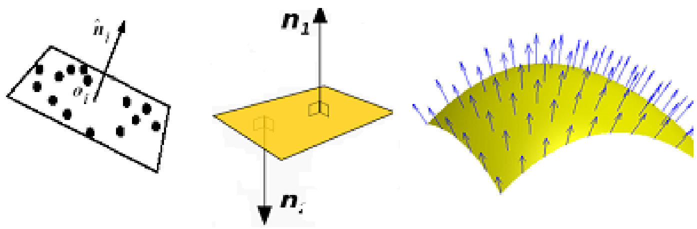


Fig. 3. "Consistent orientation" of the planes

The points which determin the neighborhood of the point $\mathbf{x_i}$ are taken from a circular region with $\mathbf{x_i}$ as centre and ρ as radius. Another criterion for selecting points is that the **n** points which are closest to x_i point form the neighborhood of x_i . The values ρ and **n** are input data. The results produced by the software are shown in Fig. 4.

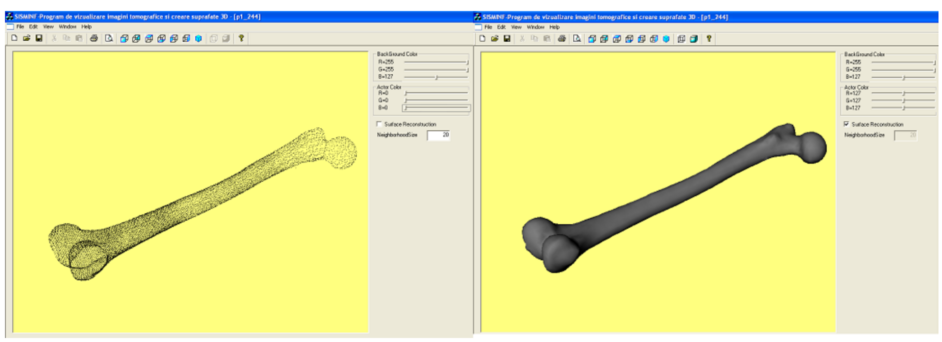


Fig. 4. 3D surface reconstruction of the femur using Hoppe's algorithm

We developed software for Hoppe algorithm using VTK library for visualization and we merged this software with the one we presented above. The software we created can deliver an STL file (a file format native to the stereo lithography CAD software) for interfacing with many other CAD software packages.

4. The use of SolidWorks for 3D models

"Point cloud" text files are files with X,Y,Z coordinates of the points taken from the surface of an object. SolidWorks contains an optional software module called

ScanTo3D which processes a “point cloud” text file and delivers either a 3D surface model or a 3D solid model (Fig. 5). In order to use this module, the operator follows a sequence of mandatory actions. We used this approach in order to ensure a unique development environment, where femur bone is modeled as a solid instead as a surface.

Fig. 5. 3D reconstruction of femur using ScanTo3D software module from SolidWorks

We obtained a virtual solid model of the human femur bone with multiple parts.(Fig. 6)

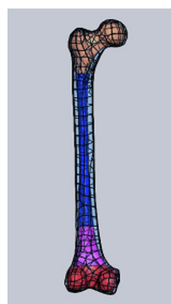


Fig. 6. Assembly of parts

The virtual model of human femur has isotropic mechanical properties.

To simulate human bone anisotropy, the following steps have been taken: Two femur bone models have been created and subtracted from each other. This has revealed the cortical bone shell (“the outer model”). “The inner model” has been divided into four parts, each part having specific material properties, in order to simulate bone anisotropy. The two models have been joined into a mechanical assembly.

If ScanTo3D software module is not available, one can use the algorithm and implementation procedures described in paper [5] submitted for publication. Spline curves are generated using sampled points on adjacent contours. All the planes and most of the spline curves are automatically generated using macros coded in Visual Basic for Application. If a certain spline curve can not be automatically obtained, the user must create it manually (see red curve below). The curves are joined together by several LOFT commands issued by the user (Fig. 7).

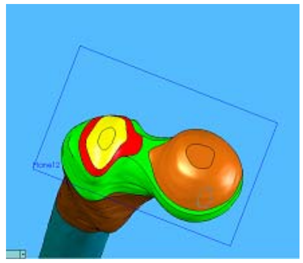


Fig. 7. 3D solid reconstruction of the femur using spline curves and LOFT command

5. Creating 3D models of fixation elements

Several osteosynthesis elements have been reproduced in SolidWorks using their real dimensions (Fig. 8).

Fig. 8. Osteosynthesis elements for distal femur

These elements are widely used for fixation of condylar fractures [7] as shown in Fig. 9 below.

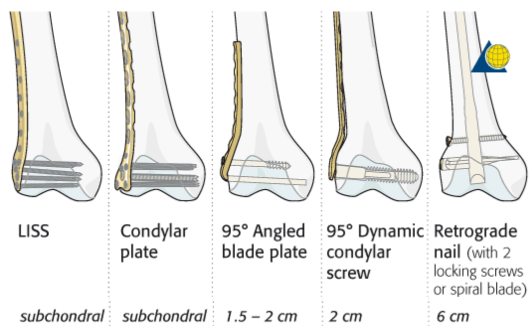


Fig. 9. Different type of plates

6. Analysis of the mechanical assembly femur–osteosynthesis element

The first stage of this activity involved the study of a “not injured” femur model in bipedal standing. Reaction force was applied on the femoral head. Values and vector orientation angles have been calculated for a man of about 80kg according to [6]. A distance of 120 mm was measured on X-ray. The reaction force is about 271 N and the displacement of the femoral head is 1.096 mm (Fig.10).

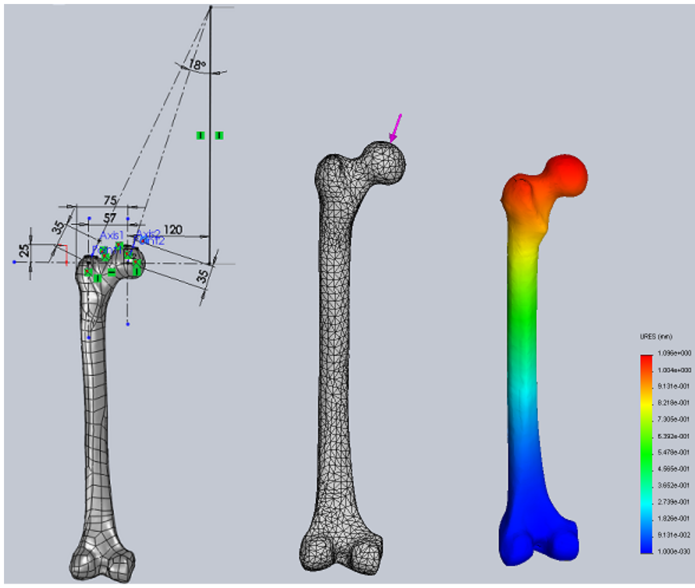


Fig. 10. Displacement calculation of femur in bipedal stance

A simplified model of bone-fixation element has been created with mounting screws being replaced by bonded constraint type. The reason for such a simplified model has been that the version of the Finite Element Analysis we have used has been unable to run the simulation on a more complicated model. A fracture line located above the femoral condyles was simulated in order to study the effect of joint reaction forces. (Fig. 11)

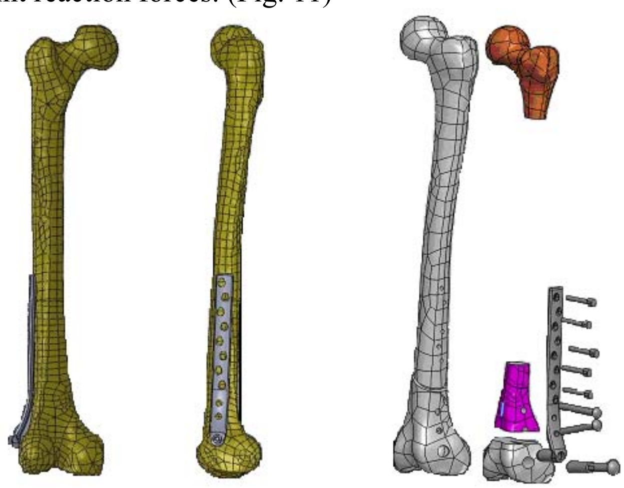


Fig. 11 Frontal and sagittal view of bone-fixation element assembly

The displacement of the femoral head was about 8.954 mm.(Fig. 12)

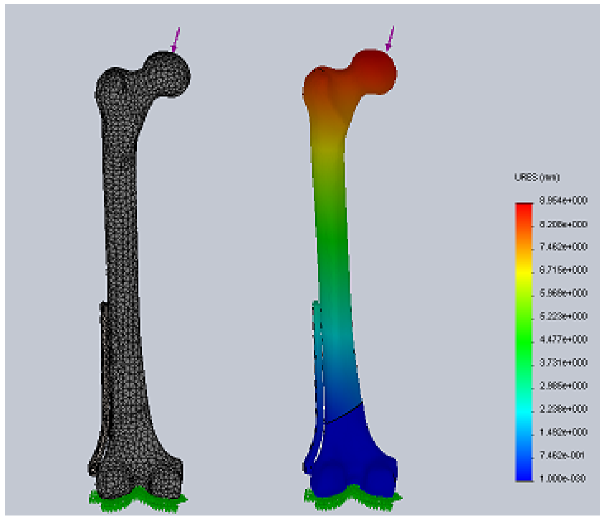


Fig.12. Displacement calculation of bone-fixation element assembly in bipedal stance

To study the femur bone model in unipedal stance, two forces have been applied: a force of 2746 N on the femur head and a force of 2143 N as the effect of thigh muscles (Fig. 13). The force values have been calculated according to [6]. The displacement of the femoral head was about 0,8891 mm.

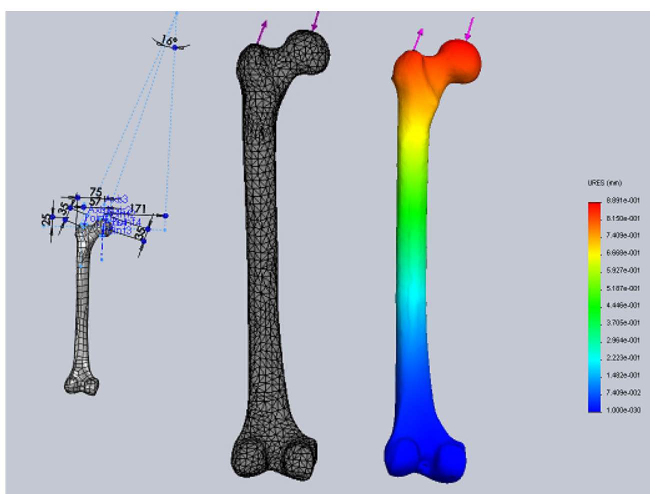


Fig. 13. Bone displacement calculation in unipedal stance

7. Conclusion

The paper presents results obtained by the authors in 3D modeling techniques applied to femur bone. It also presents the simulation of femoral head displacement when forces are applied.

We have created a program using Microsoft Visual C++ and the VTK library, which has following key characteristics:

- Implementation of the "Marching Cubes" algorithm for the reconstruction of the 3D image of the human pelvis area by using sets of DICOM files received from the X-ray computed tomography (CT) devices;
- Implementation of the Hoppe algorithm for the reconstruction of the 3D image of the human femoral bone by using text files with points coordinates
- Display of the 3D images from various angles
- Display of the 3D model simultaneously or alternating with various orthogonal section planes, or with an arbitrary section plane
- Various ways to display the 3D model (solid or mesh)
- Microsoft Foundation Class type software approach for visualization using specific patterns for each type of graphic file: STL, native VTK, DICOM, Text;
- Browsing and visualization of a set of DICOM files available in a folder, having following functions:
  - Change of image contrast and saturation, image flip along the Y axis
  - Importing the values of every pixel from an image of a DICOM file
  - Displaying the value of the current pixel indicated by the mouse pointer
- Computing stage and status displayed on the status bar;
- Triangles' coordinates saved in point cloud type files;
- Save and display of images from several graphic files: JPEG, BMP
- Change of background color and image color as well as of image opaqueness.

The software implementation of the Marching cubes is fast, but may produce artifacts.

The software implementation of Hoppe algorithm may deliver good results if the theoretical conditions are met, such as point sampling and point distance. However, the implementation on regular PC's tends to be slow for large data sets and may not close the sharp corners.

All surface mesh models can be exported to STL files for further processing.

We used SolidWorks CAD software for 3D modeling as follows:

- We have created 3D solid models of the human femoral bone by using spline curves in successive planes joined together with the LOFT command
- We have built a 3D solid model of the femoral bone by using the two “point clouds” files obtained with the visualization application and the ScanTo3D module of SolidWorks .
- A SolidWorks assembly was created from the femoral bone model obtained as indicated above and an osteosynthesis element.

We also used SolidWorks CAD software for Finite Element Analysis:

- Simulation of the behavior of the intact bone in unipedal stance and bipedal stance
- Simulation of the behavior of the “fractured” bone and osteosynthesis element assembly in bipedal stance

ScanTo3D software module can produce solid native models for SolidWorks software. The model can be used as it is or can be exported in Parasolid format. The Finite Element Analysis delivers numerical values about displacements, stresses and strain of the bone and fixation elements assembly. The success of the software simulation depends on many terms, as model correctness and FEA software capabilities.

R E F E R E N C E S

[1] *W.E Lorensen., H.E Cline.* ,”Marching cubes. A high resolution 3d construction algorithm”, Computer Graphic 21(4), July 1987, pp 163-169,

[2] *Dinu M. Antonescu,*“Patologia aparatului locomotor vol. I”, (Musculoskeletal pathology) Editura Medicală 2006,pag. 694, ISBN 973-39—0559-3 (in Romanian)

[3] *Will Schroederl*, “The Visualisation ToolKit. An Object Oriented Approach To 3D Graphics”, KitWare Inc.,2004, pag. 149-152, ISBN 1-930934-12-2

[4] *Hoppe Hugues,* “Surface Reconstruction From Unorganized Points” Ph. D. Thesys, University of Washington 1994

[5] *Constantin Anton Micu, Paul-Nicolae Ancuța*, “Virtual volume modeling of human femur using 3D CAD Software”, Paper submitted for approval to the Journal of the Romanian Society of Mechatronics,2011

[6] *Mihai Popescu, Lucian Căpitanu*, “Proteze totale de şold.Inginerie şi ortopedie”(Total hip prostheses. Engineering and Orthopedics) Editura BREN 2006, Bucureşti, pag. 54-57
[7] *** http:/aofoundation.org