Archives of Materials Science and Engineering

Volume 42
Issue 2
April 2010
Pages 119-125

International Scientific Journal
published monthly by the
World Academy of Materials
and Manufacturing Engineering

A comparative approach to modelling of hard tissues

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Received 11.02.2010; published in revised form 01.04.2010

ABSTRACT

Purpose: Investigating the capabilities of commercial CAD/CAM systems in producing 3D models of body bones from 2D medical images and application of resulting models in rapid manufacturing of customized implants.

Design/methodology/approach: Geometrical information of 2D medical images extracted via an image processing and filtering mechanism, and converted into 3D models by Commercial CAD software systems. After applying a median filter to improve the quality of 2D images, they are segmented and bone edges are detected with histogram threshold method. With the aid of an Auto LISP program, detected edges are transferred to AutoCAD as a series of points. Splines are drawn over the points and redundant points deleted. Then by transferring resulted splines into the modeler, 3D models are constructed. Different implant manufacturing methods have been studied and rapid manufacturing methods have been recognized to be suitable for customized implant fabrication.

Findings: A number of CAD software packages proved to be capable of producing 3D models using generated information, however, human intervention is needed for all systems tested. Different systems tested exhibited strenthnesses and weaknesses.

Research limitations/implications: Automatic generation of 3D models of body bones from 2D images is desirable. Also development of an intelligent system for manufacturing of customized implants is highly desirable.

Originality/value: Method of extracting geometric data from medical images and presenting this data in a format suitable for commercial CAD systems for making 3D models is of high value. Also the performance comparison of various CAD systems is very important.

Keywords: CAD; Modelling; Manufacturing; Customized; Implant

Reference to this paper should be given in the following way:

M. Tolouei-Rad, A comparative approach to modelling of hard tissues, Archives of Materials Science and Engineering 42/2 (2010) 119-125.

TECHNICAL PAPER

1. Introduction

In recent years biomedical engineering has opened a new window to CAD and this technology has been extensively used in many application areas. Among these, modelling hard tissues has been of interest to some researchers [1-4]. The main objective has been to produce three-dimensional (3D) CAD models since it is difficult to visualize hard tissues from conventional two-dimensional (2D) medical images. 3D models may provide a better visualization of the patient's anatomical structure and virtually expose damaged bones and hard tissues to surgeons and physiotherapists before a surgery begins. This provides the surgeon with the possibility of necessary consultations and preparations for an easier and more successful surgery. 3D models provide the possibility of rotating and viewing damaged bones from different directions and produce cross-sections from any position and at desired orientations. It is also possible to use these 3D models for many other purposes. For instance, Wang et. al. [5] transferred the geometrical data of these 3D models to finite element software systems for further analysis such as stress-stain analysis.

With emergence of Rapid Prototyping and Manufacturing (RP & M) techniques, it is now possible to rapidly produce physical models from complex 3D computer models. This possibility is of great importance for specific applications where *time to market* is a crucial factor for the manufacturer. These include implant fabrication for medical applications. Researchers are interested in using RP & M techniques for fabricating customized implants [6-7]. For example, Javelin Company is producing artificial bones and implants from Aluminum, Zirconium and Phosphor based alloys [6].

When a 3D model is constructed by a CAD system, its geometrical data can then be imported into a rapid prototyping system. This data can then be edited and used for producing a physical model with desired accuracy and size quickly, often in minutes. In this research an approach for constructing 3D models from 2D medical images is presented. Four commercial CAD systems have been used and a comparison of the results obtained is presented highlighting strenthnesses and weaknesses of each system employed. The work described here would result in saving of time and cost required for developing application specific software packages.

2. Description of the approach

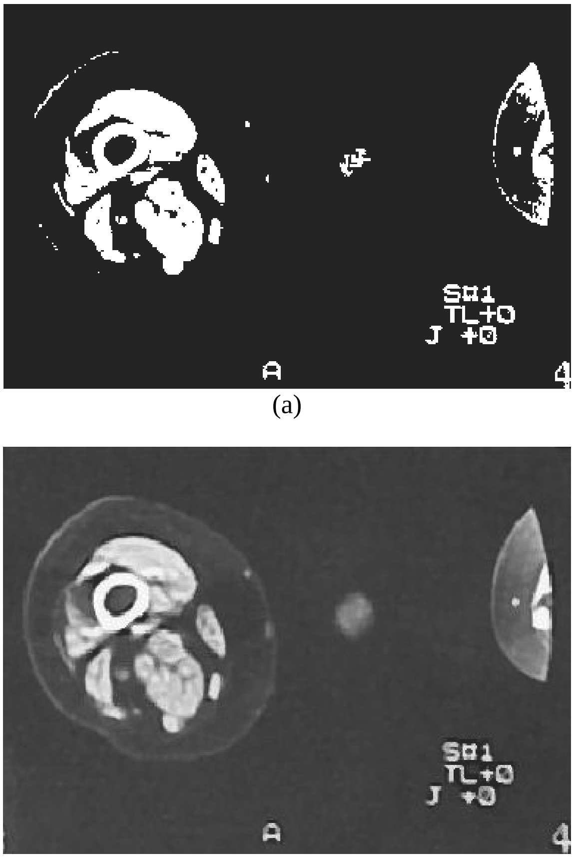
In this research two different processes are of great concern and to be need to be explained in details: (1) processing of two-dimensional image and (2) three-dimensional modelling.

2.1. Processing of two-dimensional image

Taking 2D medical images for desired section of the patient's body is the first step towards constructing 3D models. These images should be taken from appropriate directions with a proper slicing distance such that each image provides a cross-sectional image of the hard tissues to be modeled. Conventional 2D X-ray images do not provide cross-sectional images with specified slicing distance. As a result, computed tomography (CT) images have been used to tackle this problem. Thinner slicing leads to a higher number of 2D images and, consequently, a better quality of the resulting 3D model. In this work a slicing distance of 5 mm has been used. However, the recommended slicing distance for complex shapes is about 2 mm or less.

The geometrical data of the 2D images should be transferred into the computer for further processing. Today modern systems are capable of directly providing digital images; however, in this work a digital camera has been used. Then 2D images should be processed to reduce noise and improve the quality of the images. A median filter has been programmed in Matlab and used. For each pixel an N by N adjacency has been determined and the brightness of these pixels resorted from the highest to the lowest or vice versa. The mean value of brightness determines the brightness of the corresponding pixel. Fig. 1 shows a CT image of a human femur before and after applying a 3 x 3 median filter. As can be seen in the Fig. 1, the amount of black and white noises, known as salt and pepper noises, has been reduced without any effect on the boundaries of different sections.

Bone edges of the image need to be identified at this stage. To do so, the histogram threshold method [8] has been used. The histogram of an image represents the density of certain brightness of the image. Fig. 2 shows the histogram of the CT image of the femur shown in Fig. 1. The horizontal axis represents the brightness of pixels ranging from 0 to 255 while the vertical axis refers to the distribution of the pixels. As seen in the Fig., the histogram includes some peaks and dips. Each peak shows a different section and the dips represent the limits or borders between sections. The histogram shows three sections: 1) background, 2) soft tissue and 3) hard tissue. The hard tissues represents bones and should be extracted from the image. Fig. 3 provides a closer look at this section of the histogram dividing soft and hard tissues. The deepest point on the curve has a brightness value of 240. This is called the thresholding value be used to separate hard tissue from soft tissue. Note that the values of pixels below the thresholding value are set to zero, and those above are set to 255. Fig. 4 shows the outcome of the process. At this stage the bone edges are identified using the Laplacian of Gous method and "edge' command of Matlab software. The result is shown in Fig. 5. At this stage the geometrical data of the pixels forming the edges of the bone are restored to be transferred to the modeling software for further processing.



(a)

(b)

Fig. 1. The CT image of a human femur a) before and b) after applying the median filter

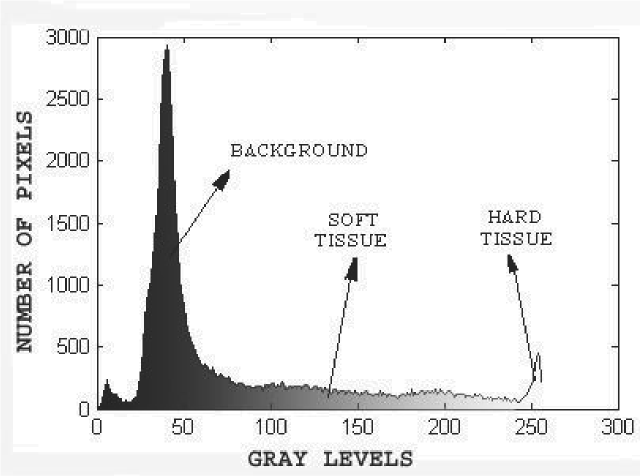


Fig. 2. Histogram of the CT image of Fig. 1

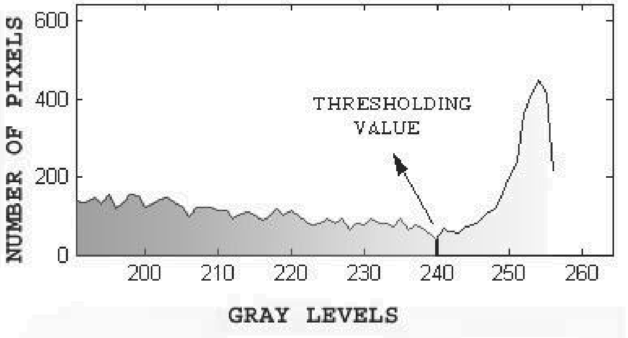


Fig. 3. Thresholding value separating soft and hard tissues

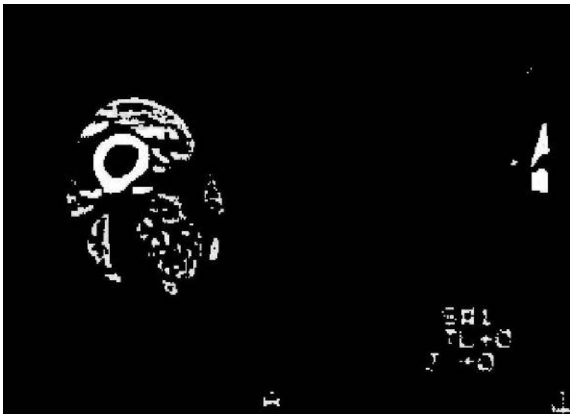


Fig. 4. Processed image (thresholding value = 240)

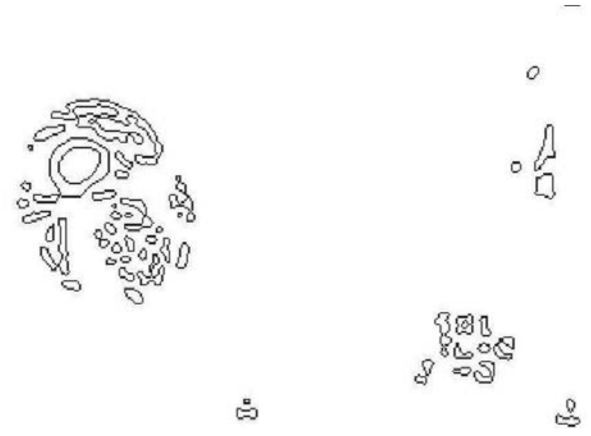


Fig. 5. Identified edges with Laplacian of Gous method

2.2. Three-dimensional modelling

As seen in Fig. 5, identified edges of the bone do not form smooth contours. Furthermore, other contours are identified that do not belong to the bones. On the other hand, modeling software in the current shape cannot use these contours. Therefore, identified contours should be transferred to an environment for further processing. AutoCAD has been selected as a good choice due to its compatibility with other CAD systems. AutoLISP is a graphical programming language capable of editing and generating graphical drawings in CAD environments particularly in AutoCAD. Accordingly, an AutoLISP program has been developed and used. The program specifies a point in AutoCAD for each point extracted from the Matlab. Then it draws a spline passing through all points belonging to the bone contour. It also deletes redundant points and contours such that for each image a clear contour belonging to the bone is achieved. This process is repeated for all images taken along the Z-axis. For this experiment, there have been numerous CT images taken from the patient’s thigh with a slice distance of 5 mm as previously mentioned. The result was a 3D wireframe model shown in Fig. 6. For constructing the 3D solid model various CAD/CAM systems have been tested. Of the systems tested, SolidWorks, Mechanical Desktop, EdgeCAM and 3DSMax proved to be capable of constructing 3D models from the given wireframe model. SolidWorks generated a 3D solid model by interpolation between the given sectional splines along Z-axis. As shown in Fig. 7, the first sectional spline and starting point for drawing the longitudinal spline should be determined by user. In other systems the first point of each sectional spline needed to be connected to each other, and therefore, care should be taken in selecting similar points as the starting points in sectional splines. Results obtained from other commertial CAD systems are shown in Figs. 8 to 11. These systems are respectively Mechanical Desktop, SolidWorks, EdgeCAM and 3DSMAX.

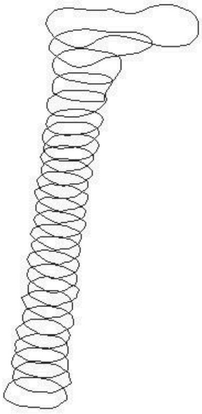


Fig. 6. Wireframe model of the femur

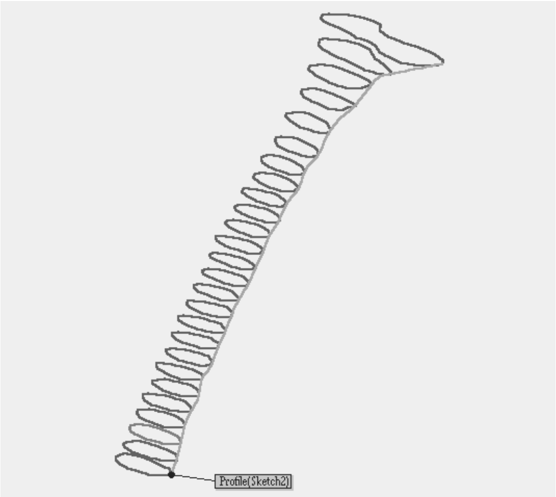


Fig. 7. Starting point for drawing longitudinal spline for constructing the 3D model

Fig. 8. 3D model from Mechanical Desktop

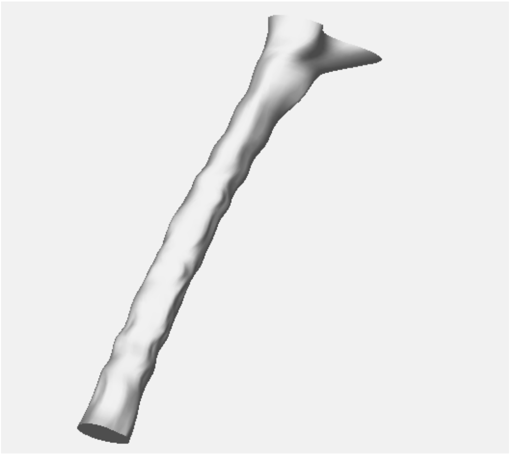


Fig. 9. 3D model from SolidWorks

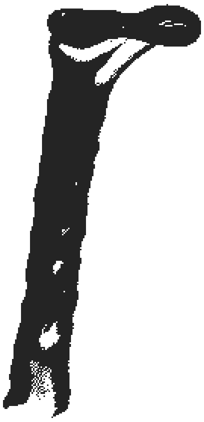


Fig. 10. 3D model from EdgeCAM

Fig. 11. 3D model from 3DSMax

3. Discussion of results

The method described above proved capable of constructing 3D solid and surface model from the data received from the image processor. While all the models produced are useful for interepretation of the data generated by the image processor there some strenthnesses and weaknesses for each of the systems used.

Table 1 presents a comparison of the 3D models generated by thses systems. On the basis of information provided SolidWorks generated a 3D solid model and other systems generated surface models for the bone in question. It is noteworthy that solid models provide volumetric information of engineering significance such as volume, mass property, center of gravity, etc. In addition solid models provide the possibility of making cross sections from any direction while surface models only provide surface-related information including total surface area and connectivitiy information of surfaces used to make the model. Obviously, volumetric information is essential in design and manufacturing of customized implants. In addition, if a surgeon requires the volume and the weight of tumor, a solid model could easily provide this information.

When the visual quality of the model is of concern, then 3DSMax gives the best result due to its powerful lightening and coloring features. In addition, the geometric information of 3DSMax models can be easily converted into STL format to be used by rapid prototyping systems. This information can then be used for rapidly producing a physical model for better visualization.

When a customized implant is to be produced by machining, EdgeCAM is capable of generating the required NC code to be used on a CNC machine, and produce the required implant rapidly.

4. Prototyping and manufacturing

Rapid prototyping (RP) was first developed in 1980s. And later renamed to rapid prototyping and manufacturing (RP & M) as a result of its integration with modern manufacturing techniques. Currently, there are at least five fundamentally different RP & M methods commercially available:

1) stereolithography,
2) Laminated Object Manufacturing,
3) Selective Laser Sintering,
4) Fused Deposition Modeling,
5) Solid Ground Curing. In addition to these, few other methods are under development.

Stereolithography (SLA), or three-dimensional printing, was the first commercially available layer additive processes to enable the generation of physical objects directly form a CAD database. The process begins when the boundary surfaces of the CAD description are tessellated or formed as a connected array of triangles. This step is performed using an interface specification developed by 3D Systems Corporation, which pioneered the Rapid Prototyping and Manufacturing (RP & M) field. The triangles can be as large or as small as developed by3D Systems Corporation, which pioneered the Rapid Prototyping and Manufacturing (RP & M) field. The triangles can be as large or as small as desired. Smaller triangles result in finer resolution on curved surfaces and improved part accuracy through reduced choral deviations, while larger triangles minimize the system storage requirements, at the expense of accuracy. As workstations attain higher processing speeds with greater memory and storage capacity, file size limitations have become less problematic.

The software generates a tessellated object description known as an STL, or stereolithography, file. This file basically consists of the X, Y, and Z coordinates of the three vertices of each surface triangle, as well as an index that describes the orientation of the surface normal. The latter feature is necessary to ensure that a clear distinction is made between inner and outer surfaces, as would typically occur in generating a model of an automobile manifold. Since its conception, The STL format has become the de-facto standard of RP & M industry. The STL format is now supported with file translators many system suppliers including major CAD vendors. Furthermore, it has been adopted by all of the various RP & M system suppliers as primary, if not the only, basis of their CAD interface. Although other software approaches have been developed, the STL format continues to be the most widely used. It is conceptually simple, topologically robust, and when used with sufficient resolution, it is capable of high accuracy.

Table 1.
Comparison of the 3D models generated by different CAD systems

CAD System	Model Type	Visual Quality	Format	Capabilities
Mechanical Desktop	Surface	Fair	DWG, DXF	• Measuring specific dimensions • Customized implant design
SolidWorks	Solid	Good	IGS	• Volumetric data such as volume, mass, center of gravity • Sectional views from any direction • Customized implant design
3DSMax	Surface	Excellent	IGS, STL	• Applying diff. materials • Finishing operations • STL format for RP
EdgeCAM	Surface	Poor	IGS	• NC code generation

Once the STL file has been generated from the original CAD description of an object, the next step involves slicing the STL file. Here, a series of closely spaced, horizontal planes, like the floors of a tall building, are mathematically passed through the tessellated object file. The result of this process, known as an STL, or slice file, is a series of closely spaced, 2D cross-sections of the tessellated STL description, each at a slightly different Z-coordinate value. In the early days of stereolithography, the most common slice thickness was about 0.5 mm. As SLA has achieved finer precision and improved accuracy, slice thickness values have decreased to the point where 100 microns layers (approximately equal to the thickness of a dollar bill) are now commonplace value. Values as low as 50 microns, about the diameter of a human hair, have been demonstrated in the laboratory. This is important because finite layers cause stair-stepping errors in Z axis. All current RP & M systems exhibit this characteristic. As layer thickness decreases, the object generated can more faithfully approach the design intent, and surface quality is correspondingly improved.

The result of all these elements is an actual, physical 3D model of the original CAD description of an object to a physical version of the object in a matter of hours is the basis of the existing and rapidly growing field of RP & M [9, 10].

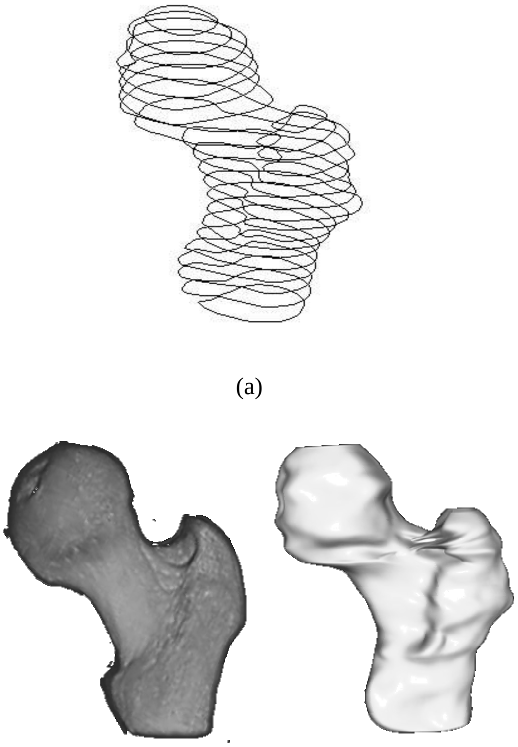
5. Manufacturing of implants

In this work, RP & M techniques just explained have been used for customized implant modeling and fabricating. A case using real models is presented in this section.

Fig. 12 (a) shows the wireframe model of a human hip joint. This wireframe model has been achieved from the 2D CT-images as explained before. Fig. 12 (b) illustrates the real bone on the left. As can be seen in Fig.12 (a), there are two closed loops in some layers of the wireframe model. This may cause confusion in constructing the 3D model by the system. To resolve this problem either human assistance is required or a different direction for taking CT images should be determined such that multiple closed contours on the same image is avoided. Again, with a slicing distance of 5 mm the quality of the model seems to be acceptable. Still a thinner slicing distance would result in a better quality. Once the model has been generated on the computer, the modeler is able to make any changes on the model before a physical model is produced.

Fig. 12 (b) also shows the fabricated customized 3D physical model of the required implant on the right. This model has been generated by sterolithography method; and a slicing distance of 130 microns has been used for constructing the physical model. Although the quality of the physical model generated is acceptable, still a closer distance would result in a higher quality. It is still possible to alter the model and make any changes, as the resulting implant is not yet produced.

At this step, the resulting CAD database of the physical model is transferred into a commercially available CAM system, EdgeCAM, using the standardized IGES format for CAD/CAM data exchange. Then, by specifying required machine tools and cutting parameters, the necessary NC code for machining the required customized implant can be generated. Alternatively, it is conveniently possible to use the information of the 3D model for designing and manufacturing of a die or mold for fabricating or mass-producing the given implant. Coating may improve mechanical and physical properties of parts such as wear resistance, surface hardness and toughness [11-17]. Accordingly, it is conveniently possible to subject customized implants to properly coatings. In addition to improving mechanical properties of the implant a thin layer of a bio-compatible material could provide a chemical barrier to decrease diffusion or reaction between the body and implant materials.



(a)

(b)

Fig. 12. Modeling and fabricating a hip joint

6. Conclusions

3D modelling of hard tissues help surgeons and physiotherapists better understanding the anatomical structures of patients. In addision, when broken bones are involved sergeons can investigate the extent of damage before surgery. This paper proposes a method for constructing 3D images from 2D CT images by means of three basic steps:

- Taking CT images from the required position;
- Image processing and edge identification (processing);
- Constructing 3D models from 2D images (post-processing).

It should be noted that conventional 2D X-ray images couldn’t be used, as these images do not provide cross-sectional images. CT images are used as they provide cross-sectional images in any desired direction with desired slicing distance appropriate for 3D modeling. Thinner slicing leads to higher number of 2D images and, consequently, a better quality of the resulting 3D model. In this work a slicing distance of 5 mm has been used.

Of the commercially available CAD systems tested, four proved to be capable of constructing 3D models based on the information given. These include SolidWorks, Mechanical Desktop, EdgeCAM and 3DSMax. The models constructed with each system posses certain strengths and weaknesses. Therefore, the user should decide which system to use considering his/her requirements. Alternatively, the user may use more than one system to better respond to his/her needs.

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