Bio-CAD Reverse Engineering of Free-form Surfaces by Planar Contours

Hacene Ameddah and Mekki Assas

Université de Batna, Algérie, hacamed@gmail.com, mekassas@hotmail.com

ABSTRACT

In this paper, an interactive application tool has been developed for creating 3D models of anatomical organs and other body structures from 2D medical imaging data. 3D models are generated by using reverse engineering algorithm and Planar Contour method by SolidWorks developed in Visual Basic Language. The research includes transferring Computed Tomography (CT) and Magnetic Resonance Imaging (MRI) images into digital matrixes, entering digital matrixes into SolidWorks environment, building feature library for 3D reconstruction, creating medical rapid prototyping models. 3D reconstruction is created by edge configuration generation and triangulated cube configuration generation in capturing section contour points from medical image per slice, creating B-spline curve with the control points in each layer, producing solid model construction in Planar Contours method. Medical rapid prototyping models are performed in SolidWorks. The results of this paper are to develop image processing 3D visualization in SolidWorks Application Programming Interface (API) using Visual Basic Language. The results reveal that the accuracy of 3D reconstruction is acceptable.

Keywords: reverse engineering, point cloud processing, NURBS.
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1 INTRODUCTION

The three-dimensional (3D) reconstruction of human anatomical organs and structures from a series of cross section image has been an intriguing problem in recent decades. New challenges have been created in the field of image analysis and pattern recognition by the introduction of modern image data collection techniques such as Computed Tomography (CT) and Magnetic Resonance Imaging (MRI). With the development of advanced bio-medical techniques, 3D geometric representations of human anatomical organs rather than the two-dimensional (2D) photographic images using CT or MRI are frequently required. These 3D geometric models, either simulation generated by computer or 3D Rapid Prototyping (RP), can be used for diagnosis of physical disorders, visualization of anatomical organs for surgical planning, and the implantation of human organs and other structures. RP is the process of converting a 3D Computer Aided Design (CAD) file into a 3D physical model. Medical Rapid Prototyping (MRP) is the production of the medical models using rapid prototyping methods [1-3]. The application of RP techniques is an invaluable contribution of engineering technology to the field of medicine [2].

Reverse engineering is an important method in constructing a CAD model from an existing physical part during part or product design [4-5]. Most of the proposed solutions for RE are realized in two steps. In the first step, the physical part is measured or digitized by a measuring device such as a coordinate measuring machine (CMM), and surface points are captured in 3D coordinates. During the second step, curves or surfaces are fitted to the measured points.

For digitizing [6] summarizes most of the digitizing techniques and the measuring principles they use for reverse engineering [7] introduces most of the commercially available digitizing systems. When the digitized points are available, the CAD model could be constructed by NURBS curves or surfaces fitting which is a method commonly available and widely used. Many papers have been published [8-9] about constructing CAD models by fitting NURBS curves and surfaces to data points [10] presented the algorithm for NURBS curves and surfaces fitting that automatically identifies the control points and their respective weights: the weights of control points are first identified through singular value decomposition, the control points are then determined by least squares minimization. Because the creation of surfaces in most practical applications is usually not a stand-alone project, they must always be subjected to boundary conditions [11] discussed the RE from digitized points subject to boundary conditions based on conventional surface fitting algorithm introduced in Ref. [10].

Based on our developed work [12-13], a method of RE modeling using digitized points subject to boundary conditions is presented.

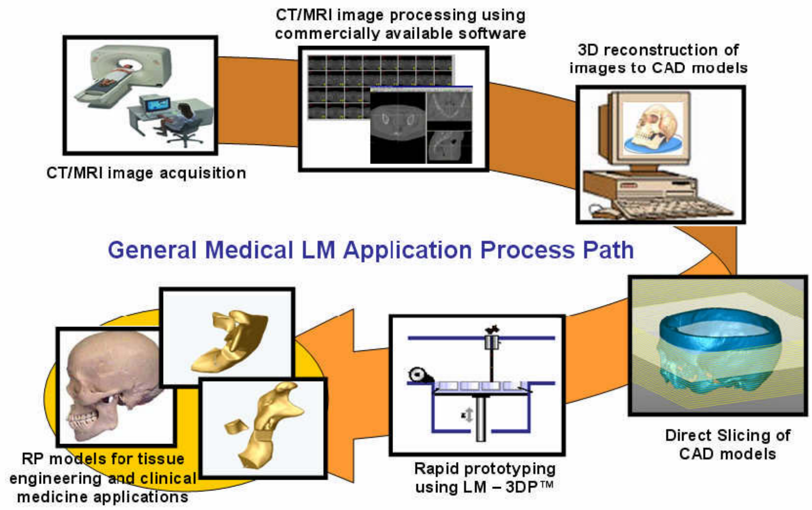

Fig. 1: General biomodeling and medical rapid prototyping process path.

2 REVERSE ENGINEERING APPROACH

Although non invasive modalities, such as CT, Micro-CT, MRI and Optical Microscopy can be used to produce accurate 3D models of anatomical organs. In general, activities in anatomical modeling design, analysis and simulation need to be carried out in a topology-based modeling environment, such as using a Computer Aided Design system and CAD-based solid modeling, which is usually represented as 'boundary representation' (B-REP) and mathematically described as Non Uniform Rational B-Spline (NURBS) functions. Unfortunately, the direct conversion of the medical imaging data into its NURBS solid model is not a simple task. In the last few years some commercial programs, for example, SurgiCAD by Integraph ISS, USA, Med- Link, by Dynamic Computer Resources, USA, and Mimics, by Materialise, Belgium, were developed and used to construct a CAD-based model from medical images. However, none of these programs has been efficiently and widely adopted by the biomedical and tissue engineering community due to the inherent complexity of the tissue anatomical structures. Effective methods for the conversion of CT data into CAD solid models still need to be developed. We have evaluated process path for generating a CAD model from Reverse engineering interface approach.

2.1 Reverse Engineering Interface

The reverse engineering interface approach uses a 3D voxel model as the starting point created from the region grow process. The 3D voxel model is converted to point cloud data form and are loaded into the reverse engineering software. The points are then used to create triangular facets to form a surface model. The faceted model is further refined and enhanced to reduce file sizes and unwanted features. The freeform surfaces of NURBS patches are used to fit upon the outer shape of the model.

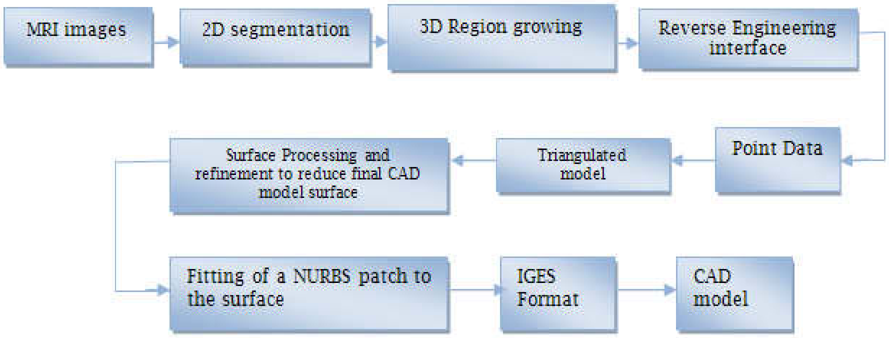

Fig. 2: Process definition to arrive at a CAD model from CT and MRI data.

2.1.1 Iso 10303(step) based NURBS Representation

Non-Uniform Rational B-Spline (NURBS) are the industry standard tools for the representation and computer aided-design of freeform models [14] in the field of automotive design, ship design etc. Within STEP files, solid and surface models may be represented as rational or non-uniform rational B-spline surfaces. Unlike STL files where the facet information of the triangle is used to obtain the slice contour, direct slicing works by using the exact mathematical representation of the freeform shapes in computing the slice contours or tool patterns. A rational B-spline surface is expressed parametrically in the form.

$$s(u,v) = \frac{\sum_{i=1}^{n+1}\sum_{j=1}^{m+1} W_{ij} P_{ij} b_{ik}(u) b_{jl}(v)}{\sum_{i=1}^{n+1}\sum_{j=1}^{m+1} W_{ij} b_{ik}(u) b_{jl}(v)} \tag{2.1}$$

Where parameters u and v range from zero to one, n and m the degree of the surface in u and v direction. The P_{ij} terms are 3D net control points of the control polygon and W_{ij} terms their corresponding weights, b_{ik} and b_{jl} are B-spline basis functions of order k and l respectively. The B-spline basis functions are defined by the Cox-de Boor recursion formulas as given by:

$$b_{j1}(s) = \begin{cases} 1 & \text{if } \mathrm{ku}_j \le u \le \mathrm{ku}_{j+1} \\ 0 & \text{otherwise} \end{cases} \qquad b_{l1}(s) = \begin{cases} 1 & \text{if } \mathrm{kv}_l \le v \le \mathrm{kv}_{l+1} \\ 0 & \text{otherwise} \end{cases}$$

$$and \quad b_{jk}(u) = \frac{(u - ku_j) b_{(j)(k-1)}(u)}{ku_{j+k-1} - ku_j} + \frac{(ku_{j+k+1} - u) b_{(j+1)(k-1)}(u)}{ku_{j+k+1} - ku_{j+1}} \tag{2.2}$$

$$b_{jk}(v) = \frac{(v - kv_l) b_{(l)(k-1)}(v)}{kv_{l+k-1} - kv_l} + \frac{(kv_{l+k+1} - v) b_{(j+1)(k-1)}(v)}{kv_{l+k+1} - kv_{l+1}}$$

Where the values of k_{uj} and k_{vl} are defined by the knot vector associated with the NURBS surface in the u and v direction respectively. The STEP file contains all information that is required to define the NURBS uniquely and a STEP reader is employed to extract the relevant information. An ID is given to each control point as contained within the CARTESIAN_POINT statement. This is followed by the definition of the B-spline surface in terms of the parameters needed to define it degree of surface in u and v direction, multiplicities and knot vectors in u and v direction and the weight associated with each control point.

2.1.2 Iso-surfacing Reconstruction

The majority of the reconstruction techniques produce planar approximations of the data set. This class of surface reconstruction methods initially constructs planar contours in each CT and MRI data slice and then connects these contours by a triangulation in three dimensional spaces. The triangulation process is complicated by the occurrence of multiple contours on a data slice. Fig. 3., shows the approximation method. The method consists of joining points of neighboring contour lines to triangles in such a manner that one obtains triangular planar elements, which delimit a polyhedron approximating the surface of interest.

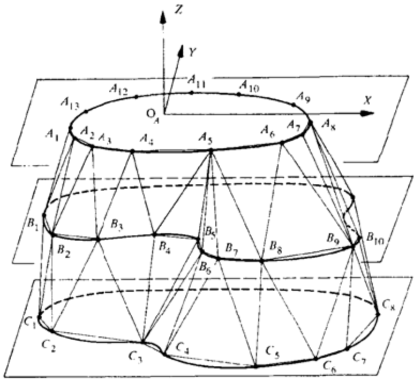

Fig. 3: Method of planar contours.

The limitation of Planar Contours is that the connected contour algorithms throw away the inter-slice connectivity that exists in the original data.

3 3D RECONSTRUCTION BY PLANAR CONTOURS

As mentioned above, 3D reconstruction models are very rough and limited, which takes time to improve the quality of 3D models. To get better 3D medical models in SolidWorks, Planar Contours, which use contour lines to approximate complex surfaces, will be employed for computer modeling and rapid prototyping. The initial planar contours method is to connect these contours by a triangulation in 3D space. The triangulation process is complicated by the occurrence of multiple contours on a data slice. In this research, planar contours method constructs 3D models by using loft command in SolidWorks, which saves the time and improves the quality. The key steps in Planar Contours approach include capturing section contour points from medical image per slice, creating B-spline curve with the control points in each layer, and producing solid model construction.

3.1.1 Section Contour Points Capture

Each section image was imported into SolidWorks and placed on corresponding sketch plane. A set of sketch planes parallel to a reference plane was created in SolidWorks. The distance between two adjacent sketch planes was set to be identical to the distance between two corresponding sections obtained from adjacent CT or MRI slices. These section contour points for teeth per slice from CT scan of a head were created, as shown in (Figure 4).

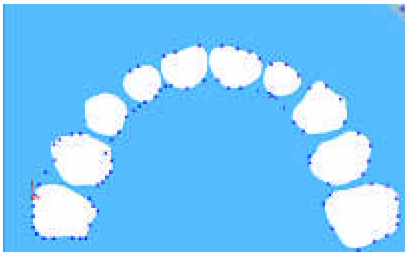

Fig. 4: Section contour points capture in SolidWorks.

3.1.2 B-Spline Curve Creation

The second step was to creation of spline, with the fit spline command in SolidWorks. This digitization was conducted by properly marking points along the exterior contours and using the point option of the spline mode in SolidWorks. Handles appeared at each spline point with arrows that controlled the vector leaving that point. Technically known as Bezier (B-spline) handles, these little arrows shape the B-spline curve. B-spline curves were formed in SolidWorks using the curve fitting technique, which employed the least square fitting for discrete points measured on a pre-selected section of an object. The best fitting curve can be obtained by minimizing the distance sum between the curve and the geometric points, as shown in (Figure 5). The shape of the B-spline curve depends on the directions of tangent vectors. Spline can have as few as two points and can specify tangency at the end points. B-spline curves are used to provide accurate interpolation of the intersection data points. To achieve higher accuracy, a larger number of linear segments are needed for the approximation.

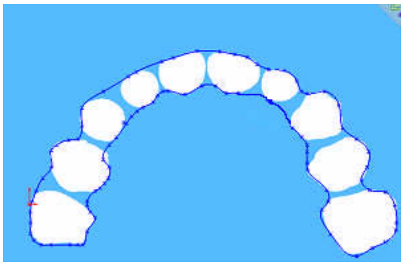

Fig. 5: B-spline curve creation.

3.1.3 Solid Model Construction

After B-spline creation, the solid model was created using the loft features in SolidWorks. The loft feature created a solid model (Figure 6.b) by connecting multiple closed curves on parallel planes (Figure 6.a). The guide curves were selected along the loft direction to enhance the smoothness of the loft features. The loft solid model created in SolidWorks is smoother and finer surface, which was helpful and convenient for further biomedical rapid design and manufacture.

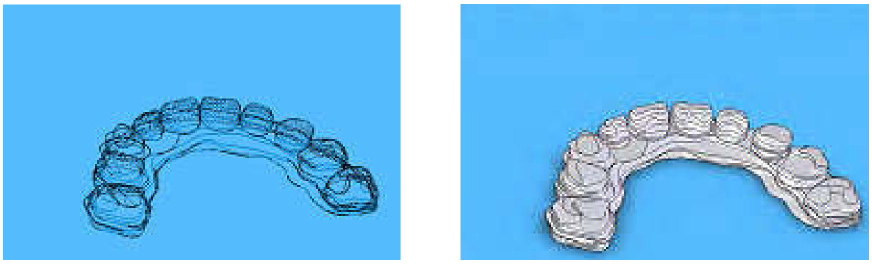

Fig. 6: (a) Layers closed curves selected for a loft feature, (b) Solid model by planar contours method.

The ability to produce physical models from the scanned data in SolidWorks is an important contribution from engineering technology to the medicine. Biomedical rapid design and manufacturing in SolidWorks could help surgery to plan, manage, and manufacture concurrently. Because 3D reconstruction is performed in SolidWorks, the fields of Finite Element Analysis, MENS, and Mechanical Engineering can be combined with the areas of surgical planning and implantation. The combination of 3D reconstruction and Rapid Prototyping will have a significant impact on biomedical engineering and surgery.

4 CONCLUSION

The results of this paper are the first step towards 3D reconstruction from original CT and MRI scan data. The manufacturing of Medical Rapid Prototyping will serve as the initial clinical study. The true advantages of 3D reconstruction in SolidWorks have yet to be determined through long-term study and clinic application. 3D reconstruction in SolidWorks can provide STL format data for Medical Rapid Prototyping manufacturing to help plan implant surgeries because SolidWorks can export STL files for direct reading by Rapid Prototyping machine.

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