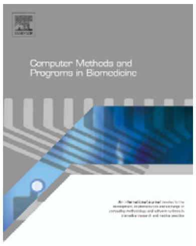
COMPUTER METHODS AND PROGRAMS IN BIOMEDICINE 86 (2007) 141–152

journal homepage: www.intl.elsevierhealth.com/journals/cmpb



# A reliable surface reconstruction system in biomedicine

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ARTICLE INFO

Article history:
Received 29 July 2005
Received in revised form
30 January 2007
Accepted 30 January 2007

Keywords:
Surface reconstruction
Contour-correspondence
Tiling
Branching
Degenerate

ABSTRACT

For common biomedical imaging facilities, such as CT, MRI, and confocal microscopy, the acquired scans are sequential parallel sections. The object of interest in each section image can be extracted by segmentation procedure to form serial parallel planar contours. How to reconstruct a trustworthy surface from these contours is a crucial issue in biomedical 3D visualization. In this paper, we propose an automatic, fast, and reliable surface reconstruction system. An improved correspondence-determining algorithm is proposed in the system to provide more reasonable contour-correspondences than the existing algorithms. It can handle more general input data, and does not produce wrong reconstruction results. A hybrid tiling algorithm is presented to tile the corresponding contours without the requirement of a contour-matching procedure. It can also handle the branching problem without any modification. For degenerate cases and branches, intermediate contours are introduced by means of contour interpolation to enhance the reconstruction results. The surface area and volume are also calculated to facilitate the practical applications.

## 1. Introduction

Computer technology advances very fast in the past two decades, which benefits biomedical imaging and facilitates its 3D visualization. We can reconstruct 3D objects and render them without altering traditional 2D imaging apparatus. 3D visualization techniques enable better understanding of the topology and shape of an object, and enable measurements of its geometrical characteristics. The extracted information is helpful in clinical diagnosis, surgical planning, and biological research. For common biomedical imaging facilities, such as CT, MRI, and confocal microscopy, the acquired scans are sequential parallel sections. Therefore, how to reconstruct a trustworthy surface from the sequential parallel 2D sections becomes a crucial issue in biomedical 3D visualization.

Some previous methods solve this problem by estimating isometric volume data from original parallel section images. The isometric volume data are also composed of parallel sequential digital images, but the stack of images is more compact. Assuming original section images to be parallel to the *xy*-plane, the isometric volume data can be obtained by raster interpolation of adjacent images along *z*-axis. The object of interest in the volume data can be extracted by 2D or 3D segmentation procedures. For further refinement of the rugged boundary, the marching cubes algorithm [1] is usually adopted to construct a polyhedral model for representation of the object. This high resolution surface model comprises many tiny triangles that are about the same size as the voxels in the volume data. Algorithms of this category provide good reconstruction results, but are very time consuming. The other methods, including our approach, deal with this problem by extracting the object of interest in each original section image first. The object boundary in each image is assumed to be composed of several non-crossing simple closed contours. The object surface is reconstructed from these parallel planar contours directly. Meyers et al. [2] have described the

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doi:10.1016/j.cmpb.2007.01.011

main problems in the reconstruction process, including the correspondence, tiling, and branching problems.

The simplest solution to the correspondence problem is to assign the correspondences manually [3], but it is not convenient. For automation, some methods deal with this problem by matching contour segments [4–6], others by evaluating overlaps of areas enclosed by the contours [7,8], and still others by constructing the areas of difference [9–11]. These methods either restrict the input data to the case without branching or handle specific data set only. They fail to provide reasonable results for some particular patterns of contour pairs. For the tiling problem, the greedy algorithm that tiles surfaces by local advancing rules is the most effortless method, but will probably introduce a self-intersecting surface while a contour and its correspondent in adjacent images are very different in shape, size, or orientation [3,12]. Some methods tile the surface by computing the optimal surface with predefined criteria [13,14]. These criterion-optimizing algorithms provide good reconstruction results but take a lot of computation time. Some hybrid approaches [4–6] are based on the two kinds of method mentioned above. A contour-matching procedure is applied to contours in adjacent images to obtain the similar contour segments. These contour segments are tiled by the greedy algorithm and the remainder by the criterion-optimizing algorithms. The hybrid methods provide reconstruction results almost as good and do not take as much time as the pure criterion-optimizing algorithms. Boissonnat [15,16] reconstructs object surfaces with a collection of tetrahedra defined from the Delaunay triangulation. The method solves the branching problem to some extent, but needs an extra correction scheme while three typical examples mentioned by Boissonnat occur.

We propose an automatic system that provides a solution to the ill-posed problem of surface reconstruction from serial parallel planar contours. An improved correspondence-determining algorithm is applied in the system to provide more reasonable contour-correspondences than the existing algorithms for some particular patterns of contour pairs. A hybrid tiling algorithm follows to tile contours without the requirement of a contour-matching procedure, and can also handle the branching problem without any modification. The reconstruction results of degenerate cases and branches can be further refined by means of contour interpolation. The system also calculates the surface area and volume of the object to facilitate practical applications.

This paper is organized as follows. Section 2 presents an overview of our system, including system architecture and computation procedures. In Section 3, the proposed algorithms are described in detail, including contour-correspondence analysis, surface tiling, rendering, and quantitative analysis. The implementation and experimental results are discussed in Section 4, and concluding remarks are made in Section 5.

## 2. System overview

As mentioned in Section 1, the system takes sequential parallel planar contours as input to reconstruct the polyhedral model of an object, and then performs 3D rendering and quantitative analysis for the polyhedral model. Fig. 1 shows the system flowchart. The proposed correspondence analysis algorithm is applied to contours in adjacent slices. If there is a one-to-one correspondence between two contours, they are tiled with a triangle strip by the proposed tiling algorithm directly. Otherwise, if the correspondence among contours is not one-to-one, i.e. the object has branches, an extra contour interpolation algorithm is applied before the tiling process to create intermediate contours. By tiling these additional contours, a better visualization result can be achieved. After going through all slices, a preliminary reconstruction result is accomplished. It is further refined by an algorithm of degenerate contour tiling. The reconstructed surface is smoother at the extremities of the object after the refinement. The final reconstruction result is represented by a polyhedral model. We render the polyhedral model to obtain 3D images of the object, and perform a quantitative analysis to obtain the surface area and volume of the object. All the procedures mentioned above will be described and illustrated in the next section.

## 3. Methods

### 3.1. *Contour-correspondence analysis*

#### 3.1.1. *Initialization*

A tree structure is constructed to describe the relationship among contours in each slice image of the image stack. The procedure is illustrated in Fig. 2 concisely. A contour with index $k$ on the slice $i$ is denoted as $C_{i,k}$. $C_{i,2}$ and $C_{i,3}$ lie in the inner part of $C_{i,1}$, so $C_{i,2}$ and $C_{i,3}$ will be the children of node $C_{i,1}$. $C_{i,4}$ lies in the inner part of $C_{i,2}$, so $C_{i,4}$ will be the child of node $C_{i,2}$. Here two types of contour, external and internal, are defined. A contour is external (internal resp.) if its immediate interior (exterior resp.) is the object's material. In fact, the type of contour is different between parent and child nodes. Since $C_{i,1}$ is an external contour, its children, $C_{i,2}$ and $C_{i,3}$, are internal contours. As a child of node $C_{i,2}$, $C_{i,4}$ is an external contour. Once the tree has been built, it can facilitate the following procedures.

#### 3.1.2. *Improved correspondence-determining algorithm*

In general, the automatic correspondence-determining algorithms can be categorized into two main groups: overlap-based approaches [7–11] and matching-based approaches [4–6]. Neither of them is adequate to provide acceptable results in some particular cases. For the overlap-based approaches, two contours are considered connected if they overlap more than a predefined threshold. Due to the limitation of computing power in former days, the overlaps were evaluated by using 2D bounding boxes [8]. It may introduce unreasonable connections in some cases of concave contours, as shown in Fig. 3(a). Although $C_{j,1}$ and $C_{j+1,1}$ should not connect to each other, their 2D bounding boxes overlap significantly. Wang and Aggarwal [7] evaluate overlaps of the areas that are enclosed by the contours themselves. This approach cannot handle complex branching problems owing to the absence of an appropriate data structure that can be used to describe the relationship among contours. Another overlap-based method determines contour-correspondences by construct-