ISSN : 0974 - 7435 Volume 10 Issue 15

2014

BioTechnology

An Indian Journal

FULL PAPER

BTAIJ, 10(15), 2014 [8457-8461]

A recursive method for the extraction of vascular tree skeleton and application

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ABSTRACT

Due to the complex nature of vascular structures, the best way to represent and analyse the topology of vasculature is to use its skeleton curves, as the skeleton of an object has the ability to naturally capture important shape characteristics in three-dimensional contexts. Thus, the extraction of vascular tree skeleton plays an important role in the area of computer-aided vascular surgery, such as the reconstruction of vasculatures, virtual angioscopy, and so on. This paper presents a simple and automatic method to extract the vascular tree skeleton from segmented vessel datasets. In the proposed method, the segmented vessel dataset is re-initialized to be a Signed Distance Function (SDF). And then, the moving sphere along the vessel tree can easily and automatically detect bifurcations and predict the location of next skeleton point with the constraint of SDF. Some experiments and application have been carried out to demonstrate the strengths of our proposed method.

KEYWORDS

Skeleton; Vascular tree; Signed distance function; Recursive method.

INTRODUCTION

3D visualization and reconstruction of vascular structure plays a crucial role in the area of computer-aided diagnosis and computer guided minimally invasive vascular surgery, such as the diagnosis of anomalous growths and stenosis[1], and virtual angioscopy[2]. However, due to the complex nature of vascular structures, it is not an easy task to deal with vascular models directly in three dimensions for topology description and user interaction[3]. A better way to represent and analyse the topology of vasculature is to use its skeleton curve. The skeleton of an object, which is identified as the locus of the centres of maximal spheres inside the object[4], has the ability to naturally capture important shape characteristics in three-dimensional contexts[5].

So far, various algorithms have been proposed to extract the skeleton of vascular structures[6-9]**.** Generally, these techniques can be classified into two categories[10]. In the first category, the skeleton of a binary volume can be extracted by the technique of morphological thinning[11]. However, this technique suffers from the problem of being sensitive to noise[10]. On the other hand, the methods based on the second category employ a step by step approach, which moves a small volume of interest, such as a parallelepiped [12] or sphere[3]along the vessel tree.

This paper presents a simple and automatic method to extract the vascular tree skeleton from segmented vessel datasets. Our method falls into the second category, but there are some main differences. In the proposed method, the segmented vessel dataset is re-initialized to be a Signed Distance Function (SDF)[13]. And then, the moving sphere along the vessel tree can easily and automatically detect bifurcations and predict the location of next skeleton point with the constraint of SDF.

PROPOSED METHOD

The main notion of our method is that, once the raw medical data has been segmented, the zero set of the embedding function ϕ can be used to represent the vessel contour $C = \{\mathbf{p} \mid \phi(\mathbf{p}) = 0\}$, where $\mathbf{p} \in R^3$; then the fast marching method[14]is employed to initialize ϕ to be SDF, which guarantees that the closer the point to the vascular axe, the bigger the value of function ϕ; under the condition of SDF, the probing sphere can easily detect the skeleton by moving towards to the point on the sphere with a maximum value of function ϕ. Figure 1 presents the flowchart of the iterative process for detecting axes points.

The main steps of the iterative process are as follows:

Add the axes point taken from the stack to the graph representing the vascular tree skeleton;

Define the probing sphere based on the current axes point C (the radius of the probing sphere is generally set as $1.5*\phi(C)$) and compute the value of function ϕ for the points on the sphere surface;

Find out the points on the sphere surface with maximum function values and test them whether they are in the direction of movement of the probing sphere;

Push the candidate points into the stack to be processed later.

Check whether the stack is empty. If the stack is empty, then finish the iterative process; else go to step 1.

Figure 1 Shows the pseudocode of the recursive function.

```
findAxesPoints_Recursive (currentAxesPoint)
{
Find out the candidate points based on the probing sphere defined by currentAxesPoint;
        If the number of the candidate points is zero,
          then return;
        Else
                {
                        For each candidate point
                        {
                                Add the current candidate point into the list of axes points;
                                Update currentAxesPoint with the current candidate point;
                                findAxesPoints_Recursive(currentAxesPoint);
                        }
          }
}
```

Figure 1 : The pseudocode of the recursive function f*ind AxesPoints_Recursive (currentAxesPoint)*

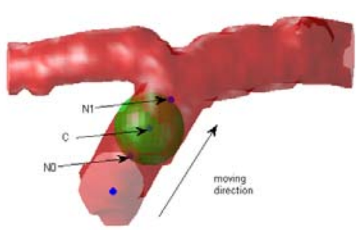

Figure 2 : The moving process of probing sphere

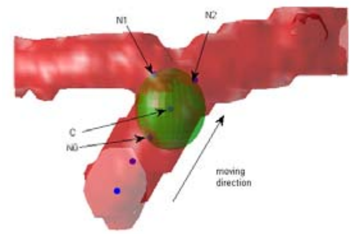

Figure 3 : The moving process of probing sphere with bifurcation

The process of moving the probing sphere is demonstrated in Figure 2, where blue points represent the detected axes points; C stands for the current axes point representing the barycentre of the probing sphere; and $N0$ and $N1$ are two points that have the maximum values of function ϕ on the surface of the current sphere. However, $N0$ is not in the direction of movement of the current probing sphere, which is discarded.

In Figure 3, the situation of bifurcation is presented. $N1$ stands for the first next axes point which has the first maximum value of function ϕ on the surface of the current sphere; and $N2$ stands for the second next axes point which has the second maximum value of function ϕ on the surface of the current sphere. Similarly, $N0$ is discarded, as it is not in the direction of movement of the current probing sphere.

EXPERIMENTS AND APPLICATION

The proposed method has been applied to more than ten datasets for extracting the skeleton of vascular structures. We firstly employ segmentation techniques to segment 3D vascular structures from raw medical data. A great many techniques have been proposed for various image segmentation problems, ranging from threshold based methods, to pattern recognition based methods, and to deformable model based methods[15]. Among all these methods, the active contour model[16]is undoubtedly one of the most attractive approaches in the past two decades. Figure 4 shows a segmentation example of cerebral vasculatures from 3-D MRA images with a resolution of $352 \times 448 \times 114$ and spacing of $0.49\text{mm} \times 0.49\text{mm} \times 0.80\text{mm}$ using the localized hybrid level-set model[17].

Figure 4 : Segmentation result of cerebral MRA dataset using the localized hybrid level-set model (from [17])

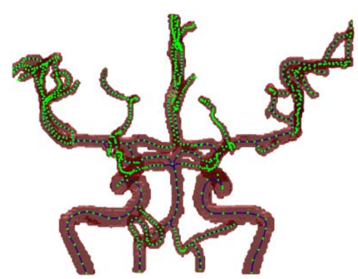

Figure 5 : Skeleton extraction of segmented vessel tree from MRA cerebral dataset

Once the 3D vascular structures have been segmented, their skeleton can be easily extracted using the proposed algorithm in Section 2. Figure 5, Figure 6, and Figure 7 demonstrate some typical examples of skeleton extraction of vessel trees segmented from 3-D medical datasets. Green points represent the extracted axes points, and smooth blue curves represent the skeletons approximated from the axes points by spline function.

Figure 6 : Skeleton extraction of segmented vessel tree from liver portal vein dataset

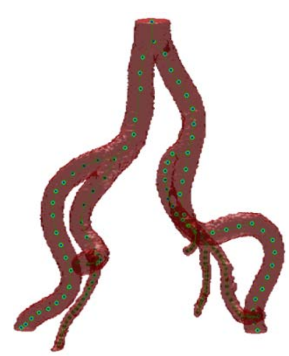

Figure 7 : Skeleton extraction of segmented vessel tree from MRA abdominal aorta dataset

The extracted skeleton is crucial for the reconstruction of vasculatures, as the skeleton-based reconstruction is regarded as the most natural option to efficiently construct the complete vascular structure[18]. Various skeleton-based methods have been proposed for reconstructing vasculatures from a segmented dataset. Figure 8 and Figure 9 present some reconstruction results based on a recently developed skeleton-based implicit modelling method[19]. As can be seen from the figures, the skeleton-based method can correctly represent the morphology and topology of vascular structures. In addition, very thin branches and curved, complex structures can be reconstructed faithfully.

Figure 8 : The reconstruction of liver portal vein using skeleton-based modeling method

Figure 9 : The reconstruction of MRA abdominal aorta using skeleton-based modeling method

The extracted skeleton is very useful for the topology description and user interaction of vascular structures. For instance, in[20], we utilize the pre-extracted skeleton as the camera path for the automatic navigation of virtual angioscopy. As shown in Figure 10, the camera moves along the skeleton, and the target point is set to a fixed distance ahead on the skeleton so that the camera can smoothly follow each vessel segment.

Figure 10 : Virtual Angisocopy using the pre-extracted skeleton as camera path: (left) 3-D overview of reconstructed vessel tree with skeleton (green arrow represents the current position and direction of virtual camera), (right) perspective view inside the vasculatures (blue line represents the ongoing camera path) (from[20]).

CONCLUSIONS

Topology analysis and user interaction of vascular structures is crucial for the area of computer-aided vascular surgery, including virtual angioscopy, vascular surgery planning and computer guided vascular surgery. However, unlike other human organs, the vasculature system is a very complex network of vessel, which makes it a changeling task to deal with 3D vascular models directly from segmented vascular datasets for topology analysis and user interaction. A better way to represent and analyse the topology of vasculature is to use its skeleton curve.

The paper presents a simple and fast algorithm to extract the skeleton of vascular structures from segmented vessel datasets. Our algorithm is based on a step by step approach to move a small volume of interest along the vessel tree. In our method, Fast marching method is firstly employed to initialize the segmented vessel data to be Signed Distance Function (SDF), which guarantees that the closer the point to the vascular axe, the bigger function value; under the condition of SDF, the probing sphere can easily detect the skeleton by moving towards to the point on the sphere with a maximum function value. Experimental results show that the skeleton of vessel trees can be easily extracted from segmented vessel data using our method. In addition, the pre-extracted skeleton is conveniently utilized as the camera path for the automatic navigation of virtual angioscopy, which demonstrates that the extracted skeleton is very useful for the topology description and user interaction of vascular structures.

Our algorithm is simple and easily-implemented; however, it may detect some false bifurcations, especially when two vessels were very close to each other. In this case, we need to adjust the radius value of the probing sphere to predict the correct axes point. In our future work, we will focus on this issue and improve our algorithm to be more robust.

ACKNOWLEDGEMENT

This work is supported by the Fundamental Research Funds for the Central Universities (Grant No. 2013121030), projects from National Natural Science Foundation of China (No.61100106, No.61402389), and MOE (Ministry of Education in China) Project of Humanities and Social Sciences (Grant No. 11YJC870027). Part of this research work has been presented as a poster at the 5th International Conference on Graphic and Image Processing[21].

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