Virtual Angioscopy Based on Implicit Vasculatures

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Abstract. Virtual endoscopy is among the most active areas in medical data visualization, which focuses on the simulated visualizations of specific hollow organs for the purposes of training and diagnosis. In this paper, we present a virtual angioscopy technique based on vasculature geometry reconstructed using skeleton-based implicit splines (SIS). The highly accurate implicit representation of the vasculature not only makes it possible to achieve high visual quality of perspective view inside the vessel structures, but also makes the implementation of an interactive virtual angioscopy a much easier task, as the issue of collision detection of virtual camera with vascular objects can be easily solved when the vasculature is represented in implicit form. Some experiments have been carried out to demonstrate the strengths of our technique.

Keywords: Virtual endoscopy, Virtual angioscopy, Implicit modeling, Interactive navigation.

1 Introduction

Virtual endoscopy is one of the most active areas in medical data visualization. It is a kind of non-invasive diagnosis technique and has no direct deleterious effects on patients [1]. It uses computers to process 3D image datasets to provide simulated visualizations of specific hollow organs, similar or equivalent to those produced by standard endoscopic procedures [2]. This technique has been applied to virtual colonscopy [3,4], bronchoscopy [5], ventriculoscopy [6,7], and so on. Virtual angioscopy [8,9] is a specialized virtual endoscopy technique for exploring the human vascular systems, which generates an interactive environment for the vascular examination from a point of view inside the vessels [10]. Virtual fly-through of vascular structures is a useful technique for educational purposes and some diagnostic tasks, as well as intervention planning and intraoperative navigation [11]. In such a virtual visualization system, it is usually essential to combine the detailed views of the inner structures with an overview of the anatomic structures.

Virtual angioscopy requires a relatively high visual quality of perspective view inside the datasets for the purposes of training and diagnosis. One of the common approaches for the visualization of a virtual angioscopy is surface rendering, yielding images close to a real endoscopy. However, the direct application of

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surface rendering algorithms (i.e. Marching Cubes [12]) to the segmented vasculatures may suffer from the typical diamond artifacts caused by the trilinear interpolation [1]. Therefore, the smooth and accurate reconstruction of vascular tree is very crucial for virtual angioscopy. In this paper, we use implicit surface to represent the vascular structures, which is reconstructed using a skeleton-based implicit reconstruction technique [13], for the virtual angioscopy system. Our method can achieve high quality perspective views as well as accurate cross sections, which is suitable for training purposes as well as diagnosis tasks. Furthermore, based on the implicit modeling technique, the collision avoidance for the camera navigation of virtual angioscopy, a key problem for implementing interactive navigation of a virtual vascular system, can be easily solved.

2 Related Work

The major issues associated with virtual endoscopy are the perspective rendering techniques and the camera navigation paradigms.

2.1 Perspective Rendering Techniques

Generally, the rendering techniques for virtual endoscopy fall into two categories: surface rendering and volume rendering. Surface based rendering typically extracts surfaces by fitting geometric primitives, such as polygons or patches, to constant-value contour surfaces in volumetric datasets [14]. It has been widely applied for virtual endoscopy because of its high rendering speed. In addition, the extracted surface, containing the space-relation information, is very useful for the navigation of virtual camera. Many current virtual endoscopy systems, such as VESA [15], VirEn [16], 3D Slicer [17] and FreeFlight [18], are based on the surface rendering technique. However, the general visual quality based on surface rendering is comparatively poor. Particularly, the direct isosurface rendering for the segmented dataset may suffer from the diamond artifacts caused by the trilinear interpolation [1]. Therefore, the smooth and accurate reconstruction of segmented results is very crucial for surface rendering-based virtual endoscopy.

Compared to surface rendering, volume rendering (sometimes called direct volume rendering) is a technique for directly displaying 3D sampled datasets in the form of 2D projection, without the intermediate geometric primitive representations used by surface rendering [14]. Generally, the volume rendering techniques, such as ray casting [19] and splatting [20], can generate higher visual quality results for virtual endoscopy. However, the frame rate they can achieve is relatively low, which requires accelerating algorithms for real time rendering. On the other hand, the texture mapping-based volume rendering [21] needs additional support of high-performance graphics hardware. There are several virtual endoscopy systems based on volume rendering, such as VI VoxelView [22] and CRS4 [23]. However, in the case of virtual angioscopy, when the vascular structures are rather small, the direct application of volume rendering techniques usually leads to severe aliasing artifacts [24]. In addition, as stated in [25] the surface rendering technique was statistically significantly better in visualizing subependymal arteries, cranial nerves, and other lesions.

2.2 Navigation Paradigms

Besides rendering, the camera navigation paradigm is another key problem required to be solved for the development of a virtual endoscopy system. It includes the interaction of the user to control camera movement, as well as the operations of mapping the input device movements to camera parameter modifications. The user should get neither a "lost-in-space" feeling nor a frustration feeling due to a heavily constrained navigation environment [26].

Various virtual endoscopy techniques can be roughly classified into three classes: automatic navigation, manual or free navigation and guided navigation [3]. With automatic navigation, the user defines a certain number of key frames where camera parameters are specified. Smooth camera movements between the key frames are calculated automatically. The drawback of automatic navigation is the lack of interactivity, which means that user interaction is limited and the irrelevant regions cannot be easily skipped [1]. By manual navigation, user can completely control over all parameters of the virtual camera without any constraints. However, the method needs to performance collision-avoidance scheme, which requires costly query operations. In addition, in contrast to automatic navigation, free navigation requires a highly interactive rendering technique, since a significant lag between interaction and rendering will severely disturb the user's interaction [1].

This guided navigation is between the two previous methods, which combines user's guidance with an efficient collision-avoidance scheme [1]. The user controls over the camera parameters but some constraints are added, such as keeping the position of the camera to the optimal path. For example, Vilanova et al. [26] have described a guided navigation system where the location of the camera is fixed to a pre-computed path, while the camera orientation can be selected freely. Another typical system is Hong et al.'s virtual voyage [3], which employs several potential fields and kinematic rules to guide the virtual camera along the human colon. Although this kind of technique can achieve higher frame rate because of the efficient collision-avoidance scheme, the user's interaction is still limited due to the additional restrictions. In addition, the generation of potential fields has the potential risk of changing the morphology of the anatomic structures (we will explain this more detail in section 4). While based on the implicit vascular geometry, the collision avoidance for the camera navigation of virtual angioscopy can be easily solved without additional generation of potential fields, since the constructed model is an connatural implicit volume, which is a favorite kind of geometric object when performing collision detection [27].

3 Virtual Angioscopy

For our virtual angioscopy system, we basically follow the standard processing pipeline [10] (see Fig. 1). Firstly, segmentation technique has been employed to

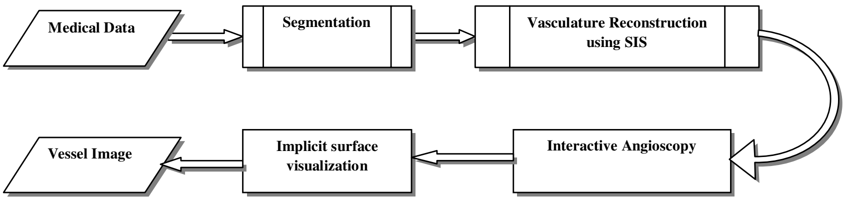

Fig. 1. Pipeline for our virtual angioscopy system

extract the vessel structures from standard 3D medical datasets, such as CT or MRA images. Secondly, in order to achieve high visualization quality, we adopt our skeleton-based implicit splines (SIS) modeling technique [13] to accurately and smoothly reconstruct the vasculatures from the segmented discrete vascular surface points. Based on the implicit vascular geometry, the virtual camera can be automatically or freely navigated along the vascular tree and acquire high-quality perspective view inside the vessel structures.

3.1 Accurate Vasculature Reconstruction Using Skeleton-Based Implicit Splines (SIS)

In this section, we will briefly introduce the technique of accurate vasculature reconstruction using SIS. For more details, please refer to our another paper [13]. This technique is based on an implicit surface modeling method that has been developed to model generalized cylinders. In this implicit generalized cylinders modeling method, the freeform cross-sections are first reconstructed implicitly using the 2D piecewise algebraic splines [27], and then, different cross-section profiles are weighted and summed up along the skeleton using the Partial Shape Preserving (PSP) spline basis functions, the 1D version of 2D piecewise algebraic splines. In addition, the smooth piecewise polynomial blending operations [28] is employed to blend the branches of implicitly constructed generalized cylinders together. This approach can construct a smooth, continuous and analytic surface. The proposed method has been applied to actual 3D medical data for the reconstruction of vasculatures. Direct visual experimental results demonstrate that this method can correctly represent the morphology and topology of vascular structures. In addition, qualitative and quantitative analysis have been performed for validating the accuracy and smoothness of the reconstructed results.

As can be seen from the Fig. 2 and Fig. 3, a visual comparison between our reconstruction results and the segmentation results gives us the first evidence that the method based on SIS can correctly represent the morphology and topology of vascular structures. The isosurface rendering of segmentation results (left column) suffers from strong aliasing artifacts like staircases, which has a strong divergence with realistic vessels and might hamper the visual interpretation of the vessel surface [24]. In contrast to the direct visualization of segmentation

Fig. 2. The reconstruction of MRA cerebral vessels: (left) the isosurface rendering of segmentation result, (right) the reconstruction result using SIS method

Fig. 3. The reconstruction of liver portal vein: (left) the isosurface rendering of segmentation result, (right) the reconstruction result using SIS method

result, the approach based on SIS can achieve superior visual quality and produce smooth transitions at branchings (right column). Indeed, the SIS method can guarantee the same high geometric continuity, as the reconstruction method that based on the convolution surfaces [29]. Furthermore, the SIS technique can achieve more accurate vessel surfaces since it is constructed without model assumptions. Generally, the SIS method can achieve quite smooth and accurate vessel surfaces. Compared with the direct visualization of segmented result, the vascular structures reconstructed by the SIS method are more faithful to the realistic vessels.

3.2 Interactive Angioscopy

As discuss above, virtual angioscopy requires high visual quality of perspective view inside the dataset. The general surface rendering techniques for segmented datasets are not sufficient to generate high-quality visualization. On the other hand, by using SIS modeling technique, the segmented vasculatures can be represented as an analytic implicit function. Based on this implicit function, we can render high-quality vessel surfaces with any required continuity and smoothness. Besides the high-quality perspective views, we can also achieve accurate cross sections, since our method is without model assumption.

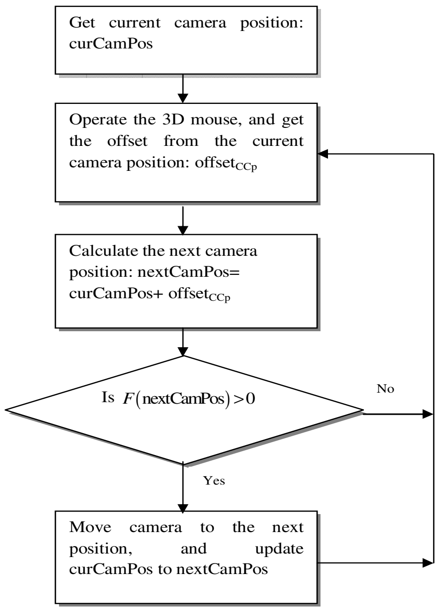

Fig. 4. The flowchart of the manual navigation of virtual camera

For the navigation of camera, we can achieve efficient collision avoidance without the additional generation of potential fields, since the SIS method can guarantee to define an implicit volume by replacing the equality of Eq. 7 in [13] with an inequality:

$$F(x, y, z) = f(X(x, y, z), Y(x, y, z), Z(x, y, z) \geq 0 \qquad (1)$$

That is, the vasculatures are represented as a global implicit function $F(x, y, z)$. When $F(x, y, z) = 0$, it represents the vessel surfaces; when $F(x, y, z) > 0$, it represents implicit volume inside the vessel structures; and when $F(x, y, z) < 0$, it represents the implicit volume outside the vessel structures. The implicit volume is a favourite kind of geometric object when performing collision detection [27]. When the vasculatures are modelled as implicit volume, one can tell directly whether a point lies inside or outside the vasculatures and the problem of collision detection can be easily solved [30]. In other words, $F(x, y, z)$ is a kind of signed distance function (SDF) [31], which guarantees that the closer the point to the vascular axe, the bigger the value of function $F(x, y, z)$.

Fig. 4 demonstrates the flowchart of the manual navigation of virtual camera inside the vasculatures. By operating the 3D Mouse (`http://www.3dconnexion.com/index.php`), the next camera position can be easily calculated. And then, we test the implicit function value: $F(nextCamPos)$. If $F(nextCamPos) > 0$, we suppose the new pre-computed camera position is inside the vasculatures, and we move the camera to the new pre-computed position and update the current camera position. Otherwise, new pre-computed position is outside the vasculatures, which requires the re-operation of 3D mouse.

4 Results

The presented virtual angioscopy system has been applied to the 3D CT angiography (CTA) images of carotid artery, the 3D magnetic resonance angiography (MRA) images of cerebral artery and abdominal aorta supplied by Intelligent Bioinformatics Systems Division, Institute of Automation, the Chinese Academy of Sciences, and the segmented liver portal vein obtained from the public resource (`http://www.ircad.fr/softwares/3Dircadb/3Dircadb1/index.php`)(see Table 1). Based on the reconstruction of vasculatures using SIS, we can easily examine the interior of the vascular systems using the technique of virtual endoscope.

Table 1. Summary of characteristics of the datasets. Voxelsizes are given in millimeter.

Dataset	Resolution	Voxelsize
CTA carotid artery	$512 \times 512 \times 206$	$0.52 \times 0.52 \times 0.63$
MRA cerebral vessels	$352 \times 448 \times 114$	$0.49 \times 0.49 \times 0.80$
MRA abdominal aorta	$512 \times 512 \times 310$	$0.70 \times 0.70 \times 0.63$
Segmented Liver portal vein	$512 \times 512 \times 151$	$0.78 \times 0.78 \times 1.60$

The skeleton of the vessel has been extracted during the process of reconstruction, thus, it is convenient to implement the automatic navigation mode of virtual angisocopy using the pre-extracted skeleton as camera path (see Fig. 5). 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.

As discussed in Section 3, compared to the direct application of surface rendering algorithms (i.e. Marching Cubes) to the segmented vasculatures (see Fig. 6 (right)), based on the SIS modeling of vasculatures, the surface rendering methods can achieve much higher quality perspective views as well as accurate cross sections (without model assumption) (see Fig. 6 (middle)), which is suitable for training purposes as well as diagnosis tasks.

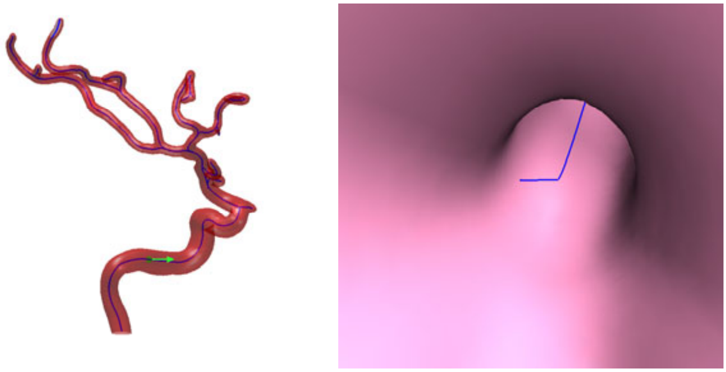

Fig. 5. Virtual Angisocopy using the pre-extracted skeleton as camera path: (left) 3D overview of reconstructed vessel tree with skeleton (green arrow represents the current position and direction of virtual camera), (right) perspective view inside the vasculatures (blue line represents the ongoing camera path)

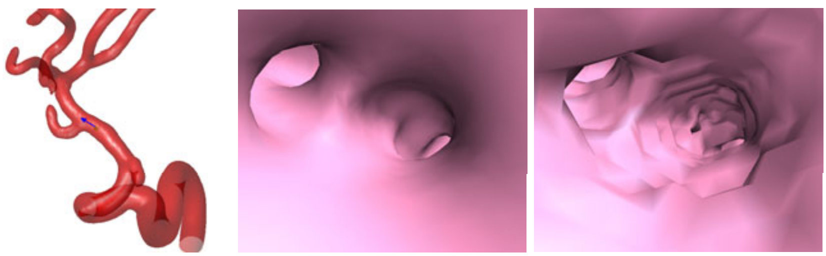

Fig. 6. Virtual Angioscopy: the overview of the vessel structures, and the arrow indicating the current position and orientation of the camera (left), the perspective view inside the vessel based on our implicit modeling vasculatures (middle), and on direct application of Marching Cubes to the segmented vasculatures (right)

For the free or guided navigation mode of virtual angisocopy, the generation of potential fields is required for achieving efficient collision avoidance. However, the generation of potential fields has the potential risk of changing the morphology of the anatomic structures. For instance, we generate the distance field coding the distance to the vascular surface using the fast marching method [32], which has changed the surface morphology of vessel (see Fig. 7 (top right), the vessel surface is not as smooth as that before the generation of distance field). Accordingly, the changes of vessel surface morphology would greatly influence the visual effect of perspective rendering inside the vasculature (see Fig. 7 (bottom right)). On the other hand, as stated in Section 3.2, we can easily achieve efficient collision avoidance based on the constructed implicit function, without the additional generation of potential fields. In addition, by taking the advantages of 3D mouse, the position and orientation of camera can be freely controlled, without the limitations of traditional input devices with limited degrees of freedom. The

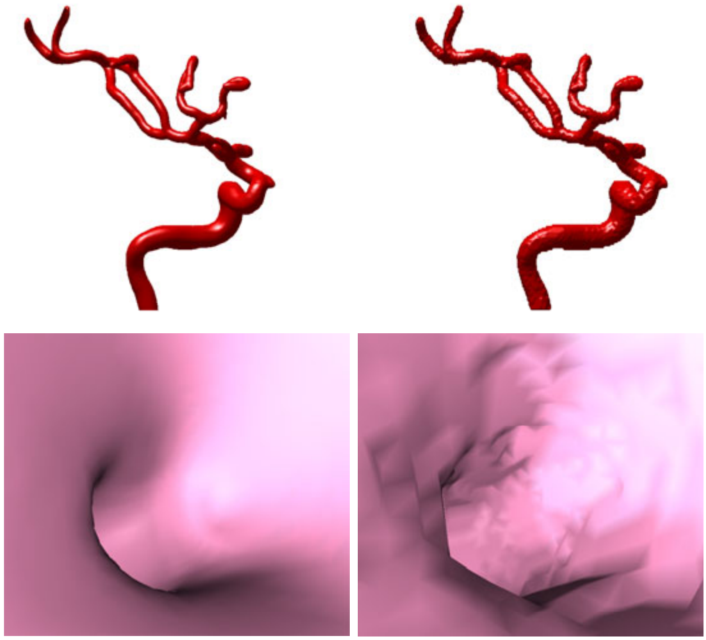

Fig. 7. The side effect of generating distance field: (top left) and (top right) are the surface morphology of vessel before and after generating distance field, and (bottom left) and (bottom right) are perspective views inside the vasculatures based on (top left) and (top right)

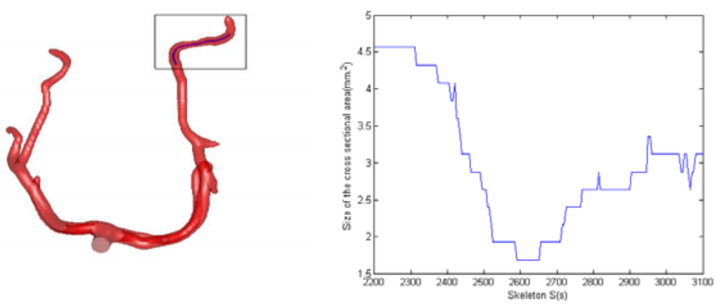

Fig. 8. The diagnosis of vessel stenosis: (left) the overview of the vessel suspected to suffer stenosis, (right) the accurate diagnosis by calculating the distribution curve of the size of the cross sectional area

users can achieve an immersive experience of flexible and effective exploration of the interior of the vascular tree, since they can easily and freely move the camera closer to an object and inspect the region of interest by changing the viewpoint.

For the purpose of diagnosing vessel stenosis, the area quantitative analysis of cross section is necessary, since the visual observation is not adequate for accurate diagnosis. For instance, as shown in Fig. 8 (left), the vessel segment in rectangle is suspected to suffer stenosis from a general overview of the vasculature. Based on our system, the accurate diagnosis can be easily achieved by exploring along the skeleton of the vessel segment to acquire the distribution curve of the size of the cross sectional area (see Fig. 8 (right)). The horizontal axis is the parametric curve $S(s)$ representing the skeleton of the vessel; and the vertical axis represents the size of cross-sectional area for the corresponding skeleton. For normal vessel, according to the surgeon's opinion, the size of the cross-sectional area should in general change gradually along a branch skeleton; while in this case, the size of the cross-sectional area change sharply, which is supposed to be suffering stenosis.

5 Conclusions

Due to the complex nature of vascular structures, it is essential to combine the detailed views of the inner structures with an overview of the anatomic structures. Virtual angioscopy (VA) technique provides us an interactive environment for exploring the human vascular system. The smooth and accurate reconstruction of vascular tree is very crucial for virtual angioscopy, since it requires a relatively high visual quality of perspective view inside the dataset for the purposes of training and diagnosis. In this paper, we present a virtual angioscopy system based on implicitly reconstructed vasculatures using SIS. Compared to the direct application of surface rendering technique to the segmented datasets, our method can achieve much higher visualization quality as well as accurate cross sections. In addition, interactive camera navigation can be easily implemented as it is very simple to perform camera-vascular wall collision detection, since the vascular geometry is represented as implicit surfaces.

The use of virtual angioscopy has several benefits. First and foremost, compared to real endoscopy, it is non-invasive or at least minimally invasive, which can provide insights into some vessel parts that might be difficultly accessible to current medical procedures. It can be easily applied for educational purpose, which provides unusual insights into the vessel of living patients. In addition, it has the potential benefits for non-invasive evaluation of vascular diseases [33]. In our VA system, the free navigation mode allows high-precision manual analysis of the vasculature under various viewing angles and better dynamic localisation of abnormalities. Furthermore, the area quantification of cross section can be easily achieved for the purpose of diagnosing vessel stenosis. However, VA has not yet been extensively evaluated. In the future, clinical evaluation of our system on vascular diseases needs to be performed. And its integration into the actual surgical intervention as a navigation aid is also a challenge for our system.

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