Surface Reconstruction Of The Branching Vessels For Augmented Reality Aided Surgery

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Abstract. This paper describes our work on the reconstruction of the complex liver vessel tree. We demonstrate our method for constructing an arbitrary smooth polygonal representation based on subdivision surfaces using vessel centerlines and radii as input.

1 Introduction

Surgery of the human liver is a complex task. It requires a good understanding of the patient specific anatomy of the liver vascular system, since the success of the liver resection depends on the accurate localization of the vascular tree segments in the liver body. Visualization techniques improve the preoperative surgery planning [1], augmented reality approaches can enhance the quality of the intervention by providing a real-time overlaid view of these structures correctly mapped to the surgeon's view. In our ARAS (Augmented Reality Aided Surgery) project [2] we enhance the surgeon's view of the patient's body by an overlaid 3D model of the liver vessels. This model has to be reconstructed from pre-operative CT data.

To guarantee a high frame rate of the vessel tree display on standard graphics hardware, we employ an optimized polygonal model of the vessel tree. This paper describes the generation of this model from the vessel tree centerlines with associated radii.

A two-step approach is used: First, a rough surface model is generated. Then this model is smoothed by a piecewise smooth subdivision surface generator based on Catmull-Clark subdivision [3, 4]. Our new recursive approach solves multiple branching in the rough model in a simple an elegant way. After subdivision, it delivers a smooth surface with smoothness given by the subdivision level.

2 Methods

Segmentation of the CT data delivers vessel centerlines at sub-pixel precision together with radii in each point [5]. For visualization purposes, the vessel centerline is down-sampled the to the resolution comparable to the vessel diameter.

A local coordinate system is then computed for each point in the down-sampled dataset. One coordinate axis is computed as the average of directions of incoming and outgoing line segments. The second coordinate axis, the up-vector, is randomly generated at the vessel root and then propagated along the tree. This propagation reduces axial twists of the surface mesh. For this propagation, the up-vector is projected to the following cross-section plane.

At the branching points, the outgoing vessel segments are classified according to their angles to the already computed average direction. The segments with obtuse angle ($\geq 90°$) are then processed at the end of the vessel incoming to the branch, i.e., at its last section. The segments with acute angle ($<90°$) are processed while tiling the first section of the segment in the straightest following direction (the outgoing direction closest to the direction of the incoming vessel segment).

The rough quadrilateral surface generation is performed recursively, by four calls of the recursive tiling procedure, where each of the four calls handles one quad. These four directions of the quads are defined by the 90° (90-degree) angle intervals in the cross-section plane, where the direction 0° is determined by the up-vector. If no branching follows in the direction of the quad, the quad is tiled by a quadrilateral surface patch. If any outgoing branch exists in the direction of the quad, the recursive tiling procedure processes the outgoing vessels. It selects the nearest vessel from the subset and tiles it to the current quad of the previously found closest vessel (see an example of a trifurcation in Fig 1. Two outgoing vessels are being connected to the closest vessel at the dark-gray quad in Fig 1a by three light-grey quads in Fig 1b). Then, the remaining vessels in the subset are classified according to the direction of the just processed nearest vessel and the procedure is called recursively for each of the directions (see Fig 1c). As mentioned above, the tiling in each recursive call finishes by drawing a quadrilateral patch if no vessel is outgoing in the just processed quad-direction (see all light-grey quads in Fig 1).

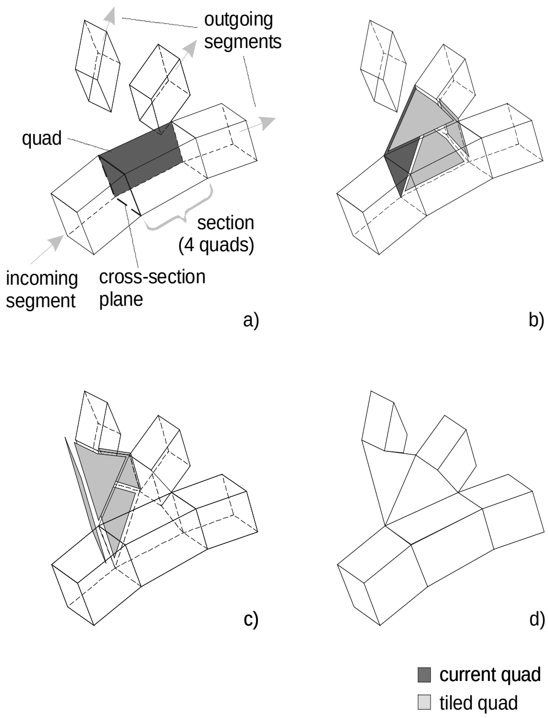

Fig 1. Construction of a trifurcation surface

3 Results

The algorithm is capable to tile complicated tubular structures with multiple branching. An example of the part of the liver vessel tree is in Fig 2. The quality of the branching joint depends on the ratio of down-sampled distance to the local diameter. If this ratio is approximately one, a nice smooth surface is created (Fig 3), if it is too small, the surface overlaps, if it is too large, an unrealistic, “over smoothed” branching is generated (see the bottom part of Fig 2).

The operational and memory complexities of the presented algorithm are linear $O(S + n)$, depending on the number of processed segments n and on the overall number of the input sections S in all segments. As $n << S$, both can be approximated by $O(S)$. See [7] for details.

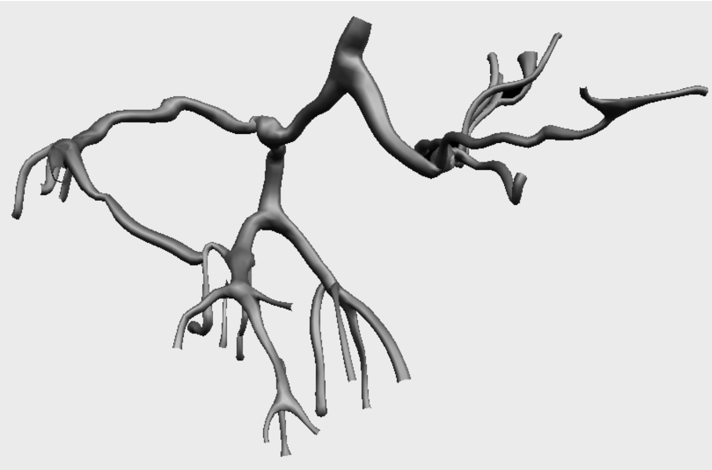

Fig 2. A liver vessel tree

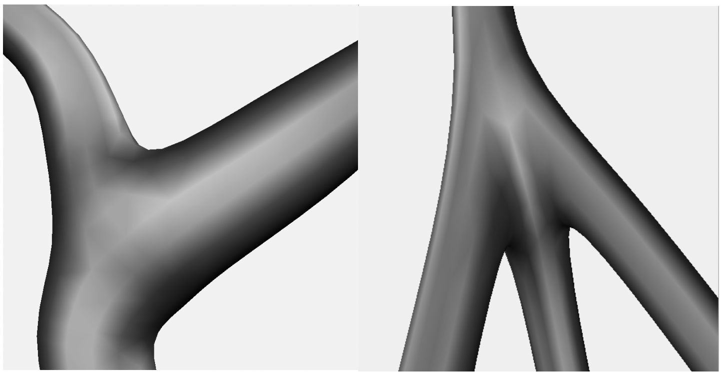

Fig 3. Vessel branching in detail

4 Discussion

The proposed algorithm delivers a topologically correct 2-manifold surface. It exhibits a minimum of axial twists, thereby avoiding constriction artifacts. It can contain self-intersections of the surface if the input data contain too narrow centerlines or overlapping branches. Self-intersections can be avoided by skipping overlapping sections (sections, whose centerlines distance are less than the sum of their radii). This is subject of our current research.

Our approach differs to the method of Hahn et al. [1]. Hahn et al. construct the vessel skeleton by fast region growing followed by the skeletonization and graph analysis. We track the vessels by means of the two-point vessel-tracking algorithm after an interactive setting of the vessel end points [5]. The centerline graph is constructed simultaneously during the interaction. We also use simpler filtering for the down sampling of the vessel centerline points. A substantial difference is in the surface model used for vessel visualization – Hahn et al. use an extension to OpenGL, `GLExtrusions` for vessel branches display. Our approach constructs a complete mesh without discontinuities at branching points. Therefore we can apply known mesh simplification algorithms (e.g. [6]) to optimize the display performance, which is critical for our application in the field of augmented reality. For further details about the rough mesh construction, see [7].

5 Conclusions

The presented algorithm constructs a topologically correct surface of branching tubular structures (in this case a vessel tree) defined by its centerline and radii. It can handle a complex multiple branching via a new recursive tiling scheme. The surface tiling is done in two steps: At first, the “quadratic” base mesh is generated. This mesh is then subdivided by means of Catmull-Clark subdivision scheme, which results in a smooth, topologically correct “watertight” surface.

We are working on a preprocessing step to avoid self-intersections when incorrect input is processed and when the outgoing branching vessels overlap.

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