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Vessel surface generation for surgical simulations

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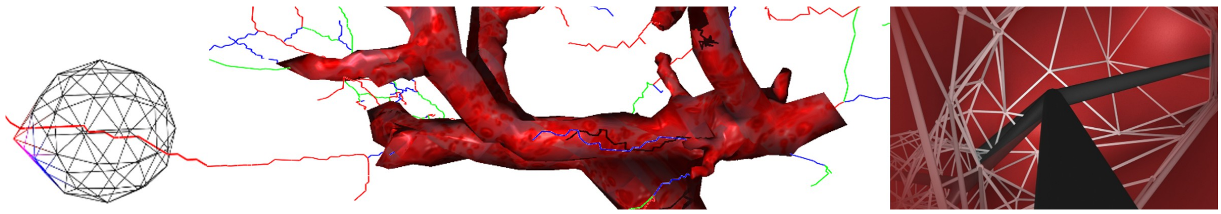

1. Introduction

In medical visualization, it is important to know the location of vascular structures. This information can be acquired from medical image data, such as computed tomography angiography (CTA) or magnetic resonance angiography (MRA). In medical planning systems and real-time visualization applications vascular structures are commonly represented by their centerline to reduce complexity. This is often used for dynamic simulations, like surgery simulators. For visualization, a surface has to be generated, where truncated cones are commonly used. The triangular properties fulfill the requirements of dynamic simulations, but they provide surface intersections at the vessel branches. These intersections are visible if the vessels are moved and are not appropriate for interior views.

We present a method to generate the surface for a centerline representation of vascular systems, for use in dynamic simulation and interactive visualization with a low resolution approximation and soft transitions at the branches.

2. Related works

Skeletons are an efficient way to represent complex shapes by their centerline. One application is to use skeletons to detect similarities in shapes by comparing the shape skeletons [ZRM08]. From a geometrical perspective, skeletons are branching line sequences. Thus it is a connectivity graph, so that methods from graph theory can be applied to the skeleton for analysis or optimization.

Skeletons of vascular systems can be generated from by various methods. For example, Montanari [Mon69] has introduced an analytical approach to compute the skeleton from polygonal shapes. Another approach in image processing is the computation of skeletons by repeatedly thinning of the shape [Kwo88]. Vincent [Vin91] has introduced an approach using a matrix to analyze neighboring pixels in image space. In [OK95] hierarchic Voronoi skeletons are introduced, which are also applicable to 3D geometries. However they result in very detailed skeletons and require additional filtering of the result to remove artifacts.

Especially in medical applications, skeleton representations are frequently used. The skeleton of a vascular system is used as simplified representation for exchange or to measure the distance between the vessel and other anatomical structures efficiently. Whereas vessels are line representations, a surface must be generated for visualization. A simple approach is to use cylinders for each line segment of the skeleton. Such approximations are efficient for visualization, but they lead to surface intersections at the branches. More advanced approaches, similar to MPU Implicits [NJZ*08] or model-free approaches applied to point-clouds [SOBP07], will prevent intersections but result in high resolution surface approximations and often require fine tunning of several parameters for acceptable results.

High resolution surfaces are adequate in medical planning applications, but are a performance issue in real-time applications such as surgery simulations. In a surgery simulation the emphasis is on organs in many cases and vessels are required to indicate bleedings if an intervention has affected the vessel. Vessels are also required as connections between the organs. In this case a surface has to be generated for visualization. A similar usage is a skeleton with a generated surface for the visualization of ligaments simlar to the ligamentum falciforme. Thus, for real-time surgery simulations a low resolution surface is required. If the vessels are moved during interaction surface intersection at the branches would be visible, so soft transitions at the branches are also needed.

Our method was initially inspired by [SLSK07], where the skeleton of geometries is computed with a deformable model evolution. A deformable model is expanded and the expanding regions, the fronts of the deformable model, are tracked, merged and filtered to obtain the skeleton of the geometry.

3. Approach

We use a small geodesic sphere geometry as initial seed (left image). This seed-primitive is placed on the skeleton acquired from vascular structures of segmented medical images. Similar to region growing, known in image processing, the seed-primitive is iteratively growing, until an approximation of the vessels volume boundary is achieved.

The seed-primitive has a triangular surface. To expand the seed-primitive each vertex $\vec{v}_i$ will be moved by a force $\vec{f}_i$. The force $\vec{f}_i$ is defined in Eq. 1 by the vertex normal $\vec{n}_i$ and the attraction vector $\vec{a}_i$ directed from the vertex position to closest point on the vessels surface. The vessels surface is described implicitly by the skeleton and additional information about the vessels radius in each point of the skeleton.

$$\vec{f}_i = (1-\beta)\vec{n}_i + \beta\vec{a}_i \quad (1)$$

The detail of the resulting surface can be controled by $\beta \in [0,1]$, which controls the influence of $\vec{n}_i$ and $\vec{a}_i$ in $\vec{f}_i$. With more influence of $\vec{n}_i$, he expansion will proceed faster and results in a lower mesh resolution.

If a vertex has reached the surface of the vessel, it has reached its final position and has not to be updated in following iterations. Because the seed-primitive is initially placed in the vessel region with the biggest diameter, vertices can reach the surface and branching vessels, with even smaller diameter cannot be reached.

For further progress, faces intersecting the skeleton are determined and subdivided, so additional vertices are generated at the edge centers of the faces. Thus additional vertices are free to move, so the approximation will proceed. To determine the intersecting faces, only faces that are affected by currently moving vertices have to be considered. This will guarantee, that faces are subdivided, as long as the approximation is not finished and the skeleton is intersecting with the vertices of the approximating surface. The method will terminate if all vertices have reached the vessels surface and no face is intersected by the skeleton anymore.

To gain more detail and less error during approximation, an additional criterion is defined for subdivision. If all vertices of a face have reached the surface and the face is not intersected by a skeleton, we compute the distance between the face center and the vessels surface. If this distance varies significantly the face is subdivided. Because a face-centric subdivision will reduce the resulting mesh quality, the face and its three neighbors are subdivided into ten new faces and three new vertices, which are free to move, so the error is compensated.

4. Results

For evaluation, we were using anatomical data from the livers portal vein. We generated a high resolution surface using marching cubes and the skeleton based on the binary data used for our method.

Our method provides a good approximation with 10% of the faces that marching cubes provides.

To compare the quality and accuracy of the approximation, the high resolution surface provided by marching cubes was reduced to approximately the same resolution. The quality was measured using the edge-metric (ratio longest to shortest edge) and the angular-metric (ratio smallest to biggest angle). Our method could increase the edge-metric by 14% and the angular-metric by 27%.

The presented method is used to generate a surface for skeletons with low resolution and soft branch transitions, that are important in interactive real-time applications.

The resulting geometry can also be used for computational fluid dynamics (CFD). However this was not the main application. For the usage in CFD, additional post-processing has to be done. The quality and resolution of the resulting surface can be adjusted after our method has finished the surface generation. Thus, the method is suitable for CFD. Howerver, the endings of the vessel should be capped, so the caps are orthogonal to the skeleton and neccessary boundary conditions can be fulfilled.

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