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ON SKELETONIZATION OF BLOOD VESSELS IN ANGIOGRAPHIC MRI IMAGES OF HUMAN BRAIN

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Abstract. The aim of this paper is to investigate the main existing 3D skeletonization methods, their properties and particularities with respect to centerline extraction of segmented blood vessels in human brain MRI images. Skeletonization of 3D objects may be performed using different approaches. Basically there are four main concepts of skeletonization algorithms which may be adopted in automatic analysis. In the article we use four algorithms representing each concept and obtain results in the cases of modeled and real vessels extracted from MRI volume. We investigate the main properties of obtained skeletons and formulate essential and preferable properties of 3D skeleton curves. According to visual analysis the most suitable method was selected and motivated.

Keywords: skeleton, centerline, blood vessels, aneurysm, 3D vizualization.

1. Introduction

One of the aims of modern medical image processing is an automatic localization of suspected regions in three dimensional (3D) images of blood vessels of human brain. The main pathologies of blood vessels are stenosis and dilatations (aneurysms). Identification of aneurysm is a complex task even for trained medical specialists. More and more often computer software is used for an automatic analysis of blood vessels of human brain. Exploration of digitally segmented blood vessels is considerably efficient if a 3D reference curve, which is centered and represents complete topology of blood vessels, is known [1]. One of possible ways of obtaining centered reference curve is 3D skeleton extraction.

Morphological skeleton operation is a general tool in digital image processing for detecting centers or centerlines of segmented two dimensional (2D) objects. Skeleton found its applications in data compression, shape analysis, object registration, visualization and other tasks. Standard algorithms for 2D skeleton extraction are based on erosion and dilation operations, however other approaches of obtaining centerline or medial axis also exist. Nowadays 3D image processing becomes relevant. Skeleton of 3D object may be used for extraction of a medial surface or a spatial centerline. 3D skeleton in comparison with 2D one requires much more computational resources and processing stages, especially when skeleton with particular properties is desired to be obtained [2]. The large amount of object's voxels, geometrical complexity and surface noise are the main factors affecting the skeletonization process and the properties of obtained skeleton.

In the article the main 3D skeletonization concepts are analyzed and their properties based on modeled and real segmented vessels of Magnetic Resonance Angiography (MRA) images are clarified. The aim of analysis is to find the most appropriate technique for extraction of centerline of segmented blood vessels and formulate its essential and satellite requirements.

2. Main techniques for 3D skeleton extraction

General definition of 3D skeleton states that skeleton is a set of points which correspond to centers of maximal radius spheres inserted into an object and touching its surface. For primitive spatial objects like cylinder or cone, skeleton matches its geometrical center or medial axis. Most of 3D skeleton extraction techniques work well on primitives however clear differences show up on complex 3D shapes (Fig. 1).

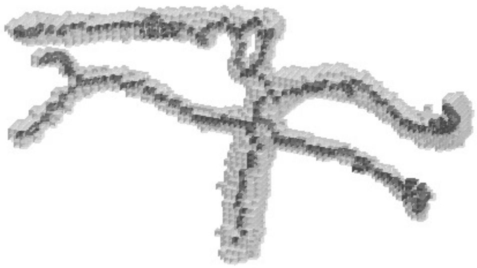


Figure 1. Segmented blood vessel from MRA volume with superimposed centerline found by iterative thining

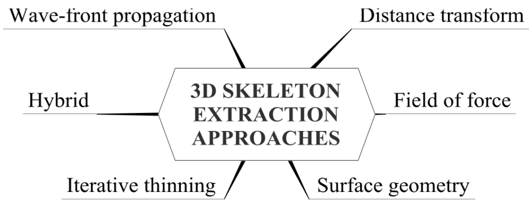
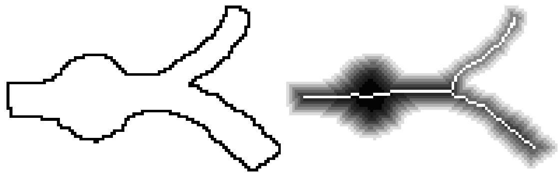


Figure 2. Main techniques for centerline extraction in 3D



(a) *2D object* (b) *distance field*

Figure 3. Example of the use of distance transform

The main factors affecting the skeleton extraction are the geometrical complexity of an object and a surface noise. Usually for an object like segmented blood vessel the skeleton extracted by inserting spheres has many disadvantages which restrict its application in practice. Fortunately there exist many other methods and algorithms for 3D object skeletonization.

3D skeletonization techniques may be classified into six groups based on the following approaches [1–3]:

- analysis of distance transform field;
- analysis of simulated field of physical force;
- evaluation of surface geometry;
- voxel classification and iterative thinning;
- analysis of simulated wave-front propagation;
- combined (hybrid) analysis.

Received skeletons can be of different type. There are surface skeletons and curve skeletons. Actually, surface skeletons are more generic since they can be reduced to curve skeletons but not vice versa. Importantly, surface skeleton can be applied for 3D image compression because it allows reconstructing the initial object by growing its skeleton. Curve skeletons have even less voxels than surface skeletons and it brings the advantage of using them as centered reference curves representing the topology of an object.

Some methods extract skeleton as a subset of an object voxels defined in discrete space. However other methods extract skeleton in real (sub-voxel) space. Skeletons of real type may be smooth and often they can be vectorized for visualization purposes. Discrete skeletons have limitations for smoothness or centeredness but they can be efficiently defined by a small number of object's voxels.

Finally skeletonization methods may be divided into fully automatic and semi automatic. Automatic methods require several or none input parameters which affect the properties of final skeleton. Semi automatic methods may require a set of human validated parameters. For example, in wave propagation methods it is preferable to manually define one or more reference voxels initially located at the center of an object.

Next we briefly introduce to main approaches of obtaining skeleton from segmented 2D and 3D data.

2.1. Distance transform based methods

Distance transform is an image processing operation which is obtained by coding of image pixels or voxels by the nearest distance to background $d_{\min}$ (for 2D example see Fig. 3).

The definition of distance depends on accepted metric. If Euclidean metric is used, then the distance between two points is calculated as a length of vector. At a particular image location with n coded voxels P_n the central voxels C_{local} are extracted as a subset by the evaluation of local maxima of distance $d_{\min}$.

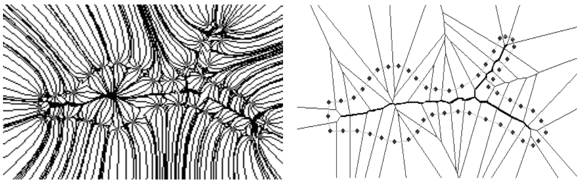
The result of maxima detection severely depends on the method of searching and the evaluation of locality (the size of window, for instance). Often distance field contains clusters of voxels with similar or identical codes. If it is desired to extract thin skeleton, then these clusters must be detected and thinned. The property of skeleton connectivity depends on the method of local maxima detection. If object has a complex shape, then maxima are easily detectable only at particular locations and between them discontinuities may occur. Finally, very detail search of local maxima may detect parasitic ones caused by surface noise. If these maxima are connected to skeleton, then parasitic branches are created. It is a complex task of detecting parasitic branches, especially at topological branches of 3D object.

Generally, distance transform may be implemented with fast algorithms and often distance field is used as supplemental information in hybrid skeletonization methods [3]. Pure distance transform with threshold function is used rarely, however, it works fine on primitive objects.

2.2. Field of force based skeleton extraction

3D object may be modeled as a thin surface on which there are placed point charges. Inside object these charges form a 3D field which may be evaluated by estimating resultant force at particular location. This field has minima at the center points of object (see example in Fig. 4a). Similarly to distance field, skeleton is extracted by searching these minima and connecting them into a curve [4]. Obviously, the evaluation of field distribution requires a huge amount of calculations since every single charge has an influence to a resulting force. From the other side, calculation has a strong averaging effect which raises immunity to surface noise and smoothes the localizations of minima. Moreover, field may be evaluated in sub-voxel space resulting in a sub-voxel skeleton.

The properties of skeleton based on simulated field of force depend on used connection methods. If simple connection techniques are applied then skeleton may



(a) *field of force* (b) *Voronoi diagram*

Figure 4. Example of two other techniques applied to 2D object presented in Fig. 3a

have a number of discontinuities and parasitic branches including loops. Only sophisticated connection methods may lead to obtaining smooth, continuous skeletons.

2.3. Skeletonization based on object geometry

Another technique of skeleton extraction is based on the evaluation of geometry of object surface. It is possible to approximate the surface by using primitive geometrical shapes like triangles. Approximation may be done using Voronoi diagrams (for illustrative example see Fig. 4b). In that case it is assumed that voxels of object's surface are generating points (nodes) and medial axis may be extracted as a sub-graph of Voronoi diagram [5]. However, when the surface of the object is noisy, then Voronoi diagram becomes very complex. This leads to complicated analysis of diagram in which discontinuities and parasitic branches may take place.

2.4. Skeletonization through iterative thinning

Centerline of 3D object can be extracted by voxel classification and iterative thinning [11]. Basically, voxels of segmented object can be classified into surface voxels, internal voxels and end voxels. It is possible to iteratively delete surface voxels by the rules preserving connectivity and end points [6, 7]. Iterations are applied until no erasable points exist. Generally thinning methods produce continuous surface skeletons of one voxel in thickness. Additional thinning iterations and rules are required for generation of a curve skeleton with one voxel in thickness. Thinning methods meet with connectivity and thickness requirements however unevenness of the surface has severe influence to smoothness and centeredness of the curve. Parasitic non-topological branches may also appear at the particular complex locations of the segmented volume.

2.5. Wave-front propagation technique

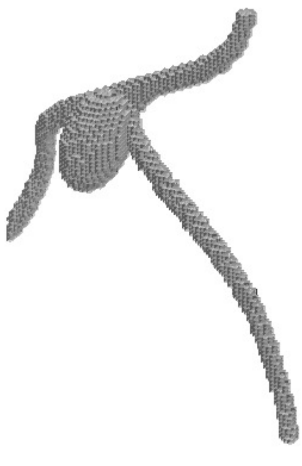
Simulation of wave-front propagation inside object is another coding method where voxels are coded by distance in relation to reference point. In each step, when wave propagates, voxels form clusters (slices) with identical codes. By checking additionally the continuity and neighborhood of clusters it is possible to evaluate branches and loops of an object [2]. However, the more distant are clusters from reference point the more complex they became. Only those clusters near the reference point may be evaluated for center finding. Generally, basic implementation of wave-front propagation does not guarantee a skeleton extraction since it depends on curve construction methods. The requirement of centered reference point and/or end point makes this technique semi automatic. However it found applications in hybrid methods.

2.6. Hybrid skeletonization methods

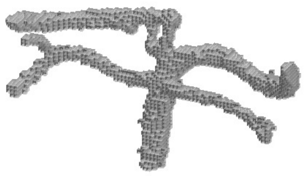
Basic skeletonization methods work well on mathematical 3D models such as cylinder, cube, brick, etc. However skeletonization of real 3D objects often requires much more stages to obtain a desirable curve. One of similar hybrid algorithm is presented in [2]. There are totally of 18 stages which include distance transform, 3D wave propagation, reconnection, pruning, centeredness correction, smoothing, etc. This algorithm as well as many other hybrid algorithms can generate almost ideal centerline, however, they require complex realization, debugging and often they have a vast amount of parameters which must be optimized to particular applications or even to particular data. To avoid the complex optimization, we investigate only stand-alone, non-composite methods.

3. Experimental data and selected methods

Let us examine the main properties of the abovementioned methods in the case of modeled blood vessel and the real vessel (see Fig. 5). The test images are volumes with dimensions $100 \times 100 \times 100$. The total number of voxels in volume of synthetic vessels is 5199, and 3446 in the case of segmented vessels.



(a) *synthetic model of blood vessels*



(b) *segmented blood vessels from MRA volume*

Figure 5. Volume images used in experiments

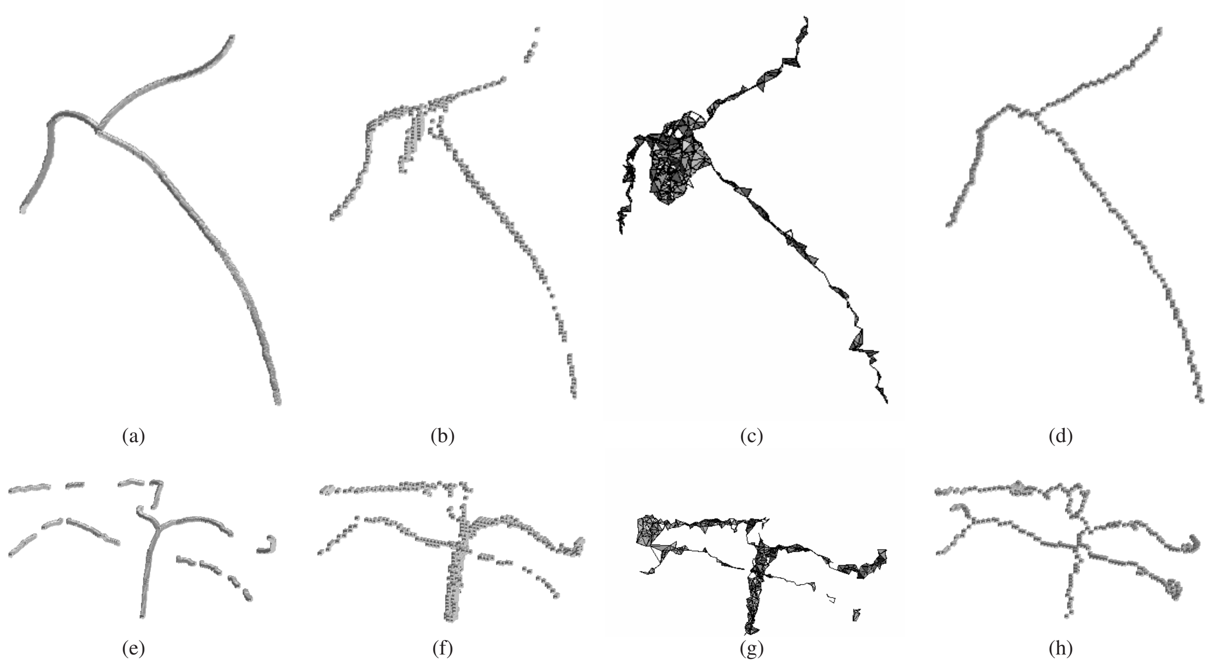


Figure 6. Results of skeletonization of artificial (first row) and natural (second row) blood vessels shown in Fig. 5. Used methods: (a, e) – distance transform; (b, f) – field of force; (c, g) – surface geometry;(d, h) – iterative thinning

There were chosen four algorithms representing distance transform, field of force, surface geometry and iterative thinning approaches. Wave propagation methods are assumed as hybrid which analysis is out of scope of this article. The selected algorithms are applied without post-processing because the quality of centerline severely depends on various post-processing techniques. Final results are obtained by selecting optimal parameters of algorithms which conform to "good" visual results.

In the case of distance transform the simplest way of obtaining center voxels by applying 3D threshold function was applied. There are number of algorithms of field of force and we have chosen one which is described in detail in [4] with its working principles and particularities of application. 3D Voronoi diagram and medial axis extraction was performed according to [5]. In the class of thinning algorithms clearly, described 12-subiteration algorithm [6], which guarantees direct extraction of centerline without additional parameters, was chosen.

4. Results of blood vessel skeletonization

Skeletons obtained in experiments were visually examined for qualitative evaluation of smoothness, discontinuities, centeredness and thickness. As it was shown in [8], some properties of skeletons may be quantified, however numerical estimators are valuable in the cases of modeled data only. In the case of segmented blood vessels such parameters like number of branches, number of end points, angles between branches, rate of branches, branch spacing, etc. only superficially reflect quality of skeleton, especially in the context of further processing.

From the first sight the best visual results are obtained by field of force method. It really generates very smooth, connected and perfectly centered centerline. However it must be noted that field of force method generates data of real type. If a discrete curve is required then coordinates of points must be rounded and connectivity should be tested additionally. In the applied method there were three parameters: strength of field, percentage of convergence points taken and distance of charges to the object. The result severely depends on the values of these parameters. For example, distance of placed charges to the surface of vessel is critical to the connectivity of the centerline. To achieve a good result, the object was dilated by eight 3D dilation iterations. In the case of real blood vessel it was unable to select a set of parameters which guarantee acceptable results. Centerline of segmented vessels has many discontinuities and further change of parameters leads to false connections or to numerous parasitic branches. Strength of field and percentage of taken convergence points have a considerable influence to generation of parasitic branches. Regarding calculation speed, the potential field method takes a long time to calculate the distribution of the field, particularly the result shown in Fig. 6 took approximately 5 minutes to complete on P4/3.4 GHz/1 GB machine.

The result of distance transform method was acquired by coding voxels according to nearest distance to background and then applying threshold of 40 % from the largest value. The main drawback is its sensitivity to the thickness of the vessel which causes the unwanted clusters of voxels either disconnections of the curve at narrow locations. The simplicity of algorithm however leads to very fast execution lasting only milliseconds on a modern computer.

Medial axis extracted from Voronoi diagram is obtained by detecting the central graph. Centerline is composed of connected triangles which are differently oriented in space. To obtain a curve, the diagram still needs additional pruning especially at the locations of branches and dilatations. Moreover, segmented vessels still have a discontinuations which requires reconnection procedures. Execution time of applied algorithm was medium, lasting seconds or so.

Conditions preserving the connectivity (continuity) of an object and saving the end voxels were used in the iterative thinning approach. A single iteration includes testing of surface voxels in all directions. Iterations are finished when no erasable points exist. The magnificence of this method is the absence of parameters since everything is concentrated in the conditions of erasable voxels. The execution time of the method was in the range of one second. The obtained centerline is continuous and one voxel in thickness, however its smoothness and centeredness is worse in comparison to potential field result.

5. Conclusions

1. Existing main 3D skeletonization methods, their properties and particularities with respect to centerline extraction of segmented blood vessels in human brain Magnetic Resonance Angiography images were investigated.

2. Four major skeletonization techniques were experimentally tested with images of segmented blood vessels from synthetic model and from MRA volume.

3. Basing on visual analysis of experimental data, iterative thinning is selected as the most suitable technique for segmentation of blood vessels.

Further study should focus on the improvement of iterative thinning algorithm in order to ensure received centerline smoothness and centeredness.

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