Liver Blood Vessels Extraction by a 3-D Topological Approach

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Abstract. We propose in this paper a new approach to segmentation of 3-D tomography of liver vessel system. The approach is based on a point-wise reconstruction with restriction to simple points manipulation to preserve the homotopy. We propose and compare two dual methods of the vessel system extraction. The efficiency of these methods is demonstrated on a raw X-ray tomography image. The desired level of detail in the vein ramification system is obtained by adjusting one parameter controlling the admitted level of light intensity.
The paper is organized as follows: In the introductory section we present the main principles of the approach using simple points. We explain the algorithm as well as the aspects of efficient computer implementation. Experiment results for different parameter values are given together with discussion and conclusions.

Keywords: Segmentation, simple point, homotopy.

1 Introduction

The proposed segmentation technique is based on a priori knowledge of the processed images. The category of images that we consider in this paper is an X-ray tomography scan of liver. Closer examination of such an image gives a rough idea of the topology, morphology and geometry which is analogous for every human being and varies only in minor changes for each patient. The blood vessel circuitry is composed of bright-textured areas surrounded by darker regions which are also non-uniformly textured. The morphology of the image is due to the used contrasting substance. The substance is most concentrated in the portal vein being therefore the region of the highest luminosity in the image. The healthy part of liver, fairly flooded with the contrasting substance appears somewhat darker. The non-flooded liver lesions appear in the image as dark areas.

The vessel system flooded with the contrasting substance is composed of one voluminous portal vein which develops into thinner ramifications. The vessel circuitry forms a system without cycles [Sol98]. The conclusions on the topology are immediate: the vessel system is a simply connected object without cavities and holes and forms itself a cavity in respect to its complement.

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The principle of the segmentation techniques proposed in this paper is based on the hypothesis that the resulting object is simply connected, contains no holes and no cavities. The resulting object is reconstructed by iterative adding simple points which ensures preservation of topology. During the reconstruction procedure we process the points in the order determined by their luminosity. The advantages of our methods is the ability to give a result that is thin, rich in detail and topologically correct. The methods complete in one phase and do not require any pre-treatment nor any subsequent correction.

The paper is organized as follows: In the introductory section we present the main principles of the approach using simple points. We explain the algorithm and also give the aspects of efficient computer implementation. Experiment results for different parameter values are given together with discussion and conclusions.

The segmentation techniques presented in this paper are new and have not yet been published.

2 Basic Notions

We present some basic notions of 3-D topology needed to outline the principles of the algorithm, see also [MR80], [BM94].

A 3-D *grey-scale image* is an application $\mathbb{Z}^3 \rightarrow \mathbb{N}$. A point $x \in \mathbb{Z}^3$ is defined by (x_1, x_2, x_3) with $x_i \in \mathbb{Z}$. We use the following neighborhoods: $N_6(x) = \{y \mid \sum_{i=1,2,3} |x_i - y_i| = 1\}$, $N_{26}(x) = \{y \mid \max_{i=1,2,3}(|x_i - y_i|) = 1\}$. The points x, y are said to be *n-adjacent* (or *neighbors*) for $n = 6, 26$ if $x \neq y$ and $x \in N_n(y)$. We use 26-adjacency and 6-adjacency for the object and the background, respectively, see also [KR89].

Let $X \subset \mathbb{Z}^3$. An *n-path* γ, $\gamma \subset X$ is a sequence of points $x_0, \ldots, x_k$, where $x_i \in X$, $\forall i = 0, \ldots k$ and x_i is n-adjacent to x_{i+1}, for $i = 0, \ldots, k-1$. We say that a path is closed if $x_0 = x_k$.

To introduce the notions of hole and simply connected object we need to outline the notion of path deformation. For exhaustive definition see Bertrand and Malandain [BM94]. Let γ and γ' be two paths. We will consider γ' an *elementary deformation* of γ if γ and γ' are identical with the exception of a little neighborhood. This neighborhood depends on the used connectivity. A non-elementary deformation of a path is obtained by successive applications of elementary deformations.

An object $X \subset \mathbb{Z}^3$ is said to be *n-connected* if for any two points $x, y \in X$ there is an n-path γ, $\gamma \subset X$ from x to y. An object X is said to be *simply connected* if every possible path γ, $\gamma \subset X$ can be reduced by successive deformations to a single point. We say that there is a *hole* in X, if there is a closed path contained in X that cannot be deformed in X to a single point.

A *cavity* in X is a finite and isolated connected component of $\overline{X}$.

A *simple point* $x \in X$ is a point the deletion of which doesn't change the topology of the object X. Bertrand and Malandain [BM94] have proposed a characterization of simple point based on calculation of connected components

Fig. 1. 2-D slice cut from a 3-D tomography scan of liver. The vessels appear as bright areas whereas the liver lesions as dark ones.

in the neighborhood of the point. A point of a cubic grid is simple if in the neighborhood of the point there is exactly one connected component of the object and exactly one connected component of the complement. Recall that different connectivities must be used for the object and for the complement.

The test whether a particular point is simple or non-simple is implemented using a fast algorithm based on binary decision diagrams [RM96]. This algorithm decomposes the neighborhood of the point to a decision tree. The complexity of this algorithm is constant in time and requires 26 tests (26 neighbors of the point) in the worst case.

3 Principle of the Segmentation Algorithm

The principle is analogous to the 3-D hole closing algorithm by Aktouf *et al.* [ABP96] and is based on iterative point-wise growing restricted exclusively to simple points. The growing is done preferentially with the points of the same or resembling luminosity. If the object is bright, surrounded with darker background then the growing proceeds with the bright points first.

The constraint of processing exclusively only simple-points ensures the homotopy. However, during the iterations of the object growing some points having once been classified as non-simple may become simple later on. This happens due to modifications in the neighborhood. The algorithm is conceived in the way that the points having once been refused for non-simplicity may be revisited later.

Firstly we present the notion of hierarchical-priority lists needed to explain the algorithm.

3.1 Priority Lists

The hierarchical priority lists is an ordered group of FIFO lists. Each list is assigned a priority value corresponding to a certain value of luminosity. The higher the luminosity, the higher the priority of the particular list.

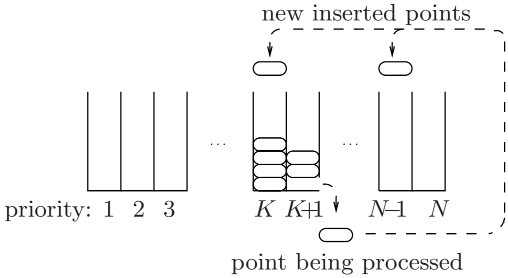


Fig. 2. Hierarchical waiting lists. $K+1$ is the current value of priority for retrieval of a point.

The maximum length each list can grow up to is known and can be decided from the picture. It equals the number of points of the corresponding grey level.

The principle is outlined in Fig. 2. The lists are accessed for insertion of new points randomly since the arriving points are of random level of grey. Retrieval of a point is done always on the non-empty list of the highest priority. The conditions on which some points are inserted in the waiting lists are explained below. It is possible that one of the arriving points has higher priority than the one of the list being processed at this moment. The list containing the new point then becomes the list of the highest priority. The lists once emptied may again be accessed for point insertion and therefore cannot be freed from memory.

See the Figure 2. The current priority of the list being read is $K + 1$. The new-arriving points are inserted in the corresponding lists. The next point to be processed in the forthcoming iteration is the one being inserted into the list $N-1$.

3.2 Principle of the Reconstruction

The procedure reconstructs an object according to a given stop criterion K. Initially the object is the empty set. The waiting lists are also empty with exception of one or more points inserted in to seed the growing. Iteratively, from the highest-priority non-empty list, a point x_i is retrieved to be processed. If this point is simple then it will make part of the output object. Whether the point is simple or not its neighbors are inserted into the respective waiting lists if their level of grey is superior or equal to K. The iteration is repeated as long as there are any points in the lists the priority of which is superior to K.

See the illustration given by Fig. 3. Let's suppose the object in form of a disc constituted by the points superior to 100. The background of the image is formed by the points inferior to this value. Let's suppose the point 120 is a marker to start the object growing.

The object growth proceeds in two directions on the boundary of the disc with the points $119, \ldots, 115$ being classified as simple. The points already inserted in the object at this moment are typeset in boldface. When the growing procedure

1	3	2	1	1	3	2
2	1	**118**	**117**	**116**	0	1
1	**119**	113	112	111	**115**	2
0	**120**	113	112	111	114	1
1	**119**	113	112	111	**115**	0
3	2	**118**	**117**	**116**	1	1
1	2	3	1	1	2	4

Fig. 3. The object is formed by points superior to 100. The point 114 once classified as non-simple is revisited for insertion.

inserts the two points of 115 then the point 114 becomes non simple. It cannot be inserted at this stage since its insertion would create a hole by disconnecting the interior from the exterior of the "C"-like object. The growing then continues with the points 113, ... , 111 filling the interior. Once the disc filled in, the point 114 is revisited. At this moment it is classified as simple and is inserted to the object.

The algorithm of reconstruction can be used in two dual modifications: *segmentation by reconstruction of the object* and *segmentation by reconstruction of the background*. We will see that these modifications are dual but not symmetric.

Segmentation by Reconstruction of the Object A marker must be given to start the object growing. It can be found manually by an expert or it may be the result of another forthcoming image analysis. A stop criterion K has to be provided to stop the growing procedure.

Segmentation by Reconstruction of the Background This method works on the grey-scale complement of the input image. The reconstruction algorithm starts with the border of the image and iteratively reconstructs the background. The points are iteratively added the bright (originally dark) points first until there are no simple points of luminosity superior to K.

The reconstructed object is free of ruptures and is reconstructed till the very extremities of the blood vessels. There is no need of marker since the object is being extracted as the complement of the background and the reconstruction is seeded with the image border.

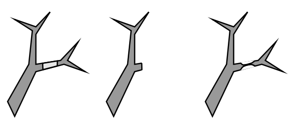
The maximum calculation complexity is equivalent for the two variants. It is almost (because of the waiting list) a liner function of the size of the image. The execution time of the two methods may however differ as it depends of the dimensions of the object. If the volume of the object is considerably smaller than the volume of the background then the reconstruction of the object is significantly faster.

4 Experiment Results

Segmentation by reconstruction of the object Let's see the segmentation results obtained by the object reconstruction method given by Fig. 5 a) and c). The result a) comprises a few principal branching of the portal artery. Lowering the threshold value however results both in rendering the result richer in the circuitry structure as well as in thickening of the arteries, cf. Fig. 5 c). It is not possible, whatever the value of the stop criterion, to obtain identical results for the two methods.

The object is topologically correct, i.e. it doesn't contain any holes or cavities in either of the two modifications. It is evident from the principle of the method that the resulting object is a simply connected 3-D object.

The disadvantage of this method is its sensitivity to noise. The growing of very thin structures deteriorated with noise can be prematurely stopped. Points which level of grey is inferior to the stop criterion will cause ruptures in the vein circuitry. See the illustration given by Figure 4. The ruptures are due to the texture-like nature of the vessels. The points which luminosity is inferior to the stop criterion are not inserted. This is the mechanism how in the worst case the cracks prevent the vessel extremities from reconstruction. This effect is quite frequent since the image is heavily noised. The segmentation by reconstruction of the background alleviates this annoying effect.



(a) (b) (c)

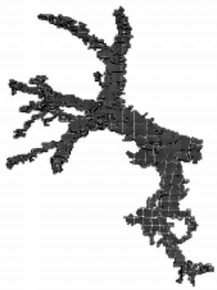
Fig. 4. The two methods give different results, a) a blood vessel with a region of faint contrast in center, b) segmentation by reconstruction of the object, c) reconstruction of the background.

Segmentation by reconstruction of the background The advantage of this method is that ruptures present in the vessels do not stop the reconstruction, see Fig. 4. The segmentation by reconstruction of the background, Fig. 4 c), is more appropriate) since the restriction to simple points prevents from creating unconnected objects.

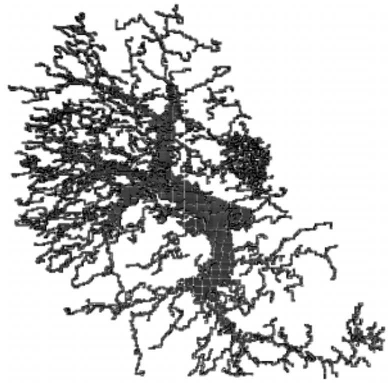
Let's now examine the results of the background reconstruction method given by Fig. 5 b) and d).

You can see that the results of segmentation by reconstruction of the background are considerably thinner than those obtained by reconstruction of the object. Fine threshold modifications enable simple means of controlling the detail level in the resulting object. The richness of the vessel structure is quite sensitive to the parameter.

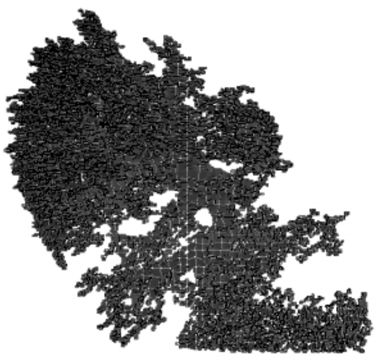
The background reconstruction method may suffer from the effect dual to the cracks in the result by reconstruction of the object. If the stop criterion is too high, this method creates thin fake vessels. This effect is caused by a noise present in the image. Bright (in the original image) points that do not belong to the object are linked with the vessel structure due to the condition of homotopy preservation.



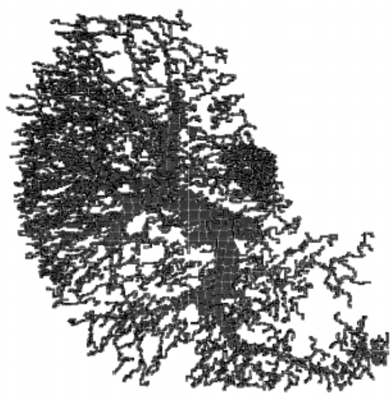
(a) Segmentation by reconstruction of the object $K = 166$



(b) Segmentation by reconstruction of the background $K = 80$



(c) Segmentation by reconstruction of the object $K = 140$



(d) Segmentation by reconstruction of the background $K = 90$

Fig. 5. Results of the liver blood vessel extraction by two dual approaches for different values of the stop criterion. (2-D rendering of 3-D objects)

5 Conclusion

Visual appraisal of the results of two segmentation methods approves the ability of the latter to produce richer and thinner result. The results of the segmentation by object reconstruction are either rather undersegmented when compared visually with the original image or too voluminous to be of practical use. The sensitivity to the stop criterion has proven better for the second method.

Further modifications and extensions : Alleviating the annoying effects of the noise doesn't seem impossible. Erroneous ramifications might be eliminated by hysteresis applied to the grey level of the branches. Employing the distance transform at the same time may give priority to filter rather the branch extremities while preserving the central artery.

The principle of the latter of the two methods enables to obtain also the skeleton of the vessel system instead of its segmentation, see [DLPB99]. To obtain the skeleton, the algorithm proceeds until unity diameter. When the current luminosity level overruns the K criterion then another condition is supplied to protect the vessel extremities from shortening. This condition is needed since the contraction of vessel extremities is a homotopic operations.

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